University of Strathclyde

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Establishing an innovative and integrated reliability and criticality based maintenance strategy for the maritime industry

by

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Ithaca

‘When you set out on your journey to Ithaca, pray that the road is long,
full of adventure, full of knowledge.

….

That the summer mornings are many, when, with such pleasure, with such joy
you will enter ports seen for the first time;
stop at Phoenician markets, and purchase fine merchandise,
mother-of-pearl and coral, amber and ebony, and sensual perfumes of all kinds,
as many sensual perfumes as you can; visit many Egyptian cities,
to learn and learn from scholars.
Always keep Ithaca in your mind.
To arrive there is your ultimate goal.’

Ιθάκη

‘Σα βγεις στον πηγαιμό για την Ιθάκη, να εύχεσαι νάναι μακρύς ο δρόμος,
γεμάτος περιπέτειες, γεμάτος γνώσεις.

…

Πολλά τα καλοκαιρινά πρωϊά να είναι που με τι ευχαρίστησι, με τι χαρά
θα μπαίνεις σε λιμένας πρωτοειδωμένους,
να σταματήσεις σ' εμπορεία Φοινικικά, και τες καλές πραγμάτειες ν' αποκτήσεις,
σεντέφια και κοράλλια, κεχριμπάρια κ' έβενους, και ηδονικά μυρωδικά κάθε λογής,
όσο μπορείς πιο άφθονα ηδονικά μυρωδικά, σε πόλεις Αιγυπτιακές πολλές να πας,
να μάθεις και να μάθεις απ' τους σπουδασμένους.
Πάντα στον νου σου νάχεις την Ιθάκη.
Το φθάσιμον εκεί είν' ο προορισμός σου.’

Konstantinos P. Kavafis (1863-1933)

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NOMENCLATURE

ABS	American Bureau of Shipping
AHP	Analytical Hierarchy Process
ALARP	As Low As Reasonably Practicable
AM	Asset Management
BBN	Bayesian Belief Networks
BCM	Business Centered Maintenance
BIMCO	The Baltic and International Maritime Council
Bir	Birnbaum
BS/ISO	British Standards / International Standards Organisation
CAD	Computer Aided Design
CAS	Condition Assessment
CBM	Condition Based Maintenance
CMMS	Computerised Maintenance Management Systems
ConMon	Condition Monitoring
Cri	Criticality
DG	Diesel Generator
DNV	Det Norske Veritas
DPA	Designated Person Ashore
DP	Dynamic Positioning
DSP	Decision Support Process
DSV	Diving Support Vessel
ECSA	European Community Ship-owners' Association
ETA	Event Tree Analysis
EU/EEA	European Union/European Economic Area
FFA	Functional Failure Analysis
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FPSO	Floating Production Storage Offloading
FPU	Floating Production Unit
FSA	Formal Safety Assessment
FSO	Floating Storage Offloading

FST	Fussy Set Theory
FTA	Fault Tree Analysis
FT	Fault Tree
F-V	Fussell-Vesely
HAZID	Hazard Identification
HAZOP	Hazard and Operability study
HSQE	Health Safety Quality Environment
HSE	The UK Health and Safety Executive
HSWA	UK Health & Safety at Work Act
IACS	International Association of Classification Societies
ILS	Integrated Logistic Support
IMO	International Maritime Organisation
IMs	Importance Measures
ISM code	International Safety Management code
ISF	International Shipping Federation
ISO	International Standards Organisation
KPI	Key Performance Indicators
LA&H	Lifting Anchoring & Hauling system
LNG	Liquefied Natural Gas
LSA	Logistic Support Analysis
MA	Markov Analysis
MADM	Multi Attribute Decision Making
MoD	Ministry of Defence
MOU	Memorandum Of Understanding
MTBF	Mean Time Between Failures
NORSOK	Norsk Sokkels Konkuranseposisjon (Norwegian Offshore Sector)
NPD	Norwegian Petroleum Directorate
OCIMF	Oil Companies International Marine Forum
OECD	Organisation for Economic Cooperation and Development
OREDA	Offshore Reliability Database
PF	Potential Failure
PMS	Planned Maintenance Systems
PoF	Probability of Failure

RBD	Reliability Block Diagrams
RBI	Risk Based Inspection
RBM	Risk Based Maintenance
RCBM	Reliability and Criticality Based Maintenance
RCM	Reliability Centered Maintenance
SDC	Submersible Decompression Chamber
SMS	Safety management System
SPHL	Self-Propelled Hyperbaric Lifeboat
SPI	Shipping Performance Indicators
SWIFT	Structured What-If Technique
SWOT	Strengths, Weaknesses, Opportunities and Threats analysis
TOPSIS	Technique Ordered Preference by Similarity to Ideal Solution
TM	Thickness Measurement
TMSA	Tanker Management Self-Assessment
TPM	Total Productive Maintenance
UKOOA	UK Offshore Operators Association
UNCTAD	United Nations Conference on Trade and Development
UTM	Ultrasonic Thickness Measurement
VBM	Vibration Based Maintenance

ABSTRACT

For a number of years ship maintenance has been considered as more of a financial burden than as a way to preserve safety, environment and high-quality transportation of passengers and goods worldwide. In the first place, the benefits from applying a sound and systematic maintenance policy emerge both in the enhancement of the reliability of a ship and the minimisation of unnecessary downtime. In this thesis, a novel maintenance strategy for the maritime industry is suggested, namely the Reliability and Criticality Based Maintenance (RCBM) strategy focusing not only on increasing the reliability of the main systems and components but also on examining which of them are the most critical for the operation of the entire system under examination. In this respect, the combination of Total Productive Maintenance (TPM) as well as Reliability Centered Maintenance (RCM) is proposed engulfing the advantages of the managerial and technical aspects of both maintenance approaches. In order to achieve the above, reliability tools and techniques such as Failure Modes, Effects and Criticality Analysis (FMECA) and Dynamic Fault Tree Analysis (DFTA) as well as the implementation of the Fuzzy Set Theory (FST) are applied in order to address a multi attribute decision making problem such as the selection of the optimum maintenance approach for a subject vessel. The above are clearly demonstrated in the case of a Diving Support Vessel (DSV A) as well as in the case of the Diesel Generator (DG) system of a motor sailing cruise ship. Outcomes of this study are the identification of the critical components of each system, the calculation of the reliability of the overall system and sub-systems, the prioritisation of the maintenance tasks as well as the suggestion of specific measures which will enhance the reliability and availability of the overall system.

Keywords

Keywords: Maintenance, maritime industry, reliability, criticality, availability, Dynamic Fault Tree Analysis (DFTA), Multi Attribute Decision Making (MADM)

1 CHAPTER 1-INTRODUCTION

1.1 Chapter outline

In this Chapter, the background information for the initiation of the present dissertation is described. A brief presentation of the different Chapters pertaining to it is also performed, clarifying their content as well as introducing the reader into the core of the thesis.

1.2 General introduction

As is well known, the maritime industry is responsible for the transportation of the vast majority of the world's commercial products. In the latest report published by the European Community Shipowners' Association (ECSA) it is mentioned that the merchandise transported in the European Union/European Economic Area (EU/EEA) zone by ships reached a level of 90% of its external trade while another 40% was carried internally among its member-states (ECSA 2010). The importance of this observation is also obvious when noting that nearly half a million seafarers are employed through the maritime sector as mentioned in the same report. Additionally, the seaborne transportation of goods worldwide is closely related to the growth of the world Gross Domestic Product (GDP). The GDP growth for various countries across the world has been increasing, reaching its peak in 2007 while since then it presents a declining trend till 2009 due to the worldwide financial crisis although it has shown signs of recovery in 2010 (UNCTAD 2010).

In the same report produced by the United Nations Conference on Trade and Development (UNCTAD, the importance of the maritime transportation of goods worldwide is also denoted when comparing the annual indices of the world merchandise trade, world seaborne trade, world GDP and OECD industrial production index. In this case, the correlation between the increase in the world seaborne trade and a similar increase in the world merchandise trade during the last years is clearly depicted. Furthermore, it is evident that despite the decline in the GDP growth in the last two years, the world economic growth has started to regain momentum and this is also shown in the numbers of the world seaborne trade which has also started to increase.

More details on the seaborne trade transported throughout the years demonstrate the interrelation between the world economic growth and the increase in the international seaborne trade. The latter has also increased in every sector of the international shipping trade including crude oil and its products, the main dry bulk cargoes (iron ore, grain, coal, bauxite/alumina and phosphate) as well as the containerised and the rest of the dry cargoes (Figure 1.1, Table 1.1).

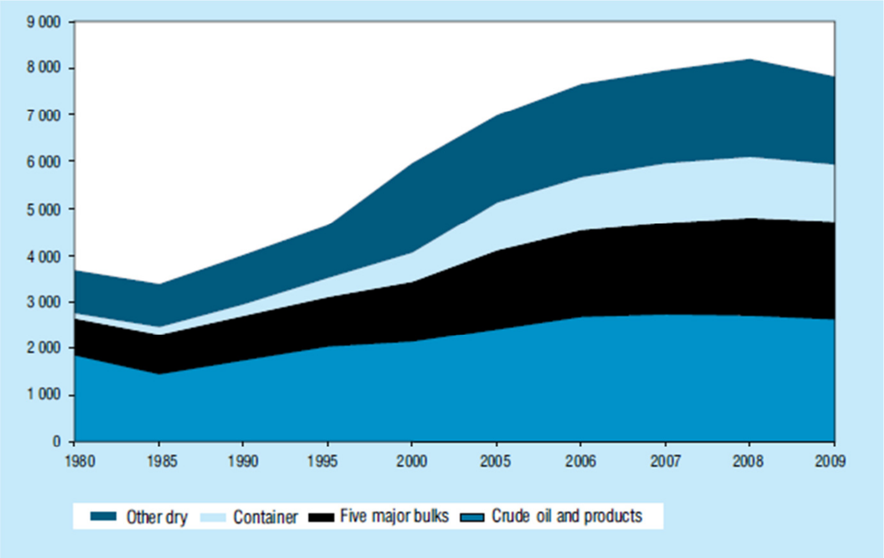

Figure 1.1 International seaborne trade-millions of tons loaded (UNCTAD 2010)

Table 1.1 Development of international seaborne trade, millions of tons loaded (adapted from UNCTAD 2010)

Year	Oil	Main bulks	Other dry cargo	total (all cargoes)
1970	1,442	448	676	2,566
1980	1,871	796	1,037	3,704
1990	1,755	968	1,285	4,008
2000	2,163	1,288	2,533	5,984
2006	2,698	1,849	3,135	7,682
2007	2,747	1,972	3,265	7,983
2008	2,732	2,079	3,399	8,210
2009	2,649	2,113	3,081	7,843

In this case, the amount of the transported cargoes has steadily risen through the years, a trend which has been followed by a proportional augmentation in the size of the worldwide ship fleet accordingly. This is demonstrated furthermore in the new-building sector as well in which the world tonnage on order for all major ship types (dry bulk carriers, oil tankers, container ships and general cargo ships) has been also gradually increasing for the past decade, while only presenting a slight decline during 2009.

However, despite the above decrease in the number of orders for new-built ships, the overall capacity available (in thousand dwt) has significantly increased when comparing the world fleet size by principal vessel types for 2009 and 2010 (Table 1.2). The latter is mainly due to the supply of new orders being delivered in 2010 (for orders placed before that period). As can be seen, the total capacity (dwt) of all major vessel types has increased in most cases between 2009 and 2010 apart from a slight decrease in the case of general cargo ships (-0.60%) and a higher reduction in the case of chemical tankers.

Table 1.2 World fleet size by principal vessel types 2009-2010 (thousands dwt) vessels 100 GT and above (adapted from UNCTAD 2010)

Principal types	2009	%	2010	%	Percentage change/increase
Bulk carriers	418,356	32.76	456,623	33.37	9.15
Oil tankers	418,266	32.75	450,053	32.89	7.60
Container ships	161,919	12.68	169,158	12.36	4.47
General cargo ships	108,881	8.52	108,232	7.91	-0.60
Other type of ships	84,895	6.65	92,072	6.73	8.45
Liquefied gas carriers	36,341	2.85	40,664	2.97	11.90
Offshore supply	22,567	1.77	24,673	1.80	9.33
Other	11,762	0.92	13,229	0.97	12.47
Chemical tankers	8,141	0.64	7,354	0.54	-9.67
Ferries and passenger ships	6,083	0.48	6,152	0.45	1.13
Total	1,277,211		1,368,210		7.12%

Summarising the above, the current world fleet size in terms of main vessel types in thousands of dwt (vessels 100 GT and above) is shown in Figure 1.2.

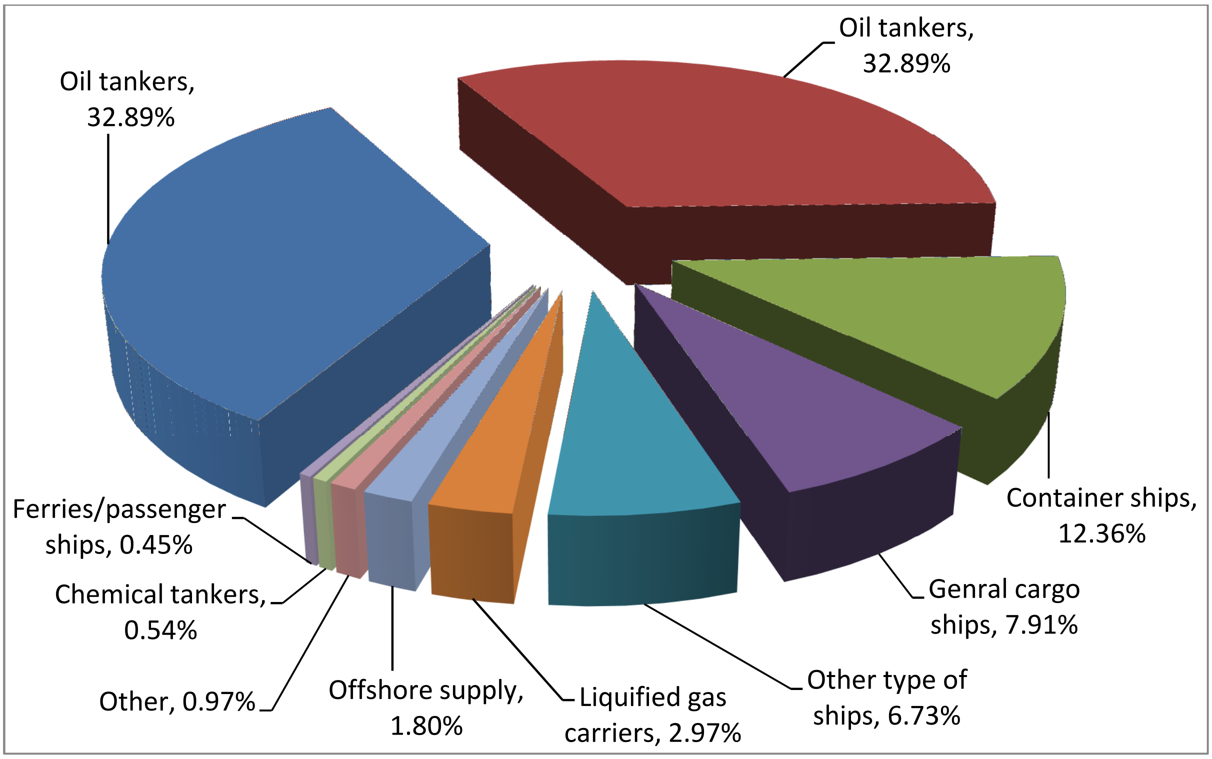

Figure 1.2 World fleet size by principal vessel types 2010 (thousands dwt) vessels 100 GT and above (adapted from UNCTAD 2010)

As can be observed, despite the fluctuations in the worldwide trade and the new ship orders placed for the last few years, the majority of the worldwide fleet is still dominated by the two major ship types; that is the bulk carriers (33.27%) and the oil tankers (32.89%). The container ships as well as the general cargo ships follow next with 12.36% and almost 8% respectively.

All the above clearly indicate that the maritime industry plays a significant role in the transportation of goods and passengers worldwide. However, there are also several concerns that need to be addressed regarding the safe and environmentally friendly operation of these same ships, for which their availability is extremely important. The latter refers to the downtime originating from the application -or even lack- of the minimum requirements for maintenance and subsequently the occurrence of unexpected failures, thus rendering the ships unavailable for a period of time. This is highly undesirable both due to the obvious cost for the repairs needed to be carried out as well as due to the loss of ship-generated income.

As a result of the above, the cost pertaining to ship maintenance activities can account for as much as 10-15% of a shipping company direct operating costs and have remained at this level for many years (Stopford 2007). Moreover, ships, which are not maintained or their equipment and structure is not monitored properly, pose risk to the environment as well to people-both crew and passengers- and cargo onboard. The latter involves accidents (e.g. *Erika* in 1999, *Prestige* in 2002) which can be partially attributed to lack of maintenance or, even more fundamental, to inappropriate maintenance procedures followed both onboard and onshore including maintenance tasks carried out either onboard by the ship's crew or in the shipyard during the dry-docking period (Devanney 2010).

Moreover, seafarers are occupied with various tasks to fulfil when sailing onboard a vessel both from operational and maintenance point of view while the ship is trading in busy and-in some cases-short distance routes. As shown in Figure 1.3, the calculated days at sea for different ship types (especially in the case of the 'working horses' of the merchant fleet-dry cargo, tanker and Ro-Ro vessels) are quite high which consequently, leaves little space for the onboard human resource to deal with any type of maintenance activities.

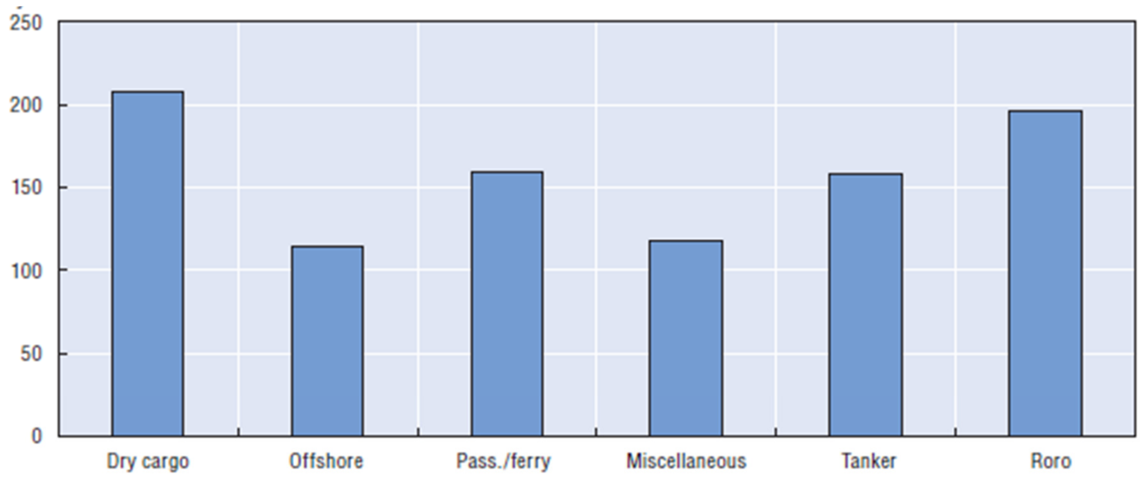

Figure 1.3 Calculated days at sea for different vessel categories (OECD, 2010)

Additionally, it is even more frequent to observe the fact that the time spent by seafarers onboard the ship is continually reduced (e.g. due to equipment automation) as well as the compilation of the crewmembers changes more often than before. Moreover, according to various studies on the subject matter, it is expected that shortages will occur in the number of crewmembers onboard ships, particularly in the case of the European owned and operated vessel fleet (BIMCO/ISF 2010, Tang 2009). Consequently, there is a need for a standard, well-understood approach for the maintenance tasks to be followed.

Regarding the issues related to crew training, it has improved drastically in recent years including full mission bridge and engine room simulators, online course material, etc. However, it is suggested that there is still space for additional improvements (Bosma et al 2011). This brings in mind the education and training techniques and methods that are already in place in other industrial sectors such as the aviation industry in which the current training and education of new and existing personnel is upgraded in order to match the high operational profile of the subject industry.

Furthermore, the maritime regulatory and administration authorities such as Flag states, Port State Control authorities and Classification Societies have increased their cooperation towards the promotion of the requirements for safe, secure and environmental friendly ship operations (with impact to ship maintenance as well) over the last years. The mentioned initiatives take the form of both formal cooperation among groups of countries introducing mandatory rules (e.g. Paris MOU, Tokyo MOU, etc.) as well as the form of guidelines introduced by other maritime stakeholders (e.g. OCIMF, IACS). In all cases, all relevant bodies strive to preserve the highest standards in the maritime industry while at the same time make every effort in order to minimise the sub-standard operators which may 'cut corners' and minimise or avoid good maintenance practices and proper ship maintenance procedures.

On top of the above, ship managers/operators still try to find a way to combine the rich practical knowledge acquired in the actual marine field with the technological advances stemming from the relevant information technology sector in an effective way. It should be noted that the key point in this respect is to identify the essential information and decide which maintenance approach is the most efficient to follow.

This comes in addition to the effects of not applying the appropriate maintenance sequence onboard a ship. This is related to expenses stemming from frequent inspections (including spare parts, attendance from company's personnel and classification society's surveyors, temporary or permanent repair measures) which may constitute a big portion of the total maintenance expenditure. Moreover, when repair works and/or spare parts are needed onboard the vessel, they have to be planned well in advance as the ship sails in different geographical locations, thus with significant functional/access restrictions.

Additionally, the technical advances in terms of the lately implemented on-line maintenance reports from the ship to the onshore headquarters of a shipping company/operator require well trained personnel and user friendly software platforms applied. Data gathering, elaboration and dissemination require an amount of human and technical resources, which are difficult to manage and operate simultaneously. It is often the case of accumulating maintenance data without being able to convert it to accessible information. Moreover, further delays occur from a shortage in efficient communication among the ship's owner/manager side, the shipyard and the supplier so as to plan the repair and maintenance process. In this case, ships may have to wait in the repair shipyard alongside the quay before any inspections are performed.

Besides of the above, the maintenance process in the maritime sector still lacks the element of applying and implementing technologically advanced tools in contrast to applications in other industrial sectors such as the defence or aerospace industry which provide real-time monitoring (e.g. condition monitoring tools and techniques) and highly available good-quality spare parts. Still, despite some cases in which condition based monitoring is applied in the maritime industry, (including research on condition based inspections and improvement of ship machinery equipment), major machinery and hull structural failures are still being reported (Imarest 2011a). Compared to land based industries in which maintenance intervals are strictly kept on schedule, condition monitoring procedures in the maritime industry are also not well established yet (Imarest 2011b).

The last issue comes in addition to the fact that the maintenance impact and procedures followed onboard a ship may differ in terms of whether passenger or cargo is transported (cruise vs. cargo ships). In the first case, the demand and requirements for the best maintenance policy followed onboard the ship is of paramount importance while in the second case alternative/corrective maintenance tactics may be involved. In these circumstances in which corrective maintenance is implemented, they usually lead to expensive repairs, significant loss of time/off-hire periods and a decrease in the ship's credibility. On the other hand, when preventive maintenance tasks are implemented, they may create an 'over-maintained' policy, in which the ship's components are replaced before the end of their operational life, thus leading to the accumulation of unnecessary and expensive spare parts/inventory lists.

Furthermore, there is neither a structured way of dealing with maintenance nor exists an overall maintenance practice followed in the maritime industry. On the other hand, the majority of the shipping companies/operators still heavily rely on the technical expertise developed in-house as well as on the knowledge that senior personnel have accumulated through the years. In most cases it's only a 'word of mouth' that is passed over from the senior to the younger management staff. When qualified personnel move to another company/industrial field, the 'know-how' moves with them and is not retained within the company/maritime industry.

Bearing the above in mind, it is apparent that there is still a gap to fulfil regarding maritime maintenance. This is related to the co-existence and coordination of the technical as well as the managerial element of maintenance in the maritime context, taking into account and supporting the existing parts of a typical shipping company. In this respect, the novel Reliability and Criticality Based Maintenance (RCBM) strategy is introduced which takes into account the identification of the most critical systems, sub-systems and eventually components for the operation of a ship; thus suggest measures so as for it to retain its functionality and thus increase its reliability and availability. The novel suggested maintenance framework is carried out at strategic, tactical and operational levels and it is developed based on the explicit needs of the maritime market when requesting solutions to specific problems arising during the actual ship operation.

More specifically, RCBM considers the combination of the advantages of Total Productive Maintenance (TPM) regarding the management and organisational aspect of the approach including leadership support, strategic planning, planning for implementation, training and re-training, communicating the decisions to all persons involved in-house (onshore and crew onboard) as well as shipyards, equipment and engine manufacturers. On the other hand, the Reliability Centered Maintenance (RCM) benefits are also incorporated regarding the technical features of the approach such as expertise involved (technical managers, captains, engineers), detailed system analysis, introduction of functional analysis and all the technical aspects of it. Instead of bringing the system back to a 'perfect' operational state, the RCBM strategy intends to bring it back to a good functional state within the operational limits of each case. This is the main purpose of the current dissertation, which will be achieved through a number of Chapters as these are shown in the next section.

1.3 Dissertation layout

The present thesis is structured in eleven Chapters as shown in Figure 1.4. It is developed in such a way so as to introduce the reader in the current research topic and at the same time make the reading flow smoothly throughout each section.

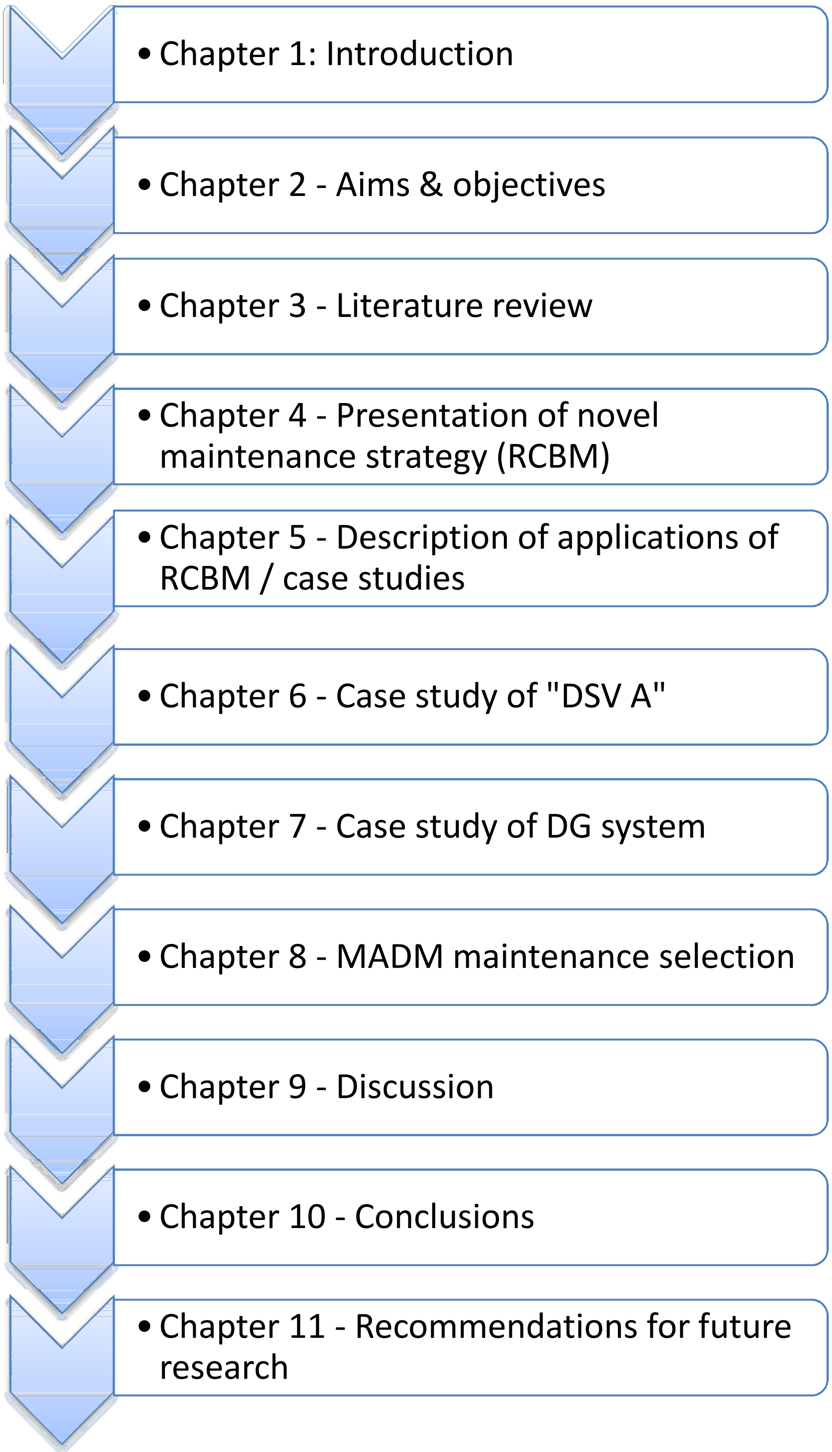

Figure 1.4 Presentation of the chapters of the thesis

In this respect, by initially introducing the main aim and objectives of the thesis in Chapter 2, the reader is familiarised with the specific elements of the research subject and thus gets prepared for the next section which is the literature review carried out on the various existing maintenance methodologies and techniques as shown in Chapter 3.

The latter is divided into three separate sections. The first one is used to draw the generic picture of the maintenance regime in the industrial world by examining the three main maintenance streams (i.e. corrective, preventive and predictive maintenance) and moreover it is supplemented by the presentation of different maintenance methodologies already applied in other industrial sectors. These include the Terotechnology model, Integrated Logistic Support (ILS) and Logistic Support Analysis (LSA), Business Centered Maintenance (BCM), Risk Based Inspection (RBI) and Risk Based Maintenance (RBM), Vibration Based Maintenance (VBM) and Condition Based Maintenance (CBM) as well as the Asset Management (AM) approach. Furthermore, the above are followed by the presentation of two of the most popular maintenance methodologies and cornerstones of the maintenance strategy presented herein; that is, Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM) approach.

The second section of the literature review identifies the existing maintenance approaches in the maritime world and how these are being implemented. A detailed review of the RCM, RBI, Condition Monitoring (ConMon) and IT applications in maintenance with specific relevance in the maritime industry are presented and explained in details. In this way, the similarities - and most significantly - the differences between the maintenance approaches in shipping and other industries are also classified. The third part of Chapter 3 consists of an in-depth examination of the various reliability tools and techniques that can be utilised in the reliability and criticality analysis of the suggested methodology. Having performed an exhaustive literature review, the foundations for the introduction of the novel maritime maintenance framework are established.

In this respect, the novel maintenance strategy for the maritime industry, that is the Reliability and Criticality based Maintenance (RCBM), is presented and furthermore explained in detail in Chapter 4. This is achieved through the combination of the managerial aspects of Total Productive Maintenance (TPM) as well as the technical features of Reliability Centered Maintenance (RCM). Moreover, specific reliability and criticality analysis tools are employed, through which the application of the aforesaid maintenance framework is realised. This is performed with the use of the DFTA and FMECA tools including a purpose-built criticality matrix. In addition to the above, the FST is employed in order to assist in the identification of the maintenance approach required when facing a multi attributive decision making problem such as the optimum maintenance methodology for a given vessel.

All the above are shown with more details when implementing the proposed novel maintenance strategy with regards to two case studies presented in Chapter 5. This includes the case of the Diving Support Vessel "*DSV A*" and the Diesel Generator (DG) system of a motor sailing cruise ship. In the first case, more attention is given to the implementation of the above novel strategy in an overall ship system, thus examining the reliability and criticality analysis of its main systems including the Power plant, Propulsion, Lifting, handling and anchoring, Water, Diving and finally the Safety system. In the second case study, higher importance is given to the technical details of a subject system by examining the application of the suggested maintenance strategy in five individual DGs of the ship (DG 1, DG 2, DG 3, DG 4, DG 5-emergency generator), which are capable of providing the entire power generation capability of the subject vessel. In this respect, the proposed maintenance strategy is examined in the case of a macro-system (entire ship) as well as in the case of a micro-system (specific machinery equipment such as the DGs of a ship).

Furthermore, the results for both applications of the RCBM strategy are demonstrated next. At first, the reliability results of each one of the main systems of "*DSV A*" are shown in Chapter 6. These are contemplated with the results of the Probability of Failure (PoF) curves of the sub-systems of "*DSV A*" followed by the results of the reliability importance measures (IMs). Then, the presentation of the cut sets for all the systems shown is demonstrated in order to assist in the identification of the most critical components of the subject vessel. In this way, additional maintenance measures can be suggested in terms of the introduction of dynamic 'SPARE' gates in the DFT modelling structure for each main system examined. Moreover, based on the results achieved through the reliability and most importantly the criticality analysis, the availability of the overall system ("*DSV A*") is also investigated, thus demonstrating the benefits attained with the use of the RCBM strategy.

In addition to the above, the second case study related to the DG system of a motor sailing cruise ship is presented in Chapter 7. Initially, the FMECA approach is examined for the overall DG system. This includes the presentation of the most critical components of each one of the DG sub-systems based on the frequency of the failures of the components as well as the severity of these failures occurring. Further investigation is also conducted with the use of the DFTA tool. The comparison of the reliability results of each individual DG before and after the introduction of 'SPARE' gates and events is also performed. This is carried out in order to investigate and identify the individual DG which has the worst reliability performance and accordingly needs to be considered for improvement. Likewise, an evaluation of the entire DG system of the subject vessel is performed; comparing the critical items of each separate DG with each other concerning the specific sub-systems mentioned. Moreover, the reliability results of the entire DG system are also examined in the light of the suggested remedial maintenance measures as well as a cost assessment pertaining to the various maintenance approaches for the subject system is additionally discussed.

The above proposed novel maintenance strategy is is moreover improved with the implementation of a methodology which further enhances the selection of the most appropriate maintenance approach in the maritime industry. This is the case of the utilisation of the Fuzzy Set Theory (FST) and its specific application in a Multi Attribute Decision Making (MADM) maintenance problem presented in Chapter 8. The MADM maintenance problem refers to the selection of the most appropriate maintenance approach for a ship based on the examination and combination of various parameters, which differ one from the other and which cannot be brought together in the first place. This is the case of the combination of parameters such as the cost of each maintenance approach, its efficiency, the improvement of the reliability of the system examined and the top management commitment. Additionally, other factors can be also combined with the above including the effect of the cost for crew training, the company's investment, the spare part inventories needed for each maintenance method and the operational loss if a specific maintenance approach is implemented. The above mentioned combination is performed by employing multiple experts' judgement through three distinctive stages in the application of FST, namely the rating, aggregation and selection stage. The above methodology is applied in the case of the DG system of the motor sailing cruise vessel presented before. Concerning the final selection step of the suggested methodology, the TOPSIS ranking tool is also used, thus concluding the proposed fuzzy set methodology.

Moreover, the discussion of the overall thesis takes place in Chapter 9 while the concluding remarks regarding the innovative maintenance strategy are demonstrated in Chapter 10. Finally, Chapter 11 concludes the thesis in hand with the recommendations for further research.

Supplementing the main part of the current research study, a number of Appendices are included at the end of the thesis. In this respect, Appendix A presents in detail the various approaches and techniques used in reliability analysis including qualitative tools such as the Failure Modes, Effects and Criticality Analysis (FMEA/FMECA), Hazard Identification (HAZID), Hazard and Operability study (HAZOP), Structured What-If Technique (SWIFT), Bow Tie and Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis tools. Moreover, quantitative methods are also presented including the Event Tree Analysis (ETA), Reliability Block Diagrams (RBD), Bayesian Belief Networks (BBN), Markov Analysis (MA), Monte Carlo simulations, the application of Fussy Set Theory (FST) in Multi Attribute Decision Making (MADM) problems and finally the Fault Tree Analysis and Dynamic Fault Tree Analysis (FTA/DFTA) and Importance Measures (IMs) as well.

Appendix B presents the Mean Time Between Failures (MTBF) used in the first case study of the diving support vessel "*DSV A*" while Appendices C and D demonstrate the full details of the Dynamic Fault Trees (DFT) structures developed for the subject vessel. Appendix E presents the DFT structure used in the case of calculating the overall availability of the subject vessel. Appendices F to H pertain to the case study of the Diesel Generator (DG) system of a motor sailing cruise ship presenting the corresponding DFTs for the second case study and the developed Failure Modes, Effects and Criticality Analysis (FMECA). Finally, Appendix I shows the questionnaire used in order to acquire the experts' responses on the Multi Attribute Decision Making (MADM) maintenance problem.

1.4 Chapter summary

In this Chapter, the introductory part of the present thesis is shown providing a brief description regarding the maintenance regime in general as well as in the maritime sector explicitly. The various difficulties and challenges that maritime maintenance faces in the current shipping context are also demonstrated. Furthermore, an outline of the Chapters that the present thesis consists of is also demonstrated, providing the reader with the necessary information for the content of the thesis which will be presented next. With this in mind, the following Chapter presents the first step towards the realisation of the current research study; that is the detailed presentation of the main aim and objectives through which the novel maintenance strategy for the maritime industry is implemented.

2 CHAPTER 2-RESEARCH QUESTION, AIM & OBJECTIVES

2.1 Chapter outline

In this Chapter, the research question as well as the main aim and objectives of the present thesis are shown and described next.

2.2 Research question

The research question of the present thesis can be formulated as following:

How can the maritime industry implement and integrate the optimal maintenance strategy based on reliability and criticality assessment in order to increase the robustness and availability of ships while minimising the cost?

2.3 Aims & objectives

The main aim of the thesis is to answer the research question stated above, thus develop an innovative and integrated maintenance strategy for the maritime industry based on reliability and criticality assessment as well as to investigate its application to ships. The objectives related to the above mentioned aim are the following:

1. Initially, investigate the existing maintenance methodologies and approaches in the literature already applied in other business sectors as well as in the maritime industry and identify their similarities, variations and gaps
2. Propose an innovative and integrated maintenance strategy for the maritime industry

and demonstrate the various elements that it consists of in full depth

3. Identify the best reliability and criticality techniques and tools which can be implemented in order to demonstrate the full results of the above strategy
4. Perform a field study to collect the failure and maintenance data regarding ships' operation while establishing the current maintenance and repair practices in the maritime industry
5. Demonstrate the application of the innovative maintenance strategy on the different systems of a Diving Support Vessel (DSV) as well as on the Diesel Generator (DG) system of a motor sailing cruise ship
6. Assess and quantify the reliability of the main system and sub-systems examined as well as identify the critical parts of the systems under investigation
7. Apply remedial measures and verify their outcome by examining the reliability index of the various systems mentioned as well as the overall availability of ships
8. Provide suggestions at both a generic and detailed level on how to improve the reliability of the maritime assets in question
9. Examine the applicability of Fuzzy Set Theory in the multi attribute decision-making maintenance environment.

2.4 Chapter summary

In this Chapter, the research question of the present thesis has been formulated along with the thesis principal aim and objectives. The next Chapter presents the literature review carried out on the existing maintenance approaches in the maritime industry as well as in the broader industrial field.

3 CHAPTER 3-LITERATURE REVIEW

3.1 Chapter outline

In this Chapter, the overall literature review of the present thesis is demonstrated. It encompasses of three parts. The first one refers to the maintenance efforts and approaches applied in various industrial sectors including the Terotechnology model, Integrated Logistic Support (ILS) and Logistic Support Analysis (LSA), Business Centered Maintenance (BCM), Risk Based Inspection (RBI) and Risk Based Maintenance (RBM), Vibration Based Maintenance (VBM) and Condition Based Maintenance (CBM) as well as the Asset Management (AM) approach. Subsequently, two of the most popular maintenance methodologies are presented, in which the suggested innovative maritime maintenance framework is based on. These are the Total Productive Maintenance (TPM) and Reliability Centered Maintenance (RCM) types. The second part of Chapter 3 refers to the literature review regarding maintenance in the maritime sector. In it, the corrective, preventive and predictive maintenance types are also examined with regards to the maritime implementation. Additionally, predictive maintenance is further investigated in terms of the RCM, RBI (in shipping and offshore sectors), Condition Monitoring (ConMon) and IT applications specifically for the maritime industry. Finally, the third part of the present Chapter examines the various reliability and criticality tools and methods available in the literature. The above is performed in order to obtain a clear insight of the existing maintenance approaches currently available, identify the existing gaps and prepare the ground for the introduction of the novel maintenance framework presented in this thesis.

3.2 Overview of maintenance methodologies

In general, there are several maintenance approaches and frameworks which have been implemented in various industrial sectors through time. These differentiate from each other in terms of whether they refer to a generic or to a more technical context, investigating different parameters of the maintenance classification (Figure 3.1). More specifically, the first category consists of approaches such as the Terotechnology model, the ILS/LSA, BCA, AM and TPM which examine maintenance in the light of an overall approach mostly referring to the management and commercial attributes related to it. On the other hand, the second maintenance category includes approaches such as the RBI/RBM, VBM/CBM and RCM, which pertain more to the technical aspect of maintenance and thus provide more details on the way the maintenance framework is being implemented. In general terms maintenance is defined as (BS 3811, 1993):

"The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required action".

In other words, for a maintenance programme to be effective, it should be able to deliver the desired performance wanted by the operator within the limits of the built-in capability of an item/component/system, taking into account the health, safety, environment and other important concerns.

As mentioned above, maintenance can be broadly sub-divided into three major categories in terms of the chronological order that these are implemented. In this regard, corrective maintenance originated first, followed by preventive and lastly by the predictive maintenance framework and these are described in detail at section §3.6.1. In the literature, one can find various definitions of these categories and their sub-categories. Cooke & Bedford (2002) present a customisation of maintenance types according to whether these may include an actual intervention to the asset to be maintained (corrective or preventive type of maintenance) or a scheduling task (calendar based, condition based, opportunity based and emergency maintenance); that is the timing that the maintenance actions take place.

In general, corrective (or run-to-failure) approach is used to carry out any maintenance job that may originate during the daily operational routine. A very small number (or even none at all) of spare parts are used and repairing the specific item is a matter of 'hands on' experience applied from the person handling the equipment. Then, preventive maintenance evolved, which is based on time-intervals deriving from the experience of the equipment operator or suggested by the manufacturer of the original piece of equipment. In this case, breakdown time is reduced or minimised though an item can be replaced even if it still is in good operational condition. In order to overcome this complexity, predictive maintenance is introduced in which the condition of an item/component/system is monitored and maintenance takes place only when the maximum operational interval is reached. In addition to the above, the current maintenance methodologies are presented next.

3.3 General outline of maintenance approaches

As mentioned above, there are two major streams regarding maintenance and its applications in various industrial sectors. In this respect, a thorough review of the mentioned maintenance methodologies applied in different industrial sectors is presented in the following paragraphs (Figure 3.1). Moreover, specific attention and description with further details is provided for the TPM as well as the RCM approaches, due to their significance in the maintenance field regarding their conceptual framework and due to their dominance in terms of the case studies in which they have been applied.

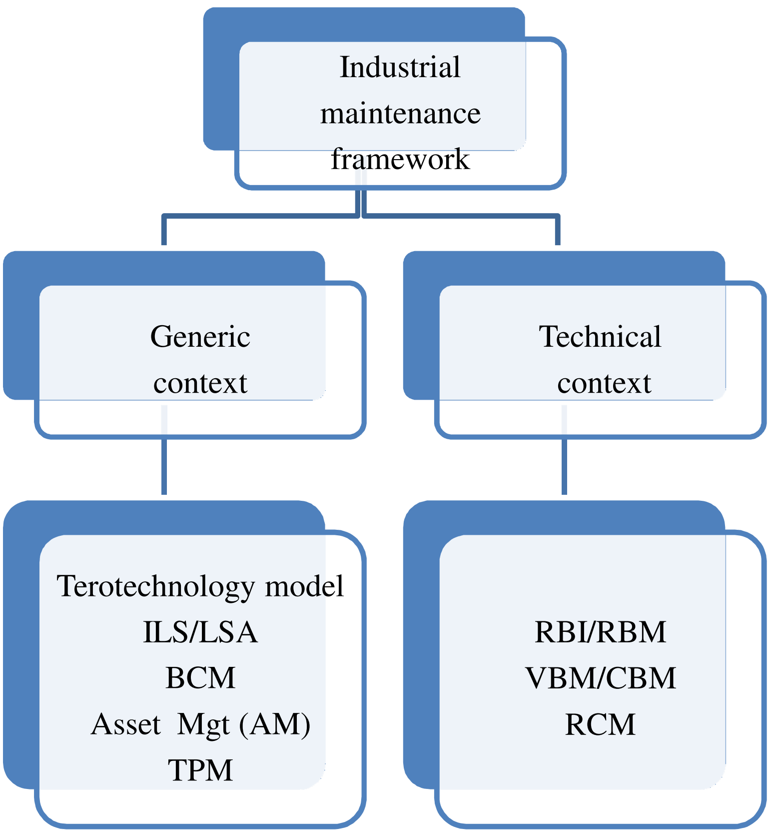

Figure 3.1 Literature review layout regarding the general industrial maintenance framework

3.3.1 Terotechnology

The Terotechnology model initiated in the manufacturing industry in the UK in the '70s in order to assess the interrelation among actual maintenance costs, improved productivity and profits originating from efficient and effective maintenance tasks. BS/ISO 3811 (1993) provide the definition of terotechnology as:

"A combination of management, financial, engineering, building and other practices applied to physical assets in pursuit of economic life cycle costs."

In this context, terotechnology focuses more in the design of physical assets and products including among others the specification, installation, operation and finally maintenance aspects providing feedback to the initial design stage. In other words, this is the origin of the maintainability concept as presented in the UK MoD (2006). As Sherwin (2000) also mentions the basic terotechnology model lacks the aspect of making clear that the maintenance department can contribute in the profit-making process of a company than just considered to be a financial burden. In these terms, the main characteristic of terotechnology is that it considers the overall managerial framework of a business in which maintenance is a small part of it. In this context, terotechnology may be considered as an early version of the Asset Management framework which is presented in the following sections.

3.3.2 Integrated Logistic Support / Logistic Support Analysis (ILS/LSA)

Integrated Logistic Support (ILS) and Logistic Support Analysis (LSA) is another management concept which also contains maintenance as part of its activities for improvement. Mostly related to the military sector (Blanchard 1992), it is described as:

'A disciplined, generalised, and interactive approach to the management and technical activities necessary to integrate support considerations into system and equipment design' (MIL-ST-1388)

As Wayyenberg and Pinelon (2002) mention, ILS and LSA refer to all aspects of support to a technical system mostly linked to the related cost and its minimisation. In these terms, this may include purchasing, product distribution, operations, inventory, maintenance and disposal cost. Going in depth specifically regarding maintenance, this includes data collection systems, consideration of spare parts, selection of the appropriate maintenance personnel as well as the suitable training required to perform the right tasks. All the above need to provide for the overall reduction of the Life Cycle Cost taking into account all the different phases of the system considered. LSA also considers the support requirements in the system design process as mentioned for the ILS concept. In LSA there are five major activity areas including program planning and control, mission and support systems definition, preparation and evaluation of alternatives, determination of logistic support resource requirements and supportability assessment. As is obvious from the above, ILS and LSA refer to more complex industrial and maintenance organisations, which on the other hand restricts them from being flexible enough to be applied in the ever-changing environment of the maritime industry.

3.3.3 Business Centered Maintenance (BCM)

Business Centered Maintenance (BCM) was initiated by Kelly (1997, 1984) and it can be categorised as an approach that includes maintenance optimisation as part of the outcomes of the overall business strategy. Overall, BCM takes into account the business objectives for a specific system/organisation and how to maximise profitability. This is the other end of the ILS/LSA approach which thrives in minimising the cost business elements. BCM on the other hand examines the inputs to the business objectives such as the production process and the production plan, management of personnel, spare parts and their suppliers, safety issues, forecasting and asset life plans among others.

Moreover, in a paper by Waeyenbergh and Pintelon (2002), the BCM approach is compared with RCM in what is described as ‘a contribution to profitability’. This is in line with Houghton and Lea (2010), who suggest that BCM is best suited to an organisation with broader business objectives (e.g. MoD). In this case, they take into account both the technical aspects of the system under consideration as well as other factors that may influence the operational characteristics such as customers’ satisfaction (in this case MoD and Royal Navy statutory body). On the other hand, even if BCM goes into technical details about failures of components and how to prevent them, it also becomes a very extensive and complicated procedure. That is the main drawback of such approaches as they require extensive use of resources including personnel, finances and in the case of such complex systems they may be extremely time consuming.

3.3.4 Risk Based Inspection / Risk Based Maintenance (RBI/RBM)

Risk Based Inspection (RBI) and Risk Based Maintenance (RBM) belong to another sub-category of the efforts for examining the maintenance issue and its industrial applications. In this respect, risk is perceived not only as a safety and public related issue but it is also attributed an economic aspect in terms of the amount of risk that can be 'traded off' providing mitigation measures or minimisation of risk. In this regard, RBI and RBM can be employed for carrying out predictive maintenance.

This is in line with the UK HSE, which suggests the use of RBI in order to provide guidance for the department of hazardous installations directorate about the plant integrity management of refineries, chemical process plants off and onshore (HSE 2004). Khan et al (2004) present a risk based inspection and maintenance system as well for the oil and gas industry using a fuzzy logic methodology to calculate the risk in the operation of onshore oil plants. In the same field of operations, Patel (2005) also discusses the application of RBI in the onshore oil and gas industry and suggests that the actual use of RBI lies within the inspection optimisation sequence. Jovanovic (2003) also discusses the RBI approach in the field of nuclear powered stations and plants and suggests that accomplishing safety and financial benefits stemming from the reduction of industrial risk is closely related to achieving high maintenance standards. Krishnasamy et al (2005) apply the risk in a broader maintenance context presenting the RBM approach and its application in the power generation sector and make a decisive step to present the next level of predictive maintenance. However, in the author's opinion, this is a development which still lacks the element of the reliability and criticality evaluation of the system and its components. In addition to the above, this can be adjusted to the specific characteristics of the maritime sector as will be described in the following sections of the present thesis.

3.3.5 Vibration Based Maintenance / Condition Based Maintenance (VBM/CBM)

Vibration Based Maintenance (VBM) and accordingly Condition Based Maintenance (CBM) are other ways of investigating the maintenance aspect. As early as 1997, Jardine et al (1997) suggest the use of CBM in order to achieve maintenance decisions based on the specific condition of the equipment/component level, thus avoiding unnecessary replacement (preventive maintenance) or unexpected (corrective) actions. This is the case for Ross (2002) as well, who states that CBM is the maintenance approach that identifies problems before they take place as well as avoids needless time-based replacement. He also mentions the application of CBM in a number of cases for the US Navy and furthermore suggests that the ratio of corrective vs. preventive maintenance has been reversed to the benefit of the latter (case study of tug vessels) after watching the obvious benefits of its applications. These include lube oil analysis of main and auxiliary engines, infrared scanning of electrical equipment, performance testing of pumps and heat exchangers and vibration monitoring of rotating machinery. However, he also mentions that the percentile of industrial application of CBM overall is still quite low (5% compared to 60% of corrective and 30% of preventive maintenance). The above figures surprisingly correlate with the author's present experience after attending the latest conferences on condition monitoring and discussing the application of CBM in the maritime industry with several experts in this field even though a decade has passed since Ross' study.

In their paper about CBM, Al-Najjar and Alsyouf (2004) also make a fundamental remark on the actual framework that overall maintenance should be looked at. That is not only by the cost reduction aspect regarding maintenance activities themselves but also by addressing the money saving implications of appropriate maintenance in other areas of the business sector such as lower production cost, higher quality and less capital tied-up for spare parts. They move further more in specialising the maintenance procedures by introducing VBM as a sub-category of CBM. In their case, they use vibration monitoring to carry out and determine the maintenance tasks of a paper mill plant in which rotating equipment is the primary equipment used. They also address the cost savings generated by reducing direct and indirect costs (e.g. minimising maintenance tasks, increasing up-time, reducing maintenance crew time and sub-contracting intervals).

Tsang et al (2006) also discuss the application of CBM as one relies on the use of various types of analysis/monitoring (oil analysis, vibration monitoring, and thermal imaging) to acquire relevant data during the actual operation of the equipment/component under consideration. They use the proportional hazards modelling (PHM) approach to derive the optimum maintenance intervals for motor transmission equipment and manufacturing processes.

Summarising the above, CBM is considered a specialised type of maintenance and a step further in achieving the goals of optimum maintenance intervals by employing the latest engineering tools and techniques. However, CBM is part of the overall solution regarding the maintenance activities as it does not take into account that in some cases (e.g. lay-up vessels, specific ship or company operational profile) preventive or even corrective maintenance may be a more preferable and profitable solution. Regarding the process of laying-up ships, there are two separate types: 'hot' and 'cold' lay-up. The first one refers to a single D/G of the ship operating providing for all its needs. In the second case, no D/Gs are operated at the lay-up condition but only a containerised D/G is operated providing for the purposes of 'running' occasionally pumps and other auxiliary machinery as well as for providing power onboard. Moreover, in such circumstances, one needs to examine the overall framework in which maintenance is carried out and suggest associated measures accordingly as is shown in the case of the proposed maintenance strategy in this thesis.

3.3.6 Asset Management (AM)

A further evolution in the maintenance regime compared to the methods and methodologies shown above is Asset Management (AM). According to Woodhouse (2006), AM is a process for '*better and more business focused maintenance*' combining risk-controlled, optimised, life-cycle management of an asset. This definition brings in mind the likes of terotechnology as well as BCM which were introduced at an earlier stage. As discussed before, business objectives are at the core of these approaches which are then furthermore transformed into maintenance objectives. AM is moreover formalised with the introduction of the Publicly Available Specification (PAS) Standard 55 on the specifications for the optimised management of physical assets (BSI 2008).

The benefits of the AM application can be traced in the literature and include among others optimising the maintenance effort and cost, increasing productivity, retaining safety and environmental levels to high standards (Hodkiewicz et al 2010, Rodriguez and Woodhouse 2002, Ledet 2002). However, these pertain to organisations with extensive industrial structure, which have been involved in large restructuring of their maintenance departments, attributing considerable financial and human resources. Additionally, desirable changes as well as promising results of the restructuring process have taken some time to emerge. On top of the above, the application of such systems was carried out in enterprises in the oil and gas, power supply and distribution, processing and mining sectors in which the profit margin can be high enough to justify such organisational reforms. With this argument lies the main difference compared to the maritime industry, which is an industrial sector with a rapidly changing market environment, a huge number of smaller and bigger shipping companies with an organisational structure cumbersome to changes and improvements.

3.4 Total Productive Maintenance (TPM)

Total Productive Maintenance (TPM) is one of the very few maintenance frameworks that are central to the maintenance literature and are applied on a number of cases worldwide. In this respect, TPM will be described to a further extent with more details as shown in the following paragraphs.

Initially, it is worthwhile mentioning that there is ambiguity regarding the origins of TPM. According to Nakajima (1988), who is considered the ‘father’ of TPM, it lays its roots in a US maintenance initiative introduced in Japan in 1971. On the other hand, Ohno (1988) suggests that TPM originated from the ‘*Toyota system*’. As the name suggests, it was initially introduced in the manufacturing industry and was considered to be a continuation of the preventive maintenance concept already applied in this sector. Overall, TPM addresses maintenance in the context of the entire management process. Based on the above, there are five pillars which are prerequisites for its implementation. These are described next.

1. Increase Overall Equipment Effectiveness (OEE)

This is performed by minimising the 'six big losses' which are: breakdowns, setup and adjustment time, small stops, reduced speed, quality defects and start-up losses. The above 'six big losses' are described best by the following formulations (Equations 3.1-3.5):

$$OEE = A \times P \times R \quad (3.1)$$

where:

OEE: Overall equipment effectiveness

A: Availability

P: Performance efficiency

R: Rate of Quality products

Moreover availability is described as:

$$A = (\text{loading time} - \text{downtime}) / \text{loading time} \quad (3.2)$$

On the other hand, performance efficiency is given by:

$$P = \text{Operating speed rate (OSR)} / \text{net operating rate} \quad (3.3)$$

while,

$$OSR = \text{theoretical cycle time} / \text{actual operating time} \quad (3.4)$$

and Rate of Quality products:

$$R = (\text{total amount of products} - \text{defect products}) / \text{total amount of products} \quad (3.5)$$

2. Establish a thorough system of preventive maintenance for the whole life cycle of the equipment
3. Include different company departments (i.e. operational, maintenance, engineering)
4. Include top management and single employees
5. Promote preventive maintenance through the motivation for autonomous small group activities

From the above it is summarised that the meaning of 'total' in this maintenance approach involves the following, which are also the main steps for applying TPM:

a. Total effectiveness

It indicates TPM's pursuit of economic efficiency and profitability which includes productivity, cost, quality, delivery, safety environment, health and morale.

b. Total maintenance

It includes maintenance prevention (MP) and maintainability improvement (MI). It refers to "maintenance-free" design through the incorporation of reliability, maintainability and supportability characteristics into the equipment design

c. Total participation

It refers to the participation of all employees through small group activities, which includes autonomous maintenance carried out by operators. The small group activities promote planned maintenance (PM) through "motivation management"

As Willmott also suggests (1999), TPM is not only about finding and implementing the best and most effective maintenance policy related to technology or systems but also about taking account of the human resources contribution to the overall effectiveness of the process. He furthermore mentions three significant elements of TPM, which include containing methods for data collection, analysis, and problem solving and methodology control; introducing the cooperation of various departments such as the design, production, maintenance, quality and finance ones; and encourage further upgrading of the components/equipment used in the process.

On the other hand, Waeyenbergh and Pintelon (2002) consider TPM more as a management than a maintenance policy. Apart from the obvious advantages of this method, they also identify some drawbacks such as not proposing a series of specific maintenance tasks (either corrective, preventive or predictive) and not taking into account the cost and profit elements of the whole operation (although, to the author's view, OEE is indeed a measure of financial control as is presented by Nakajima). Waeyenbergh and Pintelon continue by identifying two additional pillars under which TPM needs to be based: safety and environmental rules and regulations as well as human resource management. In conclusion, they mention that a maintenance management system and relevant undertakings should be customised for the specific cases which are due to be implemented.

In addition to what is already mentioned, as the TPM implementation is applied in different industrial sectors, it is also expanded and updated. In this direction, different studies refer to the safety, health and environmental business perspective, a TPM main office for better organising the implementation procedure as well as the management of maintenance improvement initiatives (Ahuja and Khamba 2008, Shamsuddin et al 2005). The latter observation is in line with Bohoris et al (1995), which present the application of TPM in an automobile plant in UK. They initially identify the reasons for which TPM is not successfully adopted in the first place (the preliminary effort was focused on too many machines at the same time, no involvement of production operators and not choosing the most critical equipment). Specific consideration is given to the training of personnel by formulating teams to supervise the training of shop-floor individuals.

Seen in a similar context, McKone et al (1999) discuss the configuration of two different contextual streams: the environmental, which is described by the specific conditions a company is operating (the specific industrial sector as well as the country in which a company is located) and the organisational, which includes the specific characteristics of a company like its size, the plant, the equipment type and age profile as well as the presence of workers' unions.

The issue of obstacles in the implementation of TPM such as lack of multi-tasked and autonomous maintenance groups is also discussed in Cooke (2000) and Chan et al (2005). They identify the so called 'organisational barriers' which may impede the successful application of TPM. These include the lack of senior management support and commitment throughout the implementation stage, financial barriers (operations and maintenance departments have their own budgets and scheduling activities), lack of long-term vision as well as specific measurement method of the results. Additionally, full cooperation does not exist between the operations and maintenance departments so as to involve production workers in simple preventive maintenance tasks (e.g. lubrication of pumps) while assigning more serious jobs to their maintenance colleagues.

Related to these remarks, the author believes that the cultural difference of the working environment in Japanese (the worker is part of the big company 'family') and Western (people are individuals, who do not consider themselves as part of the company 'family') companies also indicates a big difference in the implementation of TPM in different industries around the world. Moreover, the maritime operational environment is directly influenced and linked to what Alsyouf (2009) and Arca and Prado (2008) suggest about the participation and competence of the human element (including knowledge, skills, motivation, ability and interest) as an essential factor for successful implementation of any maintenance approach. The latter could not be more relevant for implementation in the shipping industry as it is an industrial sector formulated out of a vast number of shipping companies (owners and/or managing companies) spread throughout the world and operating with multinational crews. Summarising the above comments, the benefits and shortcomings of the implementation of the TPM approach are shown in Table 3.1.

Table 3.1 Benefits and shortcomings of TPM implementation

Benefits	*Shortcomings*
• Management support for thorough implementation • Cooperation of different departments • Performance indicators in place • Human resources element • 'Autonomous' maintenance	• Lack of detailed technical aspect in the tasks involved • No specific maintenance measures suggested • Can be a cumbersome activity to perform (organisational barriers) • Extensive resources required • Results can take a long time to show

3.5 Reliability Centered Maintenance (RCM)

The second major maintenance framework which has been also widely discussed in the literature as well as presented in several applications is Reliability Centered Maintenance (RCM). Its origins lay in the review of the civil aviation preventive maintenance programme for the-new at that time-Boeing 747 aircraft by United Airlines (ATA 1968). The research performed concluded with the publication of the first handbook of the Maintenance Steering Group (MSG-1) with two updated versions following next (MSG-2 and MSG-3). Eventually, it was the third update which was further introduced as the RCM methodology we currently know. According to Moubray (1991), one of the gurus of RCM, this is defined as:

"A process used to determine what must be done to ensure that any physical asset continues to fulfil its intended functions in its present operating context"

He also suggests that the following seven questions need to be asked before the RCM methodology is applied on any asset. These are as follows:

1. which are the *intended functions* and *performance characteristics* of the asset under consideration
2. which are the possible *failures* that might occur
3. Which are the *failure causes*
4. Which are the failure consequences
5. In what way does *failure matter*
6. Which are the potential *preventive* measures
7. What should be done if *no preventive* tasks are worth implementing

Moubray also suggests that the implementation of RCM should be carried out by a group of experts including a RCM facilitator, an operation and engineering supervisor, an operator, a floor-worker and an external technical specialist (i.e. dealing with environmental issues) if deemed necessary. In this case, the group gathers all the information needed for the asset or system under investigation regarding its function(s), failures, failure causes, and the failure results at various levels in a worksheet. Following this, a decision diagram is created with the maintenance measures suggested to be taken. Finally, the above are combined into one decision worksheet giving details about the proposed maintenance task and the inspection sequence for each item. In the same book by Moubray, an updated version of the original method is introduced (RCM II) regarding environmental threats originating from the failures identified in the previous process.

As mentioned before, RCM has been implemented in various cases worldwide. In the defence sector, even though the application of RCM retains the characteristics of the original RCM, it becomes more complex and formal than previous applications bringing in mind the terotechnology model presented before. This is due to the fact that the same maintenance process needs to be described in even more details in the case of military systems and also need to encompass various others parameters regarding the complexity and strategic importance of the assets under investigation.

In this respect, the US Naval Air Systems Command produced a manual in order to address the implementation of RCM in the new and in-service military assets such as aircrafts, engines, weapons, electrical systems and support equipment (Navair 2005). A steering committee was also created in order to share the findings and results of the application of RCM in this sector with maintenance programmes developed in other departments of the defence systems of the US army as well as share information with the academia and other research institutes. The UK MoD Defence standard (2006) also utilizes RCM for the preventive maintenance programmes for the assets it manages. In this case, the most effective maintenance strategy for a specific end-item is suggested together with the creation of a purpose-built database with the in-service data and input originating from the actual implementation of the specific maintenance tasks.

In the same standard, RCM is considered within the more generic LSA process, which in turn is a part of the Defence ILS process combining procurement, storage and transportation of manufactured goods and systems. LSA also provides for the training, skills and resources required to apply a maintenance task as decided by the RCM in the first place. Apart from the above, the additional feature in this Defence standard is that the reliability and maintainability of structures is also examined and treated in the same framework as the ones of machinery and other mechanical and electrical equipment. This brings to mind the application of the maritime RCM and RBI approaches, which will be discussed with more details in the following sections of this thesis.

Moreover, the last generation of RCM applications offers a combination of the typical RCM with a computerised maintenance system which provides for all the capabilities of RCM in a software package. In this respect, in Fonseca and Knapp (2000) the RCM approach for the chemical process industry is shown. The combined application of RCM with a CMMS in the case of a water-feed process of a nuclear power plant is also presented in Gabbar et al (2003). Rausand and Vatn (2008) show the detailed application of RCM in the field of the railway sector with the help of a computerised maintenance module.

In another study by Backlund and Akersten (2003) the difficulties in the early application stage of RCM are examined. These include the lack of a CMMS dedicated to the specific application, lack of plant and asset register, unavailability of proper documentation and information (no historical reliability data), no maintenance terminology specified in the first place, poor communication among stakeholders (operation and maintenance departments) and lack of maintenance management. They conclude that the maintenance strategy should be obvious from the first steps of implementing RCM as well as making evident from the beginning where the RCM approach fits in the 'big maintenance picture'.

From the cases presented above, it is obvious that RCM is a well-structured maintenance approach providing detailed description of the system structure under consideration as well as facilitating the cooperation among different departments within the same company. It can also reflect the support of company's top management in the various tasks involved during its implementation although this might not be sufficient enough to accomplish the optimum results to a full degree as the support required may be extensive with a lot of man-hours required for implementation and execution. In addition to the above, results may be apparent after some time from the RCM initial implementation (depending on the size of the company) while competent analysts/facilitators are required to assist with the preliminary execution of tasks needed. RCM can also prove to be complicated if too detailed. On the other hand, it can be superficial if not applied correctly whereas limited financial resources may be an obstacle for its continuation. In conjunction to what is stated above, a major difference between defence and industrial RCM applications is that big organisations (such as in the defence sector) consider RCM as part of the overall integrated enterprise. According to the author of this thesis, it is this last remark which highlights a significant RCM drawback; that is the lack of an overall maintenance management system which will concurrently be flexible enough to suit each specific company/plant/case. Bearing in mind all the above, the benefits and shortcomings of the RCM implementation are summarised in Table 3.2.

Table 3.2 Benefits and shortcomings of RCM implementation

Benefits	*Shortcomings*
• Detailed description of the structure of systems and sub-systems identified • Multi-disciplinary cooperation among different departments (maintenance, production, operation) • Technical and organisational insight in the core of the work performed (maintenance, operation, design) • Involvement through-out the organisational structure (top level management to floor workers) • Create a complete and thorough maintenance database	• Requires extensive managerial involvement for implementation and execution • Requires significant resources • Results are shown after a long time (2-3 years' time) • Requires skill and experience from analysts • Can be complicated if too detailed and superficial if not applied correctly • The cost element could be an issue for RCM application

After examining the maintenance methodologies and applications in the general context, the overview of similar methodologies applied in the maritime sector are shown in the following sections.

3.6 Overview of maintenance methodologies in the maritime industry

Maintenance in the maritime sector has always been part of the day-to-day ship operations to a lesser or greater extent. Originating from the corrective or 'run-to-failure' approach, it has developed to include preventive and lastly a more predictive sequence of tasks (Figure 3.2).

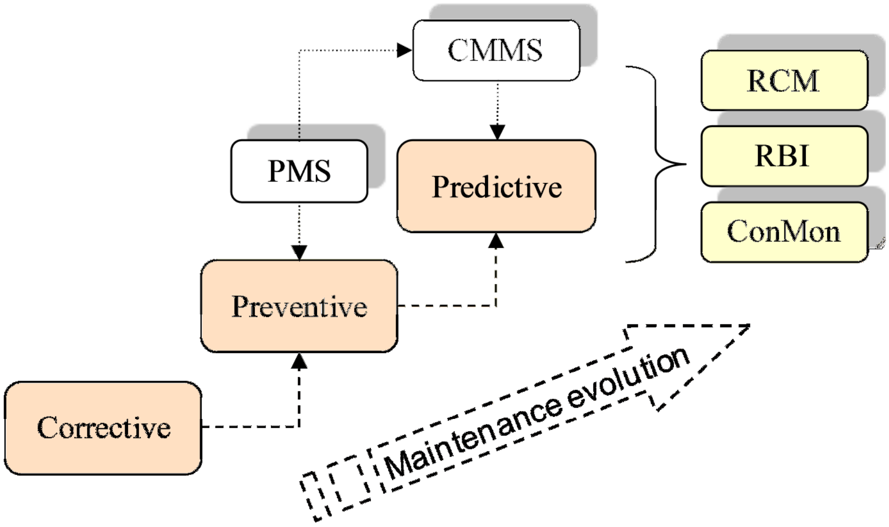

Figure 3.2 Maintenance approaches in the maritime sector

As shown in Figure 3.2, preventive or planned maintenance is complemented by the formalised Planned Maintenance System (PMS) introduced by the IMO ISM code. This has been expanded in the form of the Computerised Maintenance Management System (CMMS) which can be applicable in the case of predictive maintenance. The latter can be broadly subdivided into three major categories; that is, the RCM, RBI (maritime and offshore) and the ConMon maintenance types. All the above maintenance categories and methodologies are furthermore presented and explained in detail in the next section.

3.6.1 Corrective

As in other industrial sectors, corrective maintenance (otherwise called run-to-failure, breakdown or reactive maintenance) is the initial and obvious step dealing with ship maintenance. Dhillon (1999) describes it as the action performed because of apparent failure or deficiencies occurring. In a more general context, it can be described as the action to repair an item to its operating condition. According to IACS (2001), a corrective maintenance procedure must consist of a process to identify the existing problem, establish the cause and propose as well as implement and evaluate feasible solutions. In this respect, the obvious drawbacks of this maintenance approach including corrective actions comprise high utilization of unplanned maintenance related activities, inadequate use of maintenance effort as well as high replacement part inventories. However, in some cases this type of maintenance may be a preferred method to employ, especially when the maritime market status is very unstable allowing for a vessel to be laid-up or when expensive and original spare parts are not readily available. In such circumstances, the crew onboard the ship usually carries out the maintenance tasks involved with whatever means are available (improvising in some cases for the best maintenance outcome).

3.6.2 Preventive

Preventive (or on-condition, scheduled or time-driven) maintenance addresses the scheduled inspections, which are performed so as to establish whether a component or equipment can still operate satisfactorily or determine the item's deterioration (Mobley, 2002). The initial structured efforts regarding maritime preventive maintenance and the technical reliability of systems and equipment are made through the IMO International Safety Management (ISM) code (IMO 1993). In section 10.3 the provision for an adequate safety management system which identifies the '*equipment and technical systems the sudden operational failure of which may result in hazardous situations'* is described. Furthermore section 10.4 states that *'the measures referred to in 10.3 should be integrated into the ship's operational maintenance routine.*' which provides a direct link to the maintenance procedure followed onboard a ship. In this case maintenance tasks that promote reliability may include testing of stand-by arrangements, testing of alarm functions, lubricating oil analysis, cooling water treatment, fuel oil analysis, vibration analysis, filter cleaning function testing etc. As can be seen, even if a major part of ISM code includes planned maintenance tasks, it is also a first step towards a more predictive maintenance approach. However, it still lacks the element of specific identification of the systems to be further investigated and enhanced, taking into account the specific characteristics of different ship types, the limited number of maintenance personnel onboard and the rest of the indications mentioned above.

Moreover, the preventive maintenance regime is further developed by the initiation of Planned Maintenance Systems (PMS) with which maintenance tasks are described in extent and their implementation is recorded. Moreover, Tanker Management Self-Assessment (TMSA) was introduced in the oil shipping market in 2004 including a maintenance parameter (OCIMF 2008). In element 4, the best practices a ship owner/operator should adopt in terms of reliability and maintenance standards are described by identifying the critical components of the vessel as well as arranging for the procedures of controlling maintenance. Key Performance Indicators (KPIs) are set from level 1 to 4 in order to illustrate the continuous improvement in this field. In this respect, a research project was also initiated in order to establish standards for performance measurements in the shipping industry (Marintek 2009). Shipping Performance Indicators (SPIs) were developed as an aggregated expression of KPIs so as to provide information about the overall performance of a vessel at particular areas.

3.6.3 Predictive maintenance

In the case of predictive maintenance, this can be further subdivided into three categories, which were also mentioned in the previous sections of the thesis in hand although their meaning and application is altered to accommodate the precise characteristics of maritime maintenance. These are the RCM, RBI and ConMon approaches. All of them are described with more details in the following paragraphs.

3.6.3.1 RCM-Reliability Centered Maintenance in maritime industry

The RCM approach in the maritime industry preserves the key elements of RCM applied in other industrial sectors and is related to the machinery equipment of ships. In this respect, Mokashi et al (2002) present the case study of the main engine of a ship to demonstrate the introduction of RCM and the way it can influence the ship management and the work of seafarers. They use a simple risk approach in terms of consequences described as the total cost of failures and the number of failures that have occurred in a specific observation interval. Moreover, they suggest an RCM index consisting of frequency, consequence, probability of consequence and detection rating so as to prioritize the maintenance tasks which should be carried out under the supervision of the onboard marine officers. In this case, they suggest that marine officers should be dual competency officers educated for both navigation and engineering tasks.

Conachey and Montgomery (2003) also apply the principal characteristics of the classical RCM approach in the maritime sector. They start with the Functional Failure Analysis (FFA), which includes the identification of the operating modes of the ship, the definition of the systems to be analysed as well as the description of the functions of the various systems and their failures. The final level of this step includes the end-items of the equipment which can be described in a discrete manner. An interesting feature of their approach is that they consider the application of FMECA either as a bottom-up approach starting with the failure of specific items (useful when dealing with an existing asset) or as a top-down approach analysing the primary functions of the systems under examination and their failures (useful when working on a new design) (Figure 3.3). Another aspect of their study is the introduction of a critical spare parts holding list, which is determined after the maintenance tasks are allocated.

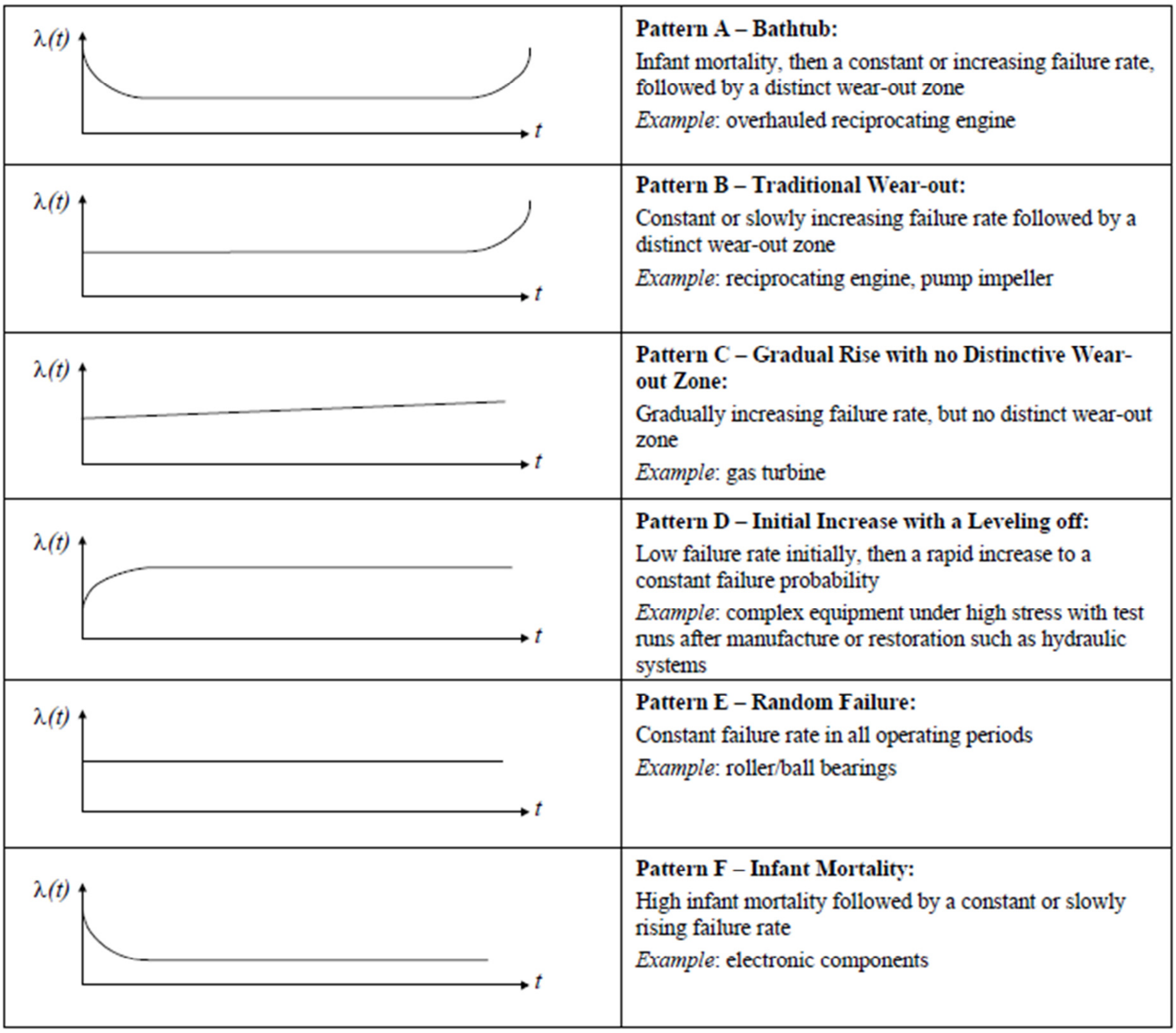

Figure 3.3 Various categories of failure rates λ according to Conachey (2005)

In another paper by Conachey (2005), the specific application of RCM is examined in the machinery of ships as well as the relevant survey requirements in order to achieve enhanced maintenance intervals. Conachey acknowledges the use of severity and frequency of failures in the context of a risk matrix created to assess the risks originating from the failure modes. Serratella et al (2007) also discuss the RCM implementation regarding the machinery and rotating equipment of ships. They also mention a sequence of ten steps with which RCM can be applied. These include the identification of the operational capabilities of the vessel and its systems along with their functions, carrying out a Failure Mode, Effect and Criticality Analysis (FMECA), selecting failure tasks to be rectified, determining spare parts criticality list, developing the RCM process and finally implementing it on the vessel.

As is shown from the research work described above, RCM keeps the benefits of the classical RCM already mentioned for other industrial sectors (more technical consideration of the asset in question, improved asset reliability and eventually cost effectiveness) and applies them onboard ships. However, the very nature of RCM restricts it from its wide application in the shipping industry. This is due to the fact that RCM requires a big number of participants (facilitator, technical managers, and engineers) involved in order to carry out the mentioned tasks as well as requiring substantial time to be implemented and obtain the initial results which will demonstrate the efficacy of such a system. On top of the above, the regulatory regime in terms of RCM application in the maritime sector is relatively young and further acceptance is needed in order to derive its optimum outcome.

3.6.3.2 RBI-Risk Based Inspection

As mentioned before, RBI is another method for carrying out predictive or probabilistic-based-maintenance regarding the primary and secondary structural elements. In the case of the maritime industry, this is related to marine structures including ship-like structures (ships, FPSOs, FSOs) and other offshore structures (e.g. jacket platforms). In this perspective, knowledge deriving from the long experience of operating and maintaining marine structures is combined with risk and reliability methods in order to suggest the best inspection and maintenance plan having in mind not only the structural details but also the probability and consequences to the safety and environment as well. In this respect, the main aim of RBI is to:

- allocate the available resources which may include the available personnel, time, equipment and cost originating from it and
- prioritise the attention of the inspection and maintenance effort to the high-risk areas

With respect to the classification societies' approach towards RBI, ABS (2003a) suggests its use in their guide for risk-based inspections for the offshore industry to identify the optimal maintenance strategy as a complimentary approach to the State and Flag authorities. The time-based prescriptive maintenance method, which is satisfactorily used so far, is superseded by an approach which additionally employs probability and consequence estimates to optimise the inspection and maintenance intervals.

DNV (2002) also describes RBI as an inspection planning tool. As in the previous case, structural elements are categorised according to their risk index both in a qualitative and a quantitative way. The qualitative approach is a quick way to determine the associated risks and is performed at low initial cost although it heavily relies on the competency and subjectivity of the risk management team which will exercise RBI. On the other hand, the quantitative approach is more accurate including the use of exact calculations performed by using data which in some cases takes time to gather and utilize.

A risk-based decision making process for the hull condition of ships is also presented in Kalghatgi et al (2009). In their paper, they expand the traditional hull inspection process, which includes overall and close-up inspection of the hull structure, examination of suspect areas (fatigue 'hot spots') and areas of substantial corrosion as well as assessing the coating and anodic protection condition. Moreover, they introduce the division of the hull structure into compartments according to IACS Rec. 87 (2006) and suggest a scoring system using a traffic-light scheme and specific inspection criteria in order to identify critical structural areas. The six inspection criteria for assessing the condition of the hull structure are: coating condition, general pitting and grooving corrosion, deformation, fractures and overall condition of the area under examination (presence of loose scale and sludge, condition of anodes and piping).

The last research study is in line with the work performed for an EU research project regarding the modelling of ship maintenance and repairs for the hull structure of ships (Turan et al 2009). In it, the steel renewal, coating and fuel oil cost are considered in conjunction with the earning element being lost due to unexpected failures and consequently unexpected repairs. It is important to notice that one of the conclusions of the mentioned work is that an increase in the thickness of primary and secondary structural members may prolong the ordinary planned maintenance interval and thus increase the operating time of the vessel and reduce downtime.

In the same area regarding the implementation of hull structure maintenance lies the research work of Jaramillo and Cabos (2006). In their study of hull condition monitoring (as part of the European funded research project CAS (Condition Assessment of aging ships for real-time Structural maintenance decision) they discuss the application of a computer hull condition monitoring system. The latter assists in the easier association of survey data with their location on board the ship. In this case, thickness measurement points obtained during the actual thickness gauging process with the help of robotic equipment are transferred automatically in a standard software template. From there the data are furthermore assessed to derive the 'hot spots' in terms of critical structural members which lie outside the gauging limits set by classification societies.

Although the above is an excellent step towards more accurate structural thickness measurement evaluation and control of the corrosion patterns onboard a ship, it is the author's view that one should also consider the related limitations presented in such cases. At first, the level of accuracy of 3D designs (in the case of no CAD files available from shipyards) is not the highest one required. Furthermore, the robotic case faces several challenges in its application. This incorporates the requirement of a previously cleaned surface, the cost of application for the TM firm (purchasing the equipment, software package etc). Moreover, employing at least two skilled operators onboard the ship at all times, which need to work on the ship while other repair works take place (especially in busy Far East shipyards). Finally, an increase in the overall cost for the entire inspection time for the ship owners/operators is inevitable.

3.6.3.3 RBI in the offshore industry

In this section, particular attention is drawn to the offshore industry, in which RBI has been widely applied. That is due to the fact that the majority of the FPSOs are converted crude oil tankers which, due to market reasons, are not capable of continuing their operation as seagoing vessels. Concurrently, operators of the oil and gas fields needed a processing and storage structure which would be available in a short notice without major modifications.

These factors led to the extensive use of tankers as FPSOs at offshore fields all around the world. Having said this, there are certain features specific to the operation of these vessels.

Ship owners and operators of the oil and gas fields where processing and production is taking place are faced with the non-stop operation of their vessels. Accordingly, this means that there is no time to take the ship out of business for dry-docking, inspection and potential repairs carried out. On the other hand, classification societies responsible for performing the structural surveys are faced with different operational procedures of the vessel under consideration which are not the same as for the seagoing ships (e.g. the periodical intervals of oil and gas loading and offloading).

Related to the above and in terms of the RBI implementation offshore, Goyet et al (2002) discuss the RBI planning concept in the case of a FPSO vessel. They consider the assessment of risks and their consequences for the whole facility in terms of personnel, environment as well as economic risks. The RBI approach includes the initial collection of information, risk screening in order to decide which structural and process components need specific attention followed by detailed risk assessment and finally inspection scheduling. After the inspection is performed, the whole process is evaluated and feedback is provided in order for the original plan to be updated accordingly.

On the continuation of the research presented above, the RBI method is applied in the case of offshore jacket steel structures in a paper by Rouhan et al (2004). They identify fatigue as the main failure cause in tubular connections and they also distinguish between the fatigue identification in the design and in the actual state. This is due to the actual operational and structural restrictions of the platform regarding the wind and waves prevailing at the area of setting up the platform, marine growth on the legs of the platform as well as the actual weight of the topside installation. They also come up with a grouping of the inspection and maintenance intervals based on high-risk items and cost parameters.

In Straub et al (2006) the RBI application is also presented regarding fatigue deterioration for offshore fixed steel structures and floating, production, storage and offloading vessels (FPSO's). The financial impact of inspection planning and repair is compared with the one stemming from inspection and repair strategies based on fixed inspection intervals. They concluded that there are benefits both in terms of cost savings as well as concentrating the inspection and repair efforts on the critical members of the structure.

Lloyd's Register also prepared a study on the FPSOs in service in the UK continental shelf (UKOOA 2003). The report is based on questionnaires distributed to operators, carrying out interviews with repair and maintenance personnel, review of current literature as well as internet search so as to locate the best practices in the field. On-site visits are also made and the final results are also discussed among the members of the group performing the survey. In almost all cases, preventive maintenance systems are in place assisted by CMMS as well as a RCM system. The repair and maintenance deficiencies identified are mostly related to design inconsistencies or design faults. Another important outcome is that even if a risk-based approach is applied, it does not progress much further than identifying potential risks when it should be desirable to assess, avoid or mitigate them. That is an existing gap in the day-to-day operation of offshore/shipping operators/managers and highlights the difference between any suggested methodology and its application in real life.

Ku et al (2004) also present a quantitative approach using strength and fatigue reliability assessment in order to apply RBI planning for a Floating Production Unit (FPU). At first, information is gathered including thickness gauging reports, past historical data from the previous operation of the vessel as a crude oil tanker (including previous repairs performed) as well as data from the present operation in the current location (environmental loading, tanks operation/usage). Then, this information is used for the FEM modelling. Next, the HAZard IDentification (HAZID) tool is applied together with the existing degradation mechanisms like corrosion rate and crack propagation to locate the high-risk structural components. Then, the strength and fatigue reliability analysis is carried out while the end results are compared with a reliability index. The latter is derived for different consequences in terms of financial loss (ranging from total loss of vessel and operation to minor consequences). Finally, the inspection interval is adjusted and improved accordingly.

Basu and Lee (2006) discuss about the RBI application on FPSOs, which in most cases are converted crude oil tankers, either double or single hull. They differentiate between the prescriptive approach based on IMO's regulations as well as IACS guidelines and recommendations (which are carried out in time-based intervals) and the probabilistic approach. The time-based intervals are described either as Annual, Intermediate or Special surveys while the probabilistic approach is based upon the probability and consequence from the failures occurring in a structural member of the vessel. They also consider the consequences in terms of safety, environment and asset as well as a total consequence ranking determined by the worst risk scoring identified in the previous categories. In a more advanced calculation stage, they take into account the corrosion rate applied on structural members, thus defining the risk assessment in more details.

Moreover, in Hamada et al (2002), a process for hull structure inspection planning similar to the RBI approach presented above is shown. They describe their approach as part of the quality control cycle of ‘plan-do-check-act’ combining the existing close-up inspection surveys, rules and regulations for ship hull structures and an integrated shipbuilding computer application to map the probable deficiencies occurring.

From all the above it is obvious that RBI refers to the second part (relevant to structural members) of the predictive maintenance approach implemented in the maritime industry. The benefits of applying it are similar to the RCM implementation but so are the drawbacks. These refer to a very complicated approach to be fully applied, extensive use of financial and human resources together with limited information available for using on new vessels. For all the above reasons, RBI still lags in effect in the maritime sector.

3.6.3.4 Condition Monitoring (ConMon)

Condition monitoring (ConMon) can be defined as a system of regular scheduled measurements of plant and machinery health. In general, ConMon systems use various tools to quantify plant health, so any change in the condition can be measured and compared. In this way, ConMon of the mechanical, electrical and thermal condition of plant, as well as identifying efficiency losses and safety critical defects can be carried out. The main objective when applying ConMon is not only to identify defects, but also to discover the root cause of failure, so that it can be eliminated and rectified.

In the maritime sector there are a few studies regarding the application of ConMon systems with regards to both the hull structure and the machinery equipment of ships. In this respect, Wang et al (2001) use ConMon for the hull structure monitoring of a naval vessel. More precisely, they study the result of embedding fibre optic strain sensors in the composite hull of a fast patrol vessel in order to carry out sea-keeping tests and provide valuable feedback on the initial ship design in order to improve it. The advantages of fibre optic compared to other sensors are that there is no need for electric cables, they can be used in risky areas (e.g. explosive environment), they are not subjected to corrosion since they are made of chemically passive materials and they have a wide operating temperature range. Concluding, Wang et al mention that the same technology can be applied in steel hull structures as well since there is no electromagnetic interfering in this type of sensor thus the data collected can be of high quality.

In a paper by Yamamoto et al (2007) a ConMon system is described for measuring the fatigue of the hull structure of ships under working conditions. This approach is based on installing fatigue damage sensors at specific locations of the hull structure which are prone to high fatigue concentration (e.g. ballast tanks, deck area, cargo area) for a period of almost two and a half years. By obtaining the actual fatigue measurements, a cross-verification is applied with the initial results obtained by a software programme used. Their study was tested on a 145,000 m^3 LNG ship, using sensors to detect the accumulated stresses on the welded structural parts for a period of time. The sensors were welded or glued on the structure and they were removed at the following dry-docking period of the vessel.

In terms of the application of ConMon systems for the machinery equipment of ships, Courtney (2009) suggests the vibration ConMon implementation including pumps, purifiers, compressors, turbochargers, thrusters as well as generators among others. He also presents a list with the approximate number of auxiliary equipment on board different ship types and the subsequent measurement points for vibration monitoring. A trained operator can carry out the measurement monitoring of the chosen equipment and upload the data collected either in an onboard computer or send them ashore for further trend analysis. He also proposes a database registration of ConMon measurements of different equipment which can be then sent to an onshore server. From there, further analysis and a maintenance report can be set up for the ship operator.

Conachey (2009) also presents a paper on ConMon systems applied in the maritime industry. He suggests that ConMon should be integrated within an overall predictive maintenance approach like RCM, which could actually enhance its application. This brings in mind the fact that ConMon is a tool which needs to be assessed for the related benefits and cost that it provides. In this regard, an example of cost benefit analysis of a ConMon application on a low speed propulsion unit is presented. The costs are related to the expenses for buying, installing and operating the necessary ConMon equipment, the training provided to the operators of the equipment, the additional cost for analysing the results and providing support by an external contractor. On the positive side, there can be a reduction on the risk for maintenance and repair in terms of potential financial losses if a breakdown occurs, which will lead to loss of operation, environmental cost plus the fuel saving cost. The sum of all the above may result in potential cost effectiveness of a few thousand dollars per vessel-year and an economically feasible ConMon application.

Chandroth (2003) discusses an overview of thermography and shows its application in the machinery space of ships. Thermography detection is used when infrared emissions emitted from an item/equipment are shown as an image in a camera operated by a person. It is based on the thermal emissivity of the surface of the object under investigation and the atmospheric attenuation in the operating environment. In this way, overheating of specific areas or items under consideration can be identified caused by short circuits, loose connections, unbalanced motors, leakages from exhaust and steam pipes and in general from the abnormal operation of mechanical equipment.

Salva et al (2004) also investigate the application of infrared scanning inspection for merchant vessels and propose a method for making an inspection plan based on thermal imaging. The application of thermography as a condition monitoring tool can also be found in naval ships in which very high failure prediction is required as well as in the case of catamaran vessels and unattended engine rooms. The authors also propose that the barrier of high acquisition cost of an infrared camera can be justified by the effectiveness of such a device in detecting hot spots as well as by its application in a fleet of ships owned by a company. They moreover suggest that an initial inspection interval of a six-month period can be utilised at either full operating condition of the inspected component either in port or en-route.

From the above it can be summarised that ConMon techniques have been applied onboard ships to some extent with considerable benefits stemming from them. However, one needs to bear in mind that the wider application of this approach needs full support from advisory and regulatory bodies (i.e. Classification Societies, IMO) in order to get the full gain out of them.

On the other hand, ConMon systems are nowadays more frequently applied onboard navy ships as the potential for better and proactive maintenance is recognised and acknowledged. However, to the best of the author's knowledge (through participation and discussions in maritime conferences in addition to author's own experience in the maritime industry), ConMon is only applied to a fraction of the merchant and passenger worldwide fleet and is still a long way from being a standard for the shipping industry.

3.6.3.5 IT systems in maritime maintenance

Computerised Maintenance Management Systems (CMMS) are a further step ahead in the development of the original PMS regarding the IT support for maritime maintenance. In today's maritime world where information flow is continuous and fast, a system which comprises a readily available information system is a prerequisite.

In this respect, Power (2004) presents an overview of CMMS in the maritime industry and suggests that the key components of such a system are the integration of all the necessary information in one central database (i.e. planned and unplanned maintenance events, machinery monitoring, inventory/spare parts lists, risk assessments for carrying out critical maintenance tasks etc). Data can be introduced in the main system either from the ship's officers onboard or from the onshore based office of a shipping company/manager/operator. That is why these systems need to be simple to employ, with user-friendly menus and toolbars. In some cases, a dedicated onshore IT department as part of the shipping company may take over the burden of dealing with the complexities of such systems.

In another CMMS application, Thobem et al (2008) present a computerised platform, which includes a combination of data sources. These include damage statistics/reports, ship's operational data like Voyage Data Recorder (VDR) details, monitoring of the main engine components, hull condition monitoring and shaft and propeller monitoring through a central server, which archives the data and sends them in a compressed format to the shore based main maintenance system for further analysis. However, apart from the obvious advantages of this system, there are some challenges that are identified as well. These refer to the manual recording of data from the various ship items/components (no real time information) as well as the fact that the information is transferred through the main server to the onshore office without informing the captain/chief engineer of the ship of the current condition of the machinery equipment of the vessel.

Furthermore, in Prioletti and Tobin (2008) a CMMS is presented regarding the application of a standardised system in the US Navy Regional Maintenance Centres (US RMC). In it, the transition from hand-written reports and repair assessment of ship's tanks and void spaces to a Personal Digital Assistant (PDA) usage is described. The general feature of this process is the combination of different work orders starting off from a ship, planning and properly scheduling the maintenance action as well as assigning the work to a specific person or team to carry it out. All this information is transferred from a centralised database (by logging in a specified website) to a touch-screen PDA which is further used by a competent assessor to complete the maintenance report while being in the tank/void space. This report is then sent back via the same operational channel to the centralised database for further investigation.

In a study by Rodseth et al (2007), the combination of a ConMon tool with technical condition indices (TCI) is presented. As its short name suggests, TCI are applied to evaluate the technical condition of a system under examination using diagnostic evaluation tools. They also present the development of a system for online monitoring/measuring spots of different machinery equipment and applied it on a gas export compression plant. TCI differ from key performance indicators (KPIs) as the latter are used to measure, evaluate and review the performance and strategy of a company/organisation at a higher level.

Hatzigrigoris et al (2008) also present the KPIs for a shipping company, which operates a fleet of tanker ships. They suggest measuring KPIs according to a departmental categorisation including operations, technical, ISM and HSQE and crew and training departments. Each one of the departments set out a number of targets to be achieved and compared related to internal as well as industry-based standards while they also mention that a KPI maybe the combination of the performance of more than one department.

Moreover, Stephen et al (2002) present a CMMS which is used in a number of ships in the UK Royal Navy. It includes/combines different sources of information such as the original general arrangement compartmental drawings of the as-built ship, machinery equipment diagrams and details, 2D, 3D and photographic formats, statutory regulations, inventory management and logistic support as well as maintenance databases. Each function can be readily accessible from either a pre-configured PC for individual use or can be browsed from a secure managed server and web service.

In addition to the above, Classification Societies also support computerised packages mainly involved in the calculation of strength and fatigue analysis of structural members as well as the reliability of machinery equipment. Nevertheless, these IT packages are still far from being broadly accepted by the shipping industry in a form that will be simple and accurate enough in order to be operated by a continually reducing number of crewmembers onboard the ship. Bearing all the above in mind regarding the various approaches and techniques used in maritime maintenance, it is useful to summarise the differences and similarities of maintenance activities among shipping and other industrial sectors (Table 3.3). In this way, the current overall perspective of maritime maintenance is clearly shown as well as the gaps identified which will be addressed in the presentation of the suggested novel maintenance approach.

Table 3.3 Differences and similarities of maintenance activities between shipping and other industrial sectors

Characteristics	Shipping	Offshore oil & gas	Manufacturing process	Chemical & Petrochemical	Nuclear	Aviation/Aerospace	Defence	Transportation (e.g. railways)
Production process	One at a time (or small number of sister ships)	One-off items	Mass design production procedure	One-off items	One-off items	Mass production	One-off items	Mass design production procedure
Ownership (companies)	Too many individuals	A few owners (mostly oil majors)	A lot of companies	A few owners (mostly oil majors)	A few owners (state companies)	A lot of companies (but same asset)	A few owners	A lot of companies
Management structure	Part of the technical department	Part of the technical department (but much more developed)	Separate maintenance department	Separate maintenance department	Separate maintenance department	Separate maintenance department	Separate maintenance department	Separate maintenance department
Operating environment	Worldwide	Offshore	Land-based	Land-based	Land-based	Worldwide	Worldwide	Land-based
Working/operating conditions	Harsh (sea/ocean)	Harsh (sea/ocean)	Land-based	Land-based	Land-based	Less harsh	Depends on the place	Land-based

Attributes	Shipping	Offshore	Manufacturing process	Chemical & Petrochemical	Nuclear	Aviation / Aerospace	Defence	Transportation (i.e. railways, automobiles)
Standards / regulations nationally and internationally	Depending on mgt procedure	Strict regulations	Strict regulations	Strict regulations	Strict regulations	Strict regulations	Strict regulations	Strict regulations
Principal maintenance personnel	Ship crew or riding squads, dry-docking	Platform crew	Maintenance dpt	Maintenance dpt	Maintenance dpt	Maintenance dpt	Maintenance dpt	Maintenance dpt
Training of personnel	Good quality / needs upgrading	High quality	High quality	High quality	High quality	High quality	High quality	High quality
Maintenance application / spare parts	Logistical restrictions	Easier to control / supply	Easy to access/implement/ monitor/control	Easy to access/implement/ monitor/control	Easy to access/implement/ monitor/control	Easy to access/implement/ monitor/control	Easy to access/implement/monitor/control	Easy to access/implement/monitor/control
Research	Limited	Extensive	Extensive	Extensive	Extensive	Extensive	Extensive	Extensive
ConMon/CMMS applications	Very limited	Limited	Extensive	Extensive	Extensive	Extensive	Adequate level	Adequate level

As can be seen, the various differences and similarities between shipping and other industrial sectors are initially categorised according to the following (it should be mentioned that the above Table presents the various differences and similarities between shipping and other industrial sectors based on the condition of a typical ship and industrial plant respectively):

- Production process

Ships are one-off items (even in the cases that a number of sister ships are produced) with their own incorporated characteristics compared to other industries (especially in the manufacturing and transportation ones)

- Ownership (companies)

Ownership is also another major difference in maritime and other industrial sectors. The majority of ships operated and managed belong to a vast number of owners, in some cases single-ship owners. The exceptions of a few major shipping groups or state-owned shipping companies tend to verify this statement compared with the small number of owners one may come across in offshore, chemical and petrochemical, nuclear and defence sectors.

- Management structure

The management structure is also a major difference between shipping and other industries. Usually maintenance is part of the technical department of a shipping company while in other industries exclusive maintenance divisions exist and take care of the day-to-day maintenance operations of the plant under consideration.

- Operating environment

Regarding the operating environment, shipping is a worldwide activity influenced by the slightest change in international trade, which is in contrast with the comparison performed especially with land-based industries such as the manufacturing, nuclear and transportation ones.

- Working/operating conditions

On top of the above, the ship operating environment can be one of the harshest in the world compared to the protected land-based environment other industrial sectors cherish.

- Standards/regulations nationally and internationally

In addition to the last statement, land-based industries are strictly regulated and conform to national and international guidelines, recommendations and rules bearing in mind the personnel and people safety, environmental protection and asset integrity. This development has started taking place in shipping as well, with major changes and enforcement especially after the case of tragic accidents occurring.

- Principal maintenance personnel employed

Maintenance works are carried out by the ship's crew or in some cases riding squads or in the case of bigger repairs needed in the shipyard's dry-dock at regular 5-year and 21/2 year intervals in comparison to the existing fully integrated and dedicated maintenance departments in other industries.

- Training of personnel

In most cases, the onboard crew is provided with sufficient training and spare parts to perform the works needed while the ship is sailing or is at anchorage waiting to enter a loading/discharge port. However, ship crew education and further training can be enhanced based on similar practices in other sectors (such as the aviation) in which training and re-training of personnel is a prerequisite to ensure safe and efficient operations worldwide.

- Maintenance application / spare parts

The maintenance procedure itself is easily implemented, monitored and controlled in other sectors due to the more structured working environment, while in shipping logistical restrictions apply and influence the maintenance works to a great extent.

- Research conducted on the maintenance subject

Research carried out in shipping regarding maintenance practices and the latest developments is catching-up with regards to what is already a norm in all other industries.

- ConMon/CMMS application

Moreover, the latest developments regarding maintenance upgrades by employing Condition Monitoring and CMMS applications are not fully realized in the maritime sector although the industry is making significant efforts towards this direction, particularly in the last few years.

For all the above reasons, it is obvious that despite all the efforts carried out throughout the years regarding the maintenance field in the maritime industry, there is still no specific maintenance structure which encompasses the technical as well as the managerial aspects of the shipping business sector. Even if there exist some applications worthwhile examining and research still carried out, these seem to be fragmented and referring to a particular area of the maritime maintenance, thus becoming useful tools with which the maintenance prospect will be viable. For instance, RCM for the machinery equipment, RBI for the hull structure, ConMon for the monitoring of the ship systems. Overall, all the above differences, advantages and shortcomings of the mentioned maintenance approaches/techniques presented herein, are summarised and compared in Table 3.4. The latter is performed in order to identify the gaps existing in these approaches and moreover prepare the grounds for the introduction of the novel maintenance strategy which is presented in the following Chapter.

Table 3.4 Advantages and shortcomings of the application of maintenance techniques/approaches and gaps identified

Approach	***Advantages***	***Shortcomings***	***Identified gaps***
Terotechnology	managerial framework, maintainability (design oriented), refers to complex organisations	not maintenance-oriented, maintenance considered as a 'by-product of the overall approach, not technically oriented	maintenance not considered as a profit-generating area, restricted to a general procedural framework
ILS/LSA	life cycle cost approach, system design process, aims at minimising cost elements, refers to complex organisations	maintenance is a small part of the overall approach, not flexible enough, not technically oriented	lack of flexibility and supportability to suit every company, technical details on application missing
BCM	business oriented, aims at maximising profitability, refers to complex organisations	maintenance is a small part of the overall approach, refer to complex organisations, extensive use of resources, time consuming	business objectives considered, complicated to implement, lack of direct maintenance involvement
RBI/RBM	safety and risk based approach, technical aspects more evident than previous approaches	missing reliability and criticality evaluation	lack of criticality evaluation of system and components, limited application in maritime industry
VBM/CBM	advanced and technically detailed approach	potential high capital cost/investment, part of the overall solution	minor application in maritime industry, not supporting the overall maintenance framework
AM	business oriented, safety and environment focused, refers to complex organisations	maintenance is a small part of the overall approach, not suitable for small-medium size companies, time consuming	lack of flexibility and supportability to suit every company, too complex and time consuming
TPM	managerial framework, preventive maintenance oriented, minimise cost elements (5 pillars), incorporate all departments within company, design oriented	maintenance is a small part of the overall management 'picture', can easily become complicated and time-consuming, no specific maintenance measures suggested	lack of profit-generated aspect of maintenance, human resources management missing, organisational barriers, lack of technical aspect
RCM	technically oriented approach, thorough description of system and components, cooperation of various dpts within company, maintenance database, cost minimisation	extensive use of resources, can be time consuming, cost implications if too detailed, no feedback loop available	lack of management aspect, managerial involvement required, close feedback loop needed

3.7 Tools and approaches examining system reliability and decision making

In the following section of Chapter 3, the main tools and approaches which are used in the examination of the reliability and criticality of a system are presented. These can be broadly subdivided into qualitative and quantitative ones (Figure 3.4). The qualitative ones include the Failure Modes and Effects Analysis (FMEA) / Failure Modes Effects and Criticality Analysis (FMECA), Hazard Identification (HAZID), Hazard and Operability study (HAZOP), Structured What-If Technique (SWIFT), Bow Tie analysis and Strengths, Weaknesses, Opportunities and Threats (SWOT) tools. On the other hand, the quantitative approaches comprise the Event Tree Analysis (ETA), Reliability Block Diagrams (RBD), Bayesian Belief Networks (BBN), Markov Analysis (MA), Monte Carlo simulations tool, Fussy Set Theory (FST) in the Multi Attribute Decision Making (MADM) field, Fault Tree Analysis (FTA) / Dynamic Fault Tree Analysis (DFTA) and Importance Measures (IMs). At this point it should be mentioned that a third category has been also identified, namely the semi-quantitative one. This is however incorporated in the description of the two major previously mentioned categories, as is shown next.

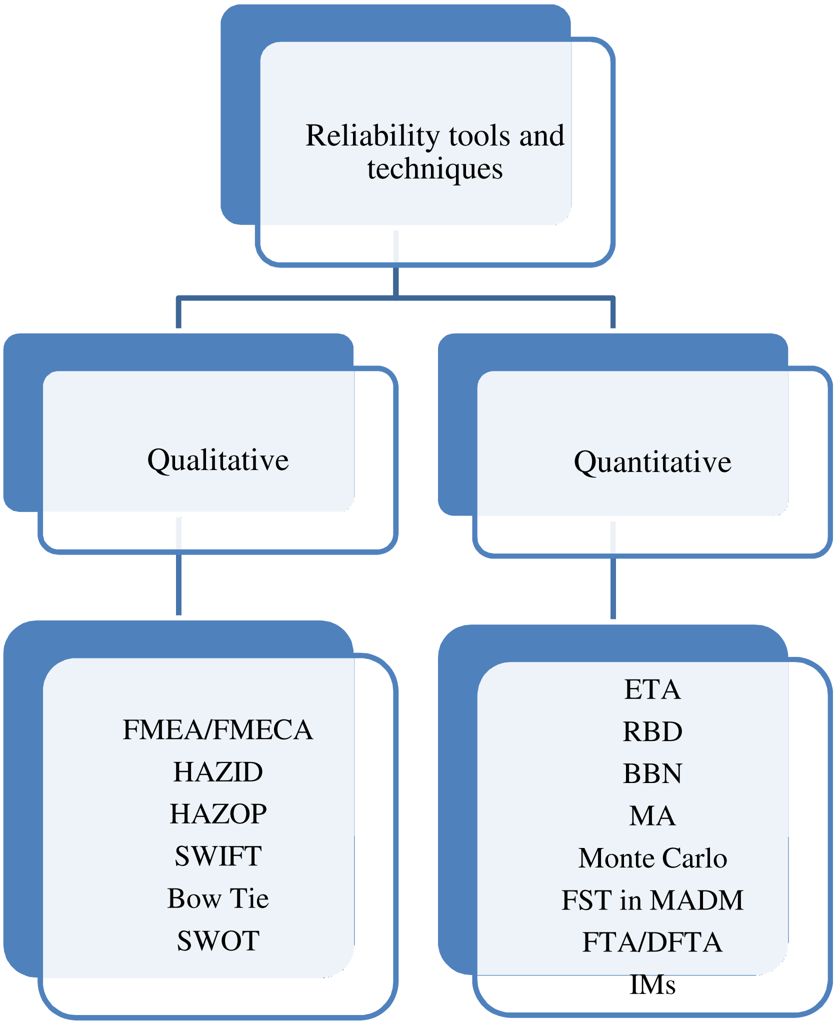

Figure 3.4 Tools and approaches examining system reliability

In this respect, it would be beneficial to present a summary of the above approaches examining various parameters such as their advantages and shortcomings, degree of expertise needed to employ each one of them, their complexity in terms of their application as well as the time-domain constraints that can be present together with the design feedback they may provide (Table 3.5). This is performed in order to obtain an overall and clear picture of the main techniques used in system reliability and criticality analysis. The latter will also assist in the selection of the most suitable tools and methods which will be employed in the application stage of the novel RCBM strategy as will be shown in sections §4.5 and §4.6. Furthermore, the presentation of the details of each one of the tools and techniques mentioned are shown in Appendix A.

Table 3.5 Summary of tools and approaches examining system reliability

Tool/Technique	Qualitative	Quantitative	Time-domain constrains considered	Design feedback	Complexity	Degree of expertise	Advantages	Shortcomings
FMEA/FMECA	+	+	-	+	medium/high	medium	Popular, analytical method, mapping the failures at the lowest level of components	Time consuming, independent failure causes
HAZID	+	-	-	+	medium/high	medium	Widely applied, experts' judgement used, able to foresee underlying risks	Full consensus among experts needed, potential difficulties for new designs
HAZOP	+	-	-	+	medium	medium	Widely applied, experts' judgement used, technical and human related hazards	Dependence on experts, thorough system description needed, time consuming
SWIFT	+	-	-	+	medium	low/medium	Experts' judgement used, flexible and easily applied	Dependence on experts, preparatory work involved (checklists)
Bow Tie analysis	+	-	-	+	low/medium	low/medium	Easy to create and communicate to non-technical stakeholders	Ineffective in the case of complex systems, balance of safeguards needed
SWOT	+	-	-	+	medium	medium	Internal/external factors considered, safety/human related, easily implemented, past information needed	Factors not assessed quantitatively, not prioritised accordingly
ETA	+	-	-	+	medium	medium	Small expert group needed, broadly accepted and straightforward tool, wide applicability	Restricted use (binary consequences), failure events considered independent from each other, over-simplistic in some cases
RBD	+	+	-	+	medium	medium	Clear representation of system layout, block preference is pre-set	Multiple sequential failure not modelled, binary states used (working/failed), partial failure not examined
BBN	-	+	+	+	high	high	Simple and powerful representation tool, model of complex systems with uncertain non-deterministic information	Great care to be taken when considering the casual interrelations among variables

Tool/Technique	Qualitative	Quantitative	Time-domain constrains considered	Design feedback	Complexity	Degree of expertise	Advantages	Shortcomings
MA	-	+	+	+	high	high	Complex systems and dynamic interrelations among states examined, graphical representation available	Laborious process when complex system is described, potential extensive calculation time needed
Monte Carlo simulation tool	-	+	-	-	medium/high	medium/high	Straightforward to employ and adjust when in lack of information, varying applicability	Relying on statistical calculations, use of sensitivity analysis tools is needed, strong software capability needed in the case of extended number of simulations
FST in MADM	-	+	-	-	high	high	Analytical approach, experts' judgement used, complex and vague information addressed	System boundaries need to be set-up clearly and efficiently, attributes defined fully and adequately, ranking method carefully selected
FTA	+	+	-	+	medium	medium/high	Popular, analytical method, mapping the failures at the lowest level of components, clear system structure represented	Time domain constrains neglected, independent failure causes
DFTA	+	+	+	+	high	high	Analytical method, mapping the failures at the lowest level of components, clear system structure represented, time domain constrains examined	Complex systems need to be clearly addressed
IMs	-	+	-	-	medium	medium/high	Analytical, precise ranking of FT end-events, easy to apply, description of multiple system characteristics	Depending on the calculation method used, unrealistic results may occur

As can be observed from Table 3.5, there exist approaches which are of medium complexity and need lower degree of expertise compared to others (e.g. HAZOP, SWIFT, SWOT, ETA, RBD) while on the other hand they are straightforward to employ and communicate their results to non-technical personnel. These tools are mostly qualitative ones while they heavily depend solely on experts' judgement in order to achieve the preliminary results of the reliability and criticality analysis.

In contrast to them, there also exist highly quantitative approaches which take into account the time-domain constrains considered when examining a complex system as well as the interrelations among the various sub-systems and components. While these tools offer superior flexibility in terms of system modelling together with the capability to adjust to uncertain non-deterministic information provided to the analyst in the first place, they tend to be time-consuming with extensive hardware and software capacity required. Additionally, the technical personnel/expert involved in such activities, need to be skilful and knowledgeable enough to identify the system boundaries and constraints so as to perform the necessary system modelling. This is the main reason why careful consideration of all available tools and approaches needs to be performed in order to address the reliability and criticality assessment of a given system.

3.8 Chapter summary

In this Chapter, the literature review of the PhD thesis has been shown. Initially, the overview of maintenance categorisation has been specified including the corrective, preventive and predictive maintenance approaches. Furthermore, the outline of existing maintenance methods present in other industrial sectors has been demonstrated. The latter includes the Terotechnology model, Integrated Logistic Support (ILS) and Logistic Support Analysis (LSA), Business Centered Maintenance (BCM), Risk Based Inspection (RBI) and Risk Based Maintenance (RBM), Vibration Based Maintenance (VBM) and Condition Based Maintenance (CBM), the Asset Management (AM), Total Productive Maintenance (TPM) and finally Reliability Centered Maintenance (RCM) approach. In addition to the above, the differences, advantages and shortcomings of these approaches have been identified in order to assist in the formation of a new maintenance framework for the maritime industry. In the second part of Chapter 3, the maintenance regime in the maritime industry has been discussed as well as an initial comparison with similar maintenance approaches in other industrial areas has been performed. At a second level, predictive maintenance is further examined in terms of the RCM, RBI (in shipping and offshore sectors), ConMon and IT applications in the shipping industry. Moreover, the third part of Chapter 3 examines specific reliability and criticality analysis tools and methods which are present in the literature. The above is performed in order to obtain a clear insight of the existing maintenance approaches and criticality tools currently available so as to identify the gaps, which the innovative suggested maintenance strategy can further fulfil. This is explicitly demonstrated in the following Chapter.

4 CHAPTER 4 – PROPOSED MAINTENANCE STRATEGY FOR THE MARITIME INDUSTRY

4.1 Chapter outline

In the previous Chapters, the existing maintenance approaches and methodologies applied in various industrial sectors have been shown as well as the current maintenance regime in the maritime industry has been explicitly described. The similarities and differences between the maintenance approaches in shipping and other industries have been also displayed but most significantly the maintenance gaps have been identified laying the foundations for this Chapter, which consists of two main parts. In the first one, the proposed innovative maintenance strategy for the maritime industry is demonstrated; that is, the Reliability and Criticality based Maintenance (RCBM) is described and explained in details in the following sections. In the second part of Chapter 4, the extensive description of the suggested reliability and criticality assessment tools and methods to be used in the proposed RCBM strategy are demonstrated. At first, the Dynamic Fault Tree Analysis (DFTA) tool is described, referring to the upgraded version of the classic FTA in terms of using static and dynamic gates. Together with the initial FT modelling, the minimal cut set theory is also used while reliability Importance Measures (IMs) are also employed to calculate the most critical components of the system under investigation and at the same time validate the results of the DFTA. Next, the FMECA tool is also used together with a purpose-built criticality matrix. Additionally, the RCBM strategy is supplemented by the portrayal of the application of the fuzzy set theory in a multi attribute decision making problem, such as the selection of the most appropriate maintenance approach in the maritime context.

4.2 Introduction of the RCBM strategy

4.2.1 Gaps in the current maintenance practices in the maritime industry

As mentioned in Chapter 3, various maintenance methodologies have been presented so far, trying to bridge the distance between the theoretical background of maintenance and its applications. However, there still exist several gaps identified in various different aspects of maintenance. At first, these particularly refer to the two main problems found in maintenance practices. The first one is the presence of corrective maintenance at which maintenance is carried out after a failure occurs. This leads to costly repairs and moreover to loss of the ship performance and its availability for a period of time, thus reducing the generated income as well as disrupting its regular service. The second major problem is that in case that the preventive/planned maintenance approach is used, some equipment and components might be replaced prematurely, thus leading to over-maintained ship equipment. However, if the condition of equipment/component can be monitored so as to be repaired/maintained only when needed/decided, this can lead to the selection of the best maintenance sequence and consequently to the optimisation of the maintenance intervals.

Moreover, another gap in the existing maintenance methods is identified in the way that the existing tools and software applications are used for monitoring selected ship equipment. These enable the gathering (through even wireless transmission) of data and seem a promising application in the maintenance field thus enabling better planned maintenance scheduling. However, as mentioned before, these are just tools which need a trained technician or crew member to use them in the correct way otherwise they just turn into expensive maintenance gadgets rendered useless after a period of time. Furthermore, these tools may have limited functionality and integration with other platforms including the ones responsible for inventory lists, spare parts and communication with the onshore personnel.

Another issue related to a gap identified in the current maintenance regime is the time that the ship may remain in dry-dock when undertaking major repairs and maintenance tasks. Initial surveys may take a few days to a week to be carried out which means further delays in the initiation of the actual repairs and maintenance works. This issue can be addressed if there is a systematic framework in place so as to carry out the ship surveys onboard while the ship is in service and the needed repairs and maintenance works are documented (including e.g. steel works, machinery equipment repairs, etc.) long before the ship approaches the shipyard, thus saving crucial repair and accordingly operating/income generating time.

On the other hand, condition monitoring systems are nowadays used in applications such as engine performance monitoring and vibration monitoring. These can be improved to include a criticality-based approach in various areas of the ship, cost effectively. At this point it must be noted that it is of the highest importance not only to learn which are the new monitoring techniques but also to decide which of them are worthwhile implementing. Additionally, in today's shipping world, maintenance and technical managers need to address the selection of the most appropriate techniques to deal with each type of failure in order to fulfil the expectations of all stakeholders, implement the maintenance measures in the most cost-effective way and achieve the active support and co-operation of all the personnel involved, which means the collaboration from top management to the crew of the ship.

In addition to the above, the main problem in this case is how to use the collected data efficiently to maximise the benefit stemming from them. It is not unusual for a few pioneering shipping companies/operators to possess maintenance databases with gigabytes of stored data with no specific functionality or usefulness. It is therefore very important that the condition monitoring is evolved into a proper assessment method. In order to do the correct condition monitoring with an immediate action plan, the recorded data should be turned into concise and clear information regarding the current criticality status of the various systems and equipment.

Moreover, the starting point for any effective maintenance strategy is the ability of the personnel-both onboard and onshore-to use it and keep it in a successful and efficient operational condition. Besides, the creation of a paperless collaborative work environment for all stakeholders (shipping companies/operators, equipment suppliers, shipyards, original engine/equipment manufacturers-OEM) is a prerequisite for the application of a novel maintenance strategy. Many of the existing ship management systems use tables and various coding features to enter and search for data. This is an obstacle for using the management system for those who are not familiar with the ship's practices and procedures, the language the system uses and the use of computers in general.

Summarising, an effective maintenance strategy must provide space so as to fulfil the below mentioned objectives:

- Well-structured and robust to cover all technical and managerial aspects of maintenance
- Flexible to be adjusted to different cases, applicable to a range of smaller or larger companies
- Obtain feedback from operational procedures
- Consider explicit (failure rates, component failure databases) and tacit data (experts' judgement, crew knowledge, skills and capabilities)
- Perform reliability and criticality assessment and prioritise maintenance tasks
- Take into account the Maintenance Information Technology systems and Decision Support platform
- Include periodical reviews and incorporate changes
- Just-in-time supply chain interface in order to eliminate waiting times and increase the availability of ships

4.2.2 Proposed RCBM strategy

Having the above gaps and prerequisites in mind, the suggested novel Reliability and Criticality Based Maintenance (RCBM) framework retains and enhances the initial given reliability of a system, item or component based on the assessment of its criticality. In this respect, it is extremely important to enable the assessment of the criticality of the vessel at an overall system and component level in order to prioritise maintenance tasks and repair works performed on a timely manner. Bearing the above in mind, the overall framework of the proposed RCBM strategy as this can be applied in the maritime maintenance is described and presented next in Figure 4.1.

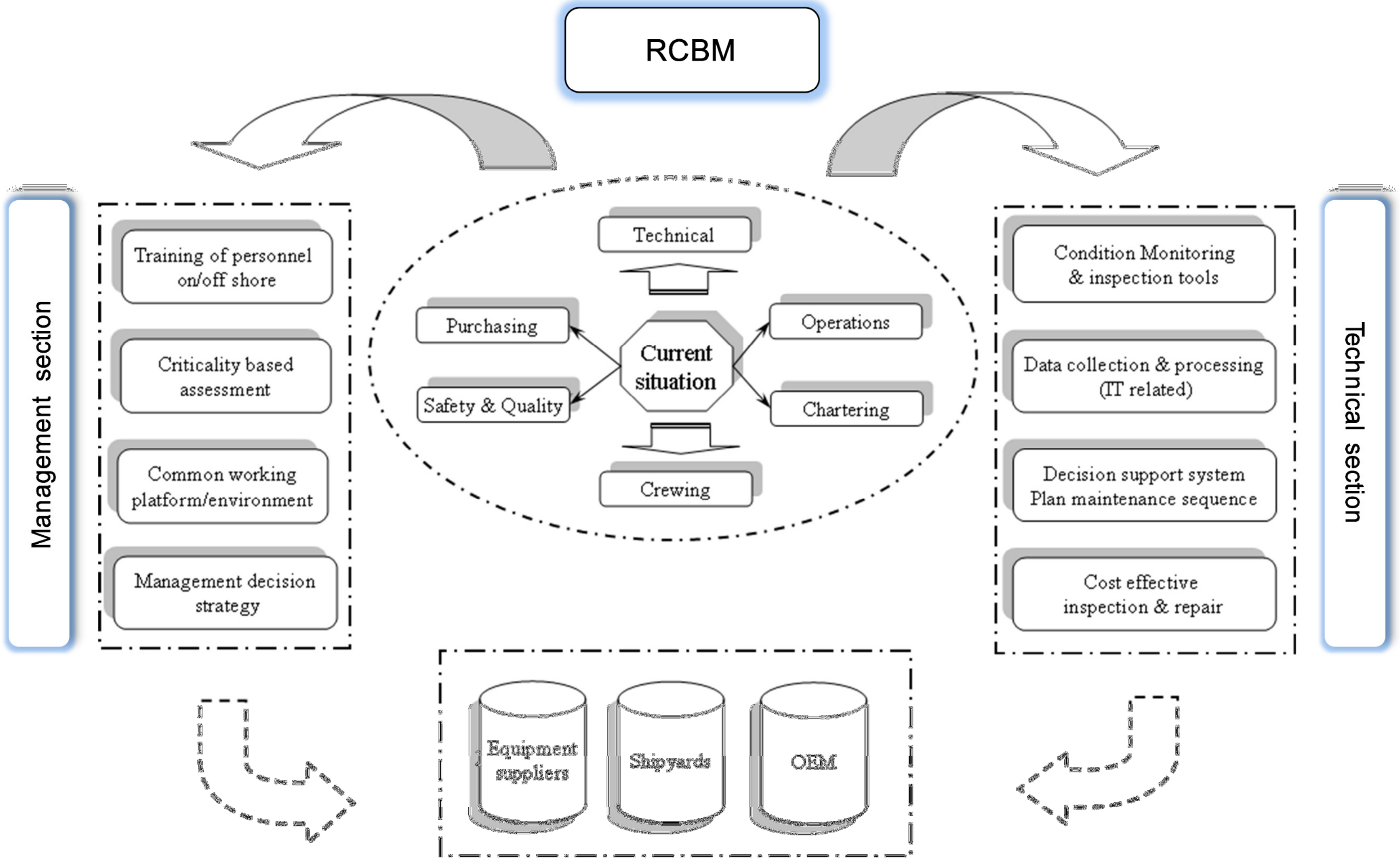

Figure 4.1 Overall framework for the innovative RCBM maritime maintenance strategy

The novel RCBM strategy eliminates the gaps existing in current practices in the maritime maintenance field by proposing a number of intrinsic features. It moreover suggests a holistic maintenance approach while it integrates the enhanced technical and management aspects of the maritime industry through the coordination of the current planned maintenance with condition monitoring, data acquisition and gathering, incorporating reliability and criticality analysis, decision support platform and supply chain seamless cooperation. Furthermore, RCBM is a framework for arriving at the most appropriate maintenance approach for a specific piece of equipment, given the knowledge about reliability characteristics, functional relationships and the failures of the equipment as well as their consequences.

Accordingly, RCBM acknowledges the importance of onboard and onshore users and links training material with the maintenance and repair schedules. The training material is delivered through the same system in user-friendly formats. Moreover, training of the crew onboard should have the following aims:

- Knowledge and skill based training to be able to detect any potential defects and report them through a paperless failure recording system
- To be able to operate any of the semi-manual inspection and condition monitoring tools
- Development of onboard resource management for proactive maintenance and repair culture as a team

Overall, the main aim of the RCBM strategy is to be available to crew on-board as well as personnel onshore. Access of the system can be introduced to a specific ship, certain ships or the whole fleet depending on the stakeholder needs. This will lead to an integrated approach to fleet maintenance and repair. RCBM will be able to evolve based on the maintenance sequence carried out onboard the ship, gathering real-time data and thus be open to be reviewed and updated. More specifically, the RCBM strategy will allow the following:

- Incorporate training material into the management system
- Store information available to all stakeholders
- Achieve data collection from the operating system (ship, office, personnel).
- Transform data to knowledge and moreover to information about the operating system
- Perform reliability and criticality assessment of individual components and systems
- Identify critical system and equipment functions

- Incorporate visual checking and continuous monitoring data into the critical maintenance schedule
- Use pictures/videos and technical drawings as an operator interface
- Allow for the combination of experts' judgement including superintendent engineers onshore, captain and chief engineer onboard the ship
- Implement a Computerised Maintenance Management system
- Maintenance performance measurement methods for the evaluation and benchmarking of the performance (KPI, TCI)
- Decision Support System for the maintenance procedure
- Supply chain seamless execution of maintenance tasks

As is shown above, the overall RCBM maritime maintenance framework consists of four major segments. More specifically:

1. Current condition/structure

The central part of Figure 4.1 presents the current condition/structure of a typical shipping company. In this context, there exist different departments such as the technical, chartering, operations, crewing, safety and quality and purchasing. These departments co-exist and cooperate in order to deliver all the required services in terms of the operation of the ship. These include the technical maintenance tasks; repair works and spare parts (technical dpt) and arranging and advising for the chartering of the vessel taking into account the availability of the vessel throughout the year (chartering dpt). Furthermore, considering the overall operational capacity of the vessel or entire fleet (operations dpt), arranging and providing for the crew that will be employed onboard the vessels as well as for the training and certificates needed for all the different levels of crew (officers and ratings) (crewing dpt), taking into account all the relevant Health, Safety, Quality and Environment (HSQE) issues for a specific vessel or fleet of vessels (safety and quality dpt) and issuing the relevant purchase orders and payments (purchasing dpt). In the suggested RCBM framework, these are supplemented by two additional sections: the technical (right hand side) and management (left hand side) ones described next.

2. Technical section

On the right side, the technical section of the RCBM strategy incorporates the benefits of applying the Reliability Centered Maintenance (RCM) approach mentioned in section §3.6.3.1 such as experts' involvement (technical managers, captains and engineers), detailed system analysis, introduction of functional FMEA/FMECA, condition monitoring and collection of data, implementation of maintenance tasks, technical support in personnel and tools needed and decision support process. In this way, instead of bringing the system back to a 'perfect' operational state, the RCBM strategy intends to bring it back to a good functional state within the operational limits of each case and so:

- Enhance the safety and reliability of the systems examined based on the most important functions
- Prevent or mitigate the consequences of failures
- Reduce maintenance costs by avoiding or reducing maintenance which is not absolutely needed (decision making process, 'what to do' procedures)

3. Management section

On the left side of Figure 4.1, the RCBM framework includes the management section which considers the advantages of Total Productive Maintenance (TPM) regarding the management and organisational aspect of this approach including leadership support, strategic planning, planning for implementation, training and re-training, communicating the decisions to all personnel involved in-house (onshore and crew onboard).

4. Supply chain interface/related stakeholders

Hence, the decisions made are then communicated to all related stakeholders such as equipment suppliers, shipyards and original engine manufacturers so as to have a lean repair and maintenance sequence either during the dry-docking period or throughout the operation of the ship in order to plan ahead for forthcoming repair works, achieve the optimum outcome during repair and maintenance tasks as well as advise and provide feedback at the design stage of a vessel.

The above mentioned RCBM framework is carried out at three different levels:

- Strategic; including in-house maintenance management of planning, implementation and control of maintenance

- Tactical; type of maintenance preferred such as corrective, preventive or predictive or combination of these
- Operational; which refers to more practical issues i.e. actual overhauls, repairs and maintenance tasks

In this way the RCBM framework overcomes the difficulties of applying specific maintenance aspects from other industrial sectors into the maritime industry, which are too complicated to implement in the first place (as described in §3.5). It also enhances the existing maritime approach towards maintenance, which does not include all aspects of the maintenance subject (being either too technical or not managerial at all) as described in §3.6. These are developed based on the explicit needs of the maritime market when requesting solutions to specific problems arising during the actual ship operation. The suggested RCBM framework keeps the last observation in-sight together with developing a strategy which engulfs both the procedures and the managerial aspects regarding ship maintenance, thus providing a consistent, integrated and overall framework applicable to the maritime industry. In this respect, the details of the RCBM framework as well as the technical and management sections are presented and described in the following paragraphs.

4.3 Technical section of the RCBM framework

Initially, the technical section of the RCBM framework is described in detail as shown in Figure 4.2. In this case, the main objective of the technical section is to collect the necessary data (either through automated condition monitoring or through crew involvement) in order to transform them into useful information and moreover identify the failures and underperforming events, thus prioritise the maintenance tasks that need to be performed. The above are thoroughly described next.

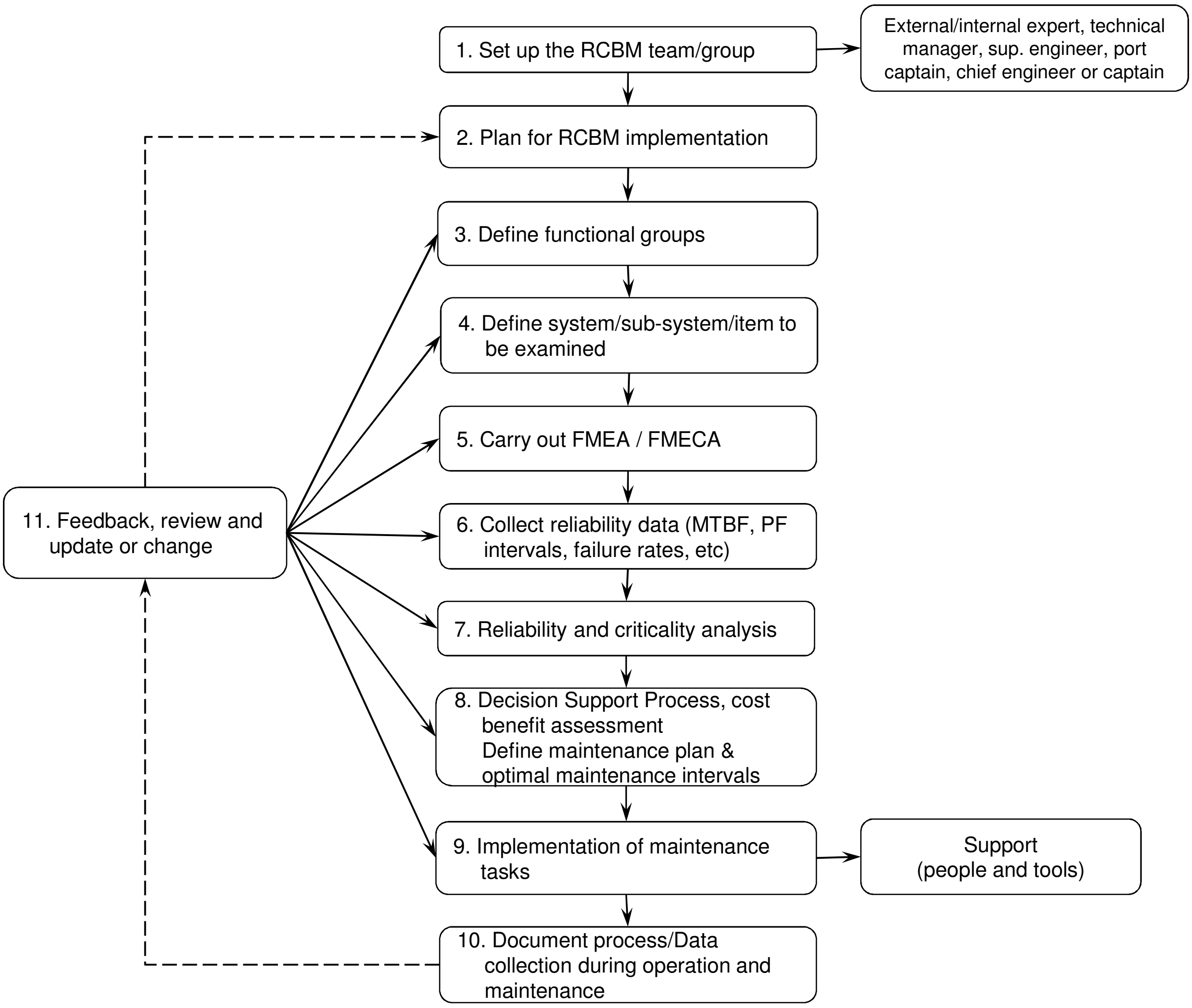

Figure 4.2 Detailed presentation of the technical section of the RCBM framework

As is shown in Figure 4.2, a detailed description of the technical section of the RCBM framework is presented. This section considers the in-depth features of all the different stages included, which consist of the following:

1. Set up of the RCBM team/group

This step includes the initial formation of the group that will consider and carry out the technical aspects of the RCBM. The initial team may include either an external or internal expert who must have sufficient experience and expertise on technical aspects regarding the criticality and reliability assessment and who will facilitate the organisation and the overall procedure and implementation of RCBM. The rest of the persons involved in the setup of the group as well as their number may range to include a technical manager overlooking a fleet of vessels within the company, a superintendent engineer responsible for a number of ships, a port captain or Designated Person Ashore (DPA) and finally an active chief engineer and captain. The number and quality of the persons for the completion of the initial RCBM group may vary from company to company according to the number and availability of personnel employed. Nevertheless, a minimum number including the facilitator, technical manager and persons from both ship disciplines (machinery and deck) should be considered.

2. Plan for the RCBM implementation

In this step, the RCBM team gathered above sets out a structured plan and accordingly this is the one that will be followed until its full implementation.

3. Identify functional groups/ship systems

At this level, the identification of the functional groups/ship systems of the examined case is carried out, assisting in the clear definition of the systems to be analysed next. Examples of functional groups of a ship can be the hull structure, machinery sector (including the main engine room group of equipment and machinery), navigation equipment as well as the safety & fire fighting equipment (Figure 4.3).

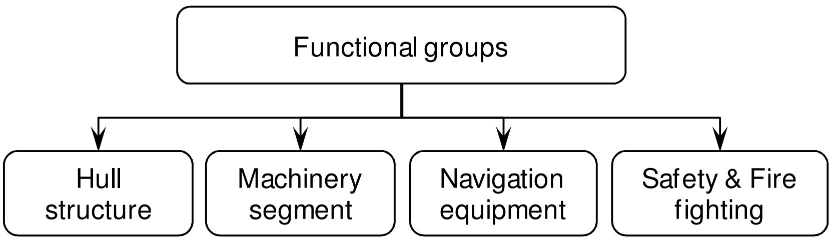

Figure 4.3 RCBM functional group diagram

4. Define system/sub-system/item to be examined and collect maintenance and reliability data (MTBF, failure rates, PF intervals, etc.)

The functional groups identified above can be further sub-divided into various areas e.g. in the case of hull structure, the sub-systems mentioned are the deck area, the ballast tanks, the cargo tanks/holds and the outer hull envelope (Figure 4.4). In the case of the machinery sector, this may include the engine room area, the machinery on the deck area and other machinery areas such as the pump room and the bow thruster room if available (Figure 4.5).

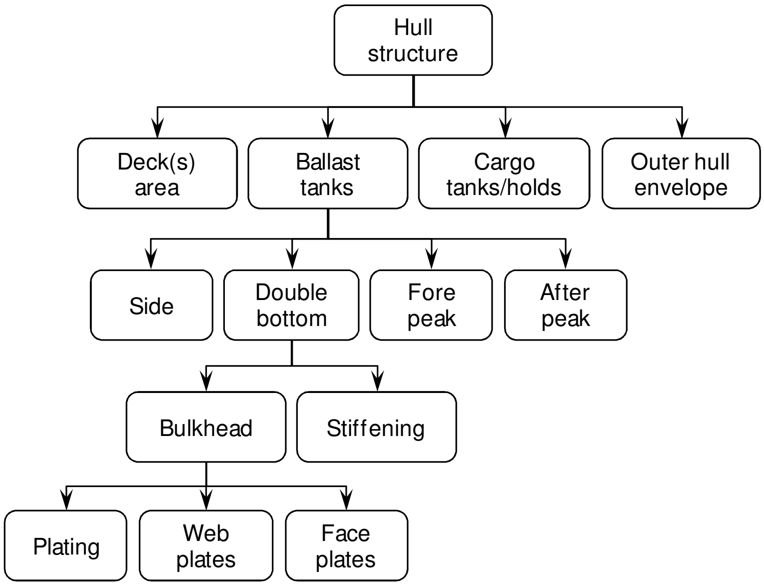

Figure 4.4 Hull structure area functional sub-group

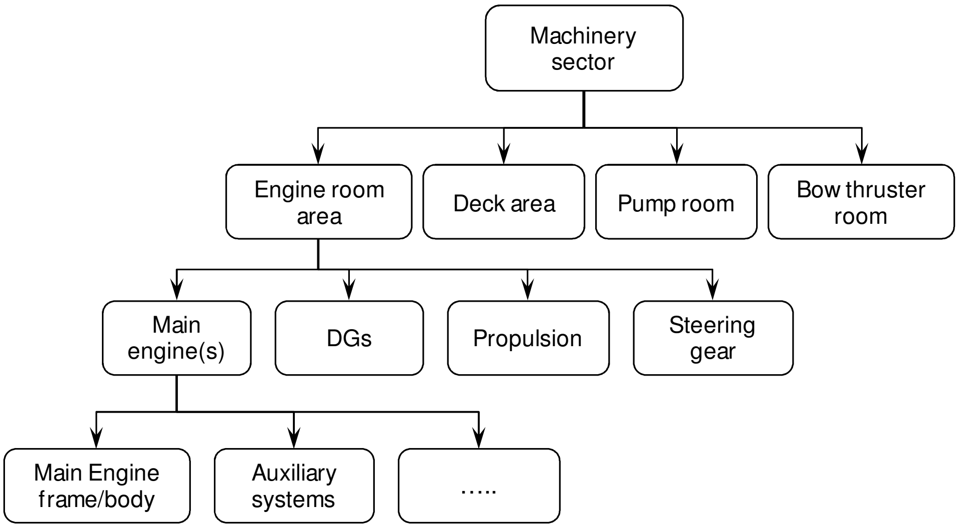

Figure 4.5 Machinery area functional sub-group

5. Carry out FMEA/FMECA

At this point, FMEA or FMECA may be performed, which can be used either as a bottom-up approach (useful when dealing with an existing asset) starting with the failure of specific items or as a top-down approach (useful when working on a new design) analysing the primary functions of the systems under examination and their failures.

6. Collect maintenance and reliability data (MTBF, PF intervals, failure rates, etc.)

After setting up the systems and sub-systems, maintenance and reliability data can be collected including MTBF, failure rates, repair times and other details such as spare parts inventory lists, personnel involved, condition monitoring equipment used, outsourcing involved, major repairs carried out including specialists' reports, etc. After proper screening out of the unnecessary or duplicated data, these will be then used to populate the appropriate reliability and criticality analysis tools to be employed further-on. A number of data collection tools may assist in this direction including thermography, lube oil analysis, vibration monitoring of the shaft of the main engine and all the rotating equipment. The devices which may be used to carry out the inspection may comprise of electronic means and on-line applications (wireless sensors, PDAs, barcodes) or manual retrieval of data depending on the availability of resources. On the other hand, if no such tools are available on-site, simple recording of the failures and maintenance tasks performed for the various components can be also employed. Alternatively, historical data gathered from original equipment manufacturers' can be used or even well-known databases from other industrial sectors (e.g. OREDA handbook) being employed to address the data requisition task.

7. Reliability and criticality analysis

In this case, the reliability and criticality tool is selected and used in order to achieve the best outcome for the system under consideration. There are a variety of tools to be employed of both a qualitative and quantitative nature. These include among others tools such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), minimal cut set theory, Markov Analysis (MA), Fussy Set Theory, Monte Carlo simulations, Hazard Identification (HAZID), Structured What-If Technique (SWIFT), Hazard and Operability study (HAZOP), Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, Bayesian Belief Networks (BBN), or Reliability Block Diagrams (RBD) (described in sections §3.7.1-3.7.2). The RCBM team may choose the most suitable tools according to the modelling of the system they will select to analyse in the first place. In this case, data will be fed from either the condition monitoring systems onboard or from the crew of the vessel. After the appropriate tools have been selected and the system has been structured, the automated criticality based assessment is performed, considering the relationships of the systems' components as well as any system restrictions pertaining to the time domain and sequence of events occurring.

8. Decision Support Process, cost benefit assessment, classification of maintenance plan/actions (corrective, preventive, predictive) and optimal maintenance intervals

After the reliability and criticality analysis is performed, the Decision Support Process (DSP) takes place and all the relevant maintenance tasks are selected and allocated accordingly (Figure 4.6). The DSP, which takes into account the criticality assessment and the real time monitoring data, can give advice on the relative maintenance options and alternatives available to the personnel onboard. It can also assist the personnel of the technical dpt onshore through the optimum actions taken by the DSP, which results in improving the ships availability through the selection of the most suitable maintenance and repair strategy for the given condition. The DSP can provide a maintenance instruction, which will then be conveyed on to the shipping company's maintenance system. The format of the instruction can be developed as well as the architecture of the interface between the DSP and the operator's system.

In the case of low-importance criticality results identified, the DSP may advise for corrective maintenance measures to be implemented. In this event, these may lead to replacement and/or instructions for redesign of the equipment/item under consideration (inspection findings may indicate potential design flaw of subject system or equipment). In the case that a specific failure is indicated as of medium criticality, preventive maintenance works may be performed. The above are carried out with respect to scheduling the maintenance job either as an overhaul (e.g. diesel generators, main pumps, turbocharger, etc.) or a replacement of the system or equipment under consideration (e.g. valves, filters, piping). The correct timing of the entire maintenance activity needs to be considered at this stage as well as the availability of spare parts and related cost implications. In the event of identification of a high criticality event/failure, predictive maintenance tasks can be performed if the condition of the subject system/equipment is not in a good functioning condition and its operation can be monitored for a period of time within safe limits. The initial monitoring procedure can be in the form of either continuous (e.g. monitoring of rotating equipment) or interval monitoring (e.g. lube oil analysis).

All the above takes into account the framework of current maritime regulations and guidelines as well as the company's own policies and procedures on maintenance. In addition to that, a cost-benefit evaluation is also performed in order to obtain a comparable reference with respect to the various maintenance options offered. Having all this information available, the Decision Support Process is developed and applied in order to give all stakeholders involved (company's managers, captain and chief engineer) a quick and thorough decision-making tool. With this in mind the optimal maintenance sequence can be planned leading to a cost effective inspection and repair action.

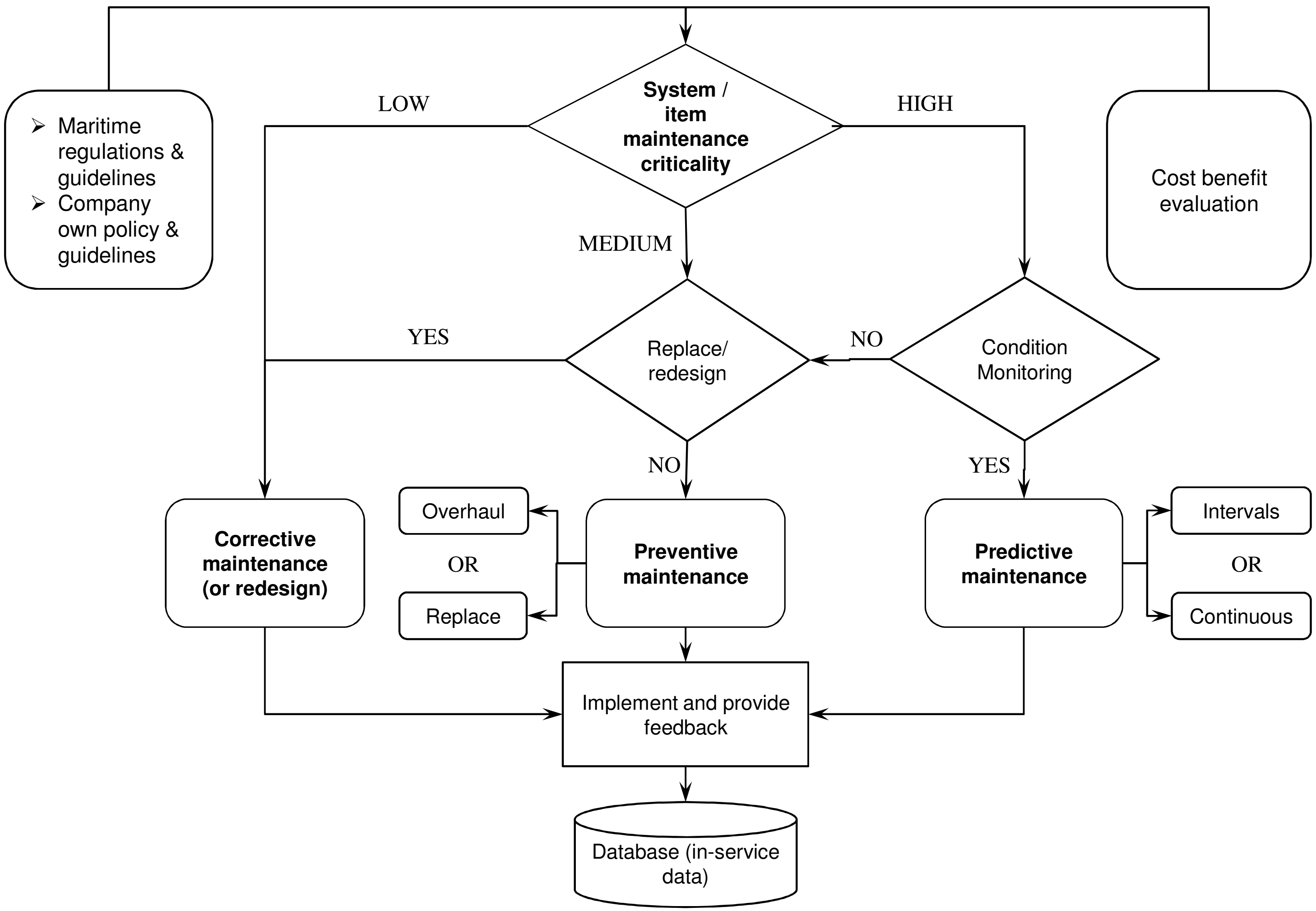

Figure 4.6 Maintenance strategy Decision Support Process

For this particular stage in the technical section of the RCBM framework, the relevant input from maritime guidelines, recommendations and regulations is also considered in order to enhance the maintenance/repair work. An example of the above is that in the case of a tanker vessel on which no hot works can be carried out when an unexpected failure/repair action occurs, then the ship needs to proceed to the nearest shipyard for repairs in case of no other existing alternatives considering the safety and environmental parameter. Furthermore, one should also consider the situation in which time is restricted in terms of arranging for a full RCBM team to take the correct maintenance decision (e.g. an unexpected failure occurs). In such case, it is usual practice for the captain and chief engineer onboard the ship to take a quick decision based on their experience, expertise, spare parts carried onboard and the adequate tools in order to amend any deficiencies that have occurred. In this last event, the company needs to arrange for all the critical spare parts to be in place onboard the vessel in decent quantity (according to the suggestions of chief engineer, captain and superintendent engineer) beforehand, which suggests proper inventory list planning and execution. This applies in the case that either corrective maintenance is needed (immediate replacement of a component) or preventive/planned maintenance is performed at predefined intervals but in which case there exist logistical restrictions especially when the vessel sails in inconvenient ports/countries far away or it is too costly to purchase the spare parts/components needed.

9. Implementation of selected maintenance tasks

At this stage, the specified maintenance tasks are carried out. At this level, corrective, preventive or predictive maintenance works may be performed depending on the most appropriate decision/selection of maintenance made in the previous steps. For this to achieve the desired and most effective outcome, a combination of resources is required in terms of personnel (i.e. including pertinent skills, expertise and knowledge required from crew and maintenance personnel) and tools to be utilized. The latter refers and is directly linked to the availability of spare parts and all the necessary equipment needed. Moreover, being able to have the correct and sufficient number of critical spare parts onboard the ship means that tied-up capital expenditure is minimised.

10. Document process/data collection during maintenance and operation sequence

After the implementation of the desired maintenance activity, the data collection sequence is documented and introduced in the data storage system of the company. This needs to be in the form of both onboard and onshore (company headquarters) documentation (e.g. electronic format). For the latter to be efficient, an electronic database system can be used and populated with the correct type of data. The data can be inserted directly from the ship through a Computerised Maintenance Management System (CMMS) by the captain or chief engineer or even the attending superintendent engineer in case of an onboard visit. Alternatively, there may be an online system which will have the capability of transferring real-time data to a centrally onshore located database/server.

11. Feedback, review and update or change

The final step in the whole RCBM technical procedure is the documentation and the continuous update of the approach. This is achieved through a post-maintenance review and evaluation of the steps taken in order to address the system/equipment failure(s) which leads to the suggested repair/maintenance works. During this stage, updates or even changes in the maintenance sequence followed may be necessary in terms of:

- data management acquisition process
- revision of the required inventory lists
- extension/modernising of the maintenance tools used and applied (e.g. ConMon tools)
- outsourcing if necessary

In addition to the above, another significant and essential part of the RCBM framework is the management section, which needs to be performed concurrently with the technical section. This is presented with more details next.

4.4 Management section of RCBM framework

The management section of RCBM framework is presented in Figure 4.7. As can be seen, it consists of the following elements: training and re-training of personnel/crew, criticality based assessment, sustain a common working platform with all stakeholders involved in repair and maintenance works and finally an overall management decision strategy which can be applied on either a single ship or a fleet of vessels. All of these are described with more details next.

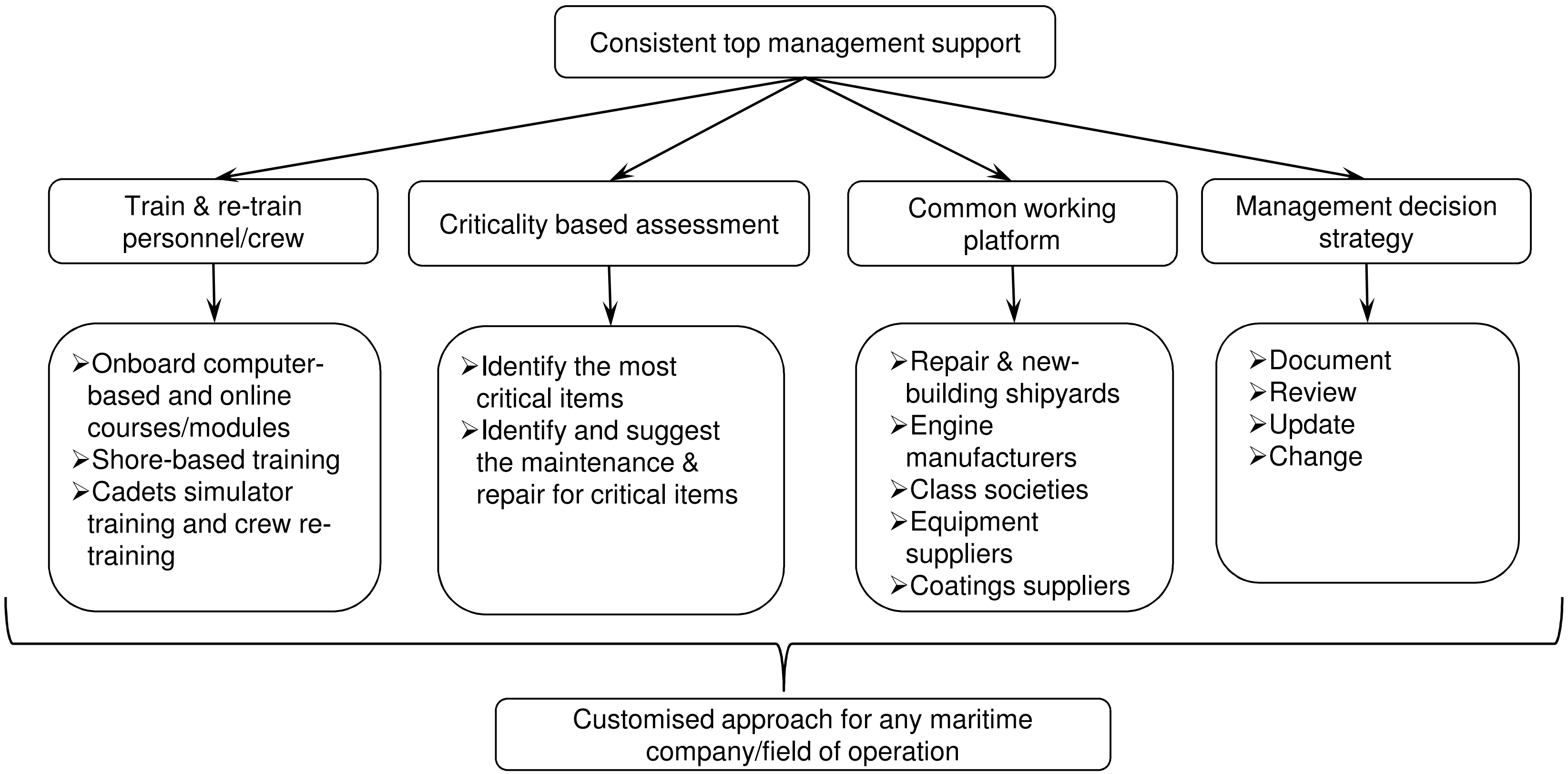

Figure 4.7 Management section of RCBM framework including company's top management support

1. Train and re-training of personnel/crew

More specifically, the training and re-training element means that the crew on board the ship needs to be trained and re-trained if necessary to be able to work with the new systems available. The latter includes both junior (cadets) and senior officers (captain/chief engineer), so as to get familiar with the technical aspects (i.e. condition monitoring tools, software applications, etc.) which will eventually assist them in the initial decision-making process. Additionally, there may be onboard computer-based and online courses/modules which will enhance the time available for the crew onboard the ship, bearing in mind the seafarers' restricted onshore availability for training courses. Moreover, the development of a proactive team culture towards repair and maintenance from the side of the marine crew can be implemented. This requires investment in onboard team organisation and crew in the form of skill and knowledge enhancement activities. What will be furthermore needed is for the crew of the vessel to be trained in fault and failure identification using tools in terms of easy fault recording techniques available on board as well as training for quality maintenance performance and recording.

This can be also complemented by using shore-based training (as is the current practice in very few shipping companies) in order to develop the onboard crew capability and knowledge especially on new developments regarding superior maintenance of ship systems, energy efficiency onboard the ship and overall enhanced ship performance. Furthermore, with regards to junior officers/cadets, integrated and full bridge and engine room simulator training and crew re-training is a necessity in order to achieve the aforementioned outcomes (Bosma et al 2010). For the onshore personnel, training includes the familiarisation with the new IT tools and databases, CMMS and decision making process as well in order to obtain a smooth operation and technologically improved profile. In this way, as soon as the relevant data are processed automatically to the onshore personnel as well in a clear and user-friendly manner, they will be able to take the most appropriate decision in the form of remedial actions to be applied regarding the criticality of the subject system and equipment.

2. Criticality based assessment

Moreover, the prioritisation of the maintenance tasks relying on the criticality based assessment instigates from the technical analysis described before. This stage includes the management decision regarding the acknowledgement of the specific maintenance action to be carried out (corrective, preventive or predictive). In this way, while the most critical vessel systems and items have been identified, the most appropriate maintenance and repair action will be carried out. At this point it should be clarified that the Decision Support Process described in § 4.3 is one of the major parts of the technical section of the RCBM strategy, referring to the specific technical elements of applying the novel maintenance framework, which is based on the timely identification of failures and underperforming events and thus prioritisation of maintenance and repair works. On the other hand, the criticality based assessment refers to the commitment at the higher management level for supporting the technical criticality assessment carried out before. In this regard, without the continuous support of the company's management team, the maintenance improvement effort may be partially implemented at the very initial stages, not bearing the fruit of the full strategy application.

3. Common working platform

What follows next is the enhancement of a common working platform including repair & new-building shipyards, engine manufacturers, Classification Societies, equipment suppliers and coatings/paints suppliers so as to achieve the best benefits stemming from the cooperation of the above stakeholders. This platform can be initiated when a computerised maintenance system which can provide an online web-link among ship owners/managers, ship-repair yards and suppliers can take place. Especially in the case that a maintenance and repair specification plan/report is prepared on behalf of the ship owner/manager company, this can be used in two ways. One way is to utilize it as a means for performing internal performance monitoring, benchmarking and auditing tasks. At a second level, it can be used for providing the essential information to shipyards and engine and equipment suppliers connecting the shipyard's activities with the sub-contractors employed, in addition to the extra repair works identified after the inspection of the ship is carried out in the ship repair yard.

4. Management decision strategy

Last but not least, the management decision strategy includes the documentation, review, update and change (if needed) of the entire process. It is most imperative for the RCBM maintenance strategy to take place to have the full support of the top management team in the initiating, implementation, updating and finally documentation stage of the RCBM strategy.

After presenting and discussing the details of the RCBM framework, the second part of Chapter 4 takes place. That is the detailed description of the reliability and criticality tools used in this dissertation in order to achieve the objectives stated before.

4.5 Tools and methods used in the RCBM strategy for performing the reliability and criticality assessment

As shown in Chapter 3, there are various tools and techniques that can be used to achieve the reliability and criticality assessment of different systems and components as mentioned in section §4.3. In this respect, the implementation of the initial technical section of the RCBM strategy is shown next, in which the FMECA and DFTA tools applying static and dynamic gates are deployed in order to derive the optimum reliability and criticality assessment results. The mentioned tools are chosen for a number of reasons, which are related to the specific nature of the ship as an entire system. More specifically, the FMEA/FMECA tool is used as it combines the qualitative features of an in-depth technical analysis of the vessel system/component under examination (FMEA tool) as well as quantitative characteristics in terms of initial identification of the criticality index of the various pieces of equipment investigated (FMECA tool). Moreover, it can provide valuable feedback on the design of the considered system while it is one of the most popular analytical approaches and is suitable to be used by analysts who initially set-up the system boundaries and parameters. Additionally, it is an approach which helps in mapping the potential system and equipment failures at the lowest component level. However, it does not provide for the important interrelations among the various systems and components as each one of them is examined separately and moreover does not include the potential time constraints involved in the operation of the systems and equipment.

This shortcoming of FMEA/FMECA is satisfied by the implementation of another tool which is performed in conjunction with FMEA/FMECA. This is the Dynamic FTA (DFTA) which considers all the drawbacks mentioned above. Furthermore, it can be applied in both a qualitative and quantitative way. In the first case, it can be used to show the interrelations of the various systems among each other as well as the ones of their components in a clear graphical tree-like representation. Then, it can be used in a quantitative way to assess the reliability and moreover criticality index of the subject systems and components, thus identifying the highest contributing/critical end-items for the function of the system under examination. It can also provide feedback on the initial system design features, especially when re-design is needed in the initial assessment stage of a piece of equipment. Thus, any faults identified can be rectified in a timely and concise way. In addition to the above, the DFTA tool considers the specific boundaries in the system time-dependant environment especially when taking into account redundant equipment or systems that work in series or in parallel as well as components that can be replaced with others in order to enhance their function and performance. In this way, an additional advantage of this tool is that complex systems (such as ship systems) can be clearly modelled and addressed and their functions simulated.

Moreover, when in need of encompassing a multitude of other parameters in order to perform the reliability and criticality analysis of a system, an enhanced method using Fuzzy Set Theory (FST) in a multi attribute decision making maintenance environment is selected. The system parameters that are considered by using FST can be other than technical ones including among others the human element involvement and training, top management commitment to a predefined maintenance and repair plan, minimisation of operation loss and increase in the ship/system availability, system maintenance efficiency, maintenance approach cost for implementation as well as, spare parts inventory lists and company investment on different maintenance approaches. The above can be also examined in the light of tangible aspects (e.g. specific objective outcomes like the cost element) and intangible aspects (e.g. subjective opinions based on experts' judgement), which cannot be defined otherwise but which are nevertheless crucial for attaining the full picture of all the parameters involved when examining a ship maintenance and repair process. The above are presented with more details in the next sections.

4.5.1 FMECA

FMECA is used as an initial step in the case of the DG system in order to assist in the identification of the sub-systems and events established for use in the DFTA. It also assists in the initial DFTA system setup. It also provides a preliminary determination of the criticality index of each failure event based on the experts' judgement. In this regard, FMECA includes two additional features which provide this approach with its specific characteristics. These are the severity and frequency indices estimating the criticality index as well. The severity and the frequency/probability of occurrence of the failure events are assessed for different categories (e.g. safety, environment, asset and operation) while the various identified failures are classified according to their criticality in the system under investigation (Figure 4.8).

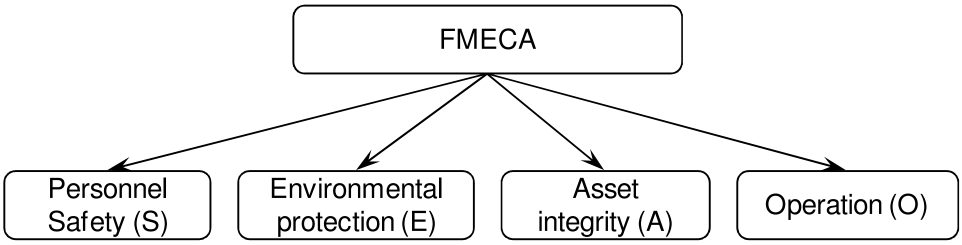

Figure 4.8 Different areas of severity effects in the FMECA table

4.5.2 DFTA

DFTA is an expanded and upgraded version of the classic FTA. It is used to describe and solve the problems occurring on complex systems in order to overcome the difficulties in the application of the original FTA. DFTA employs static as well as dynamic gates for modelling the structure of a FT. Dynamic gates model the structure of the associating gates and basic events of the FT considering the specific sequential and time constraints imposed by the examined system, thus allowing for a more precise representation of the existing failure events. The application of DFTA retains the advantages of the classic FTA such as being a popular and well-understood reliability approach within the research and industrial community, addressing multiple system failures at the lowest component level and presenting a clear graphical picture of the examined system while at the same time deals with the classic FTA shortcoming (i.e. time domain constraints) by introducing the dynamic gates modelling which retains its capability for calculating the reliability and availability of complex systems. Additionally, no further knowledge of more complicated reliability techniques is needed (e.g. Petri Nets).

DFTA is applied in various cases which can be traced in different industrial sectors. Examples of this can be found in the electrical power supply system (Rao et al 2009) and the maintenance activities of the safety equipment of a nuclear power plant (Cepin and Mavko 2002). Expanded research in the application of DFTA has been carried out in the aerospace industry as well (NASA) including the work of Rao et al (2009) and Dugan et al (2000, 1993). In the maritime area, the application of DFTA has so far been investigated on the pod propulsion system of a Roll on-Roll off (Ro-Ro) vessel (Aksu et al 2006) as well as in the diesel generator system of a cruise ship (Lazakis et al 2010) and the initial application on a diving support vessel (Turan et al 2011).

As already mentioned, part of the DFTA is the use of the well-known static 'AND' as well as 'OR' gates. These gates are described at time t as:

$$P_{ANDgate}(t) = P\,\{C_1 \cap C_2 \cap C_3 \ldots \cap C_n\} = P\,(C_1)\,P\,(C_2) \ldots P\,(C_n) \tag{4.1}$$

$$P_{ANDgate}(t) = P\,(e_1)\,P\,(e_2) \ldots P\,(e_n) \tag{4.2}$$

and

$$P_{ORgate}(t) = P\,\{\,C_1 \bigcup C_2\, \ldots \bigcup C_n\,\} = 1 - [1 - P\,(C_1)\,]\,[1 - P\,(C_2) \ldots \ldots [1 - P\,(C_n)] \tag{4.3}$$

$$P_{ORgate}(t) = 1 - [1 - P\,(e_1)\,]\,[1 - P\,(e_2)] \ldots .\,[1 - P\,(e_n)] \tag{4.4}$$

where:

$P_{ANDgate}(t)$ = probability for the 'AND' gate

$P_{ORgate}(t)$ = probability for the 'OR' gate

$e_i \ldots e_n$ = independent basic events

Another gate that is used in the static FTA is the 'TWO-OUT-OF-THREE' gate which describes the probability of the redundant components in the system. This is given as follows:

$$P_{2\,OUT\,OF\,3}(t) = P\,\{C_1 \cap C_2\} \cup P\,\{C_1 \cap C_3\} \cup P\,\{C_2 \cap C_3\} = P\,(C_1)\,P\,(C_2) + P\,(C_1)\,P\,(C_3) + P\,(C_2)\,P\,(C_3) - - 2\,P\,(C_1)\,P\,(C_2)\,P\,(C_3) \tag{4.5}$$

4.5.2.1 FT Dynamic gates

Moreover, the reliability and criticality assessment is enhanced with the use of dynamic gates. More specifically, the Priority AND (PAND) gate is used to show that the output condition (gate) occurs when all input events occur in a particular order. The input events depend on the order they are placed in the FT structure, that is the left-most event will occur first, then the next to the right and so on. The Sequence Enforcing (SEQ) dynamic gate denotes that events also occur in a particular order (from left to right) as they are placed in the FT structure. This gate is used when the output occurs if and only if all input events are constrained to occur in a specified order as shown in the FT structure otherwise the gate becomes inactive. This is the main difference with the PAND gate meaning that the output of a SEQ gate is constrained to occur from left to right. A SEQ gate usually denotes gradual degradation and can be also used when modelling a system with a particular failure sequence.

SPARE gates are another example of dynamic gates and are used to represent cold, warm, and hot spares in the FT system examined. This type of gate is active if and only if all spare events/inputs occur. Spare events are a special event type used to model spare usage. Cold, hot and warm spare events are distinguished according to the dormancy factor they have, that is the ratio of failure rate in the standby and operational mode. Cold spares are the spare events which have a dormancy factor of zero. That means that the spare event has zero failures in the standby mode. On the contrary, hot spare events have a dormancy factor of one, which means that the spare event is always activated in the standby mode. A warm spare event has a dormancy factor value between zero and one and is partially powered in the standby mode until it is needed.

4.5.2.2 Calculation method for DFTA

Having defined the dynamic gates above, the next step is to determine the calculation method that is employed in the thesis for the reliability and criticality application of the technical aspects of RCBM. In this respect, the calculation method based on the estimation of the cut sets is employed in order to achieve less computational memory and thus higher speed to carry out the calculations. In this way, computer capacity overloading is avoided which has led to computer systems ‘crashing’ in previous efforts, especially when using the multiple calculations needed for the dynamic gates. In the case of the cut-set estimation, the DFT initially estimates the overall minimal cut-set for each tree, followed by the calculation of the probability of occurrence of each minimal cut-set and finally the calculation of the top event probability. The calculation of each minimal cut-set is estimated based on the combination of the basic events comprising a FT as shown below:

$$C_1 = \{ C_{1,1}, C_{1,2}, \dots, C_{1,n1}\} = \{\bigcup_{j=1}^{n1} C_{1,j} \} \quad (4.6)$$

$$C_2 = \{ C_{2,1}, C_{2,2}, \dots, C_{2,n2}\} = \{\bigcup_{j=1}^{n2} C_{2,j} \} \quad (4.7)$$

$$C_m = \{ C_{m,1}, C_{m,2}, \dots, C_{m,nm}\} = \{\bigcup_{j=1}^{nm} C_{m,j} \} \quad (4.8)$$

where:

$C_{m,j}$ = the basic event in the group of a minimal cut-set

Depending on the size of the DFT model, there can be several cut-sets in place while the ones that have the fewest number of events will ultimately have the highest probability of occurrence. Mathematically, the above is described as:

$$P(TE) = P\{ C_1 \cup C_2 \dots \cup C_m \} = P\{\bigcup_{i=1}^{m} C_i \} \quad (4.9)$$

where:

$P(TE)$ = the probability of the occurrence of the top event

($Ci....i = 1,2 ,...,m$) = the cumulative summation of the minimal cut sets

Based on the above cut-set theory, the Esary-Proschan (E-P) approximate probability calculation method is employed in the present thesis. For the E-P calculation method upper and lower bounds are calculated for the DFT gates probability of occurrence using path sets. In this case, a path set is the opposite of a cut set, meaning that it forms a group of basic events in which if one of them does not occur, the top event (or gate) will not occur as well. In general, the E-P method is a suitable method if the system is considered as a coherent system so that the occurrence of an item failure always results in system degradation and each basic event appears in at least one minimal cut set (Kumamoto and Henley 1996). This is described as:

$$\prod_{i=1}^{m\,(p)} P\,(B_i) \leq \; P\,(TE) \; \leq 1 - \prod_{i=1}^{m\,(c)}[\,1 - \,(C_i)] \tag{4.10}$$

where:
Bi =minimal path sets
$m(p)$ = total number of minimal path sets
$m(c)$ = total number of minimal cut sets

4.5.2.3 Reliability Importance Measures (IMs) used in RCBM

So far, the calculation method regarding the determination of the systems and components which present the highest reliability level that is employed in the present thesis has been demonstrated. On top of the above, the most essential investigation of the criticality of the system under consideration is taken place by using the reliability IMs. The latter is performed so as to identify which of the above determined high-reliable systems and components are at the same time the most critical for the function of the main system. In order to address this issue, reliability importance measures are investigated. In this case, reliability IMs provide an analytical and accurate display of the ranking of the DFT end-events, examining a variety of different system characteristics, which determine the importance of each end-event of the dynamic DFT examined. In particular, the Birnbaum (Bir), Fussell-Vesely (F-V) and Criticality (Cri) IMs are proposed for use in the suggested RCBM strategy.

The Bir IM provides the rate of change in the top event/gate probability when a change occurs in the availability of a basic event. Therefore, the ranking of events obtained using the Bir IM is helpful when selecting which end-event needs to be improved so as to concentrate the improvement effort on this event. The Bir IM for event A can be also calculated as the difference in the probability of the top event given that event A did occur minus the probability of the top event given that event A did not occur, that is:

$$I_i^B(A) = (P\{X|A\} - \; P\{|X|{\sim}A\}) \tag{4.11}$$

where:

$I_i^B(A)$ = Birnbaum importance measure for event *A*

A = the event whose importance is being measured

~*A* = the event did not occur

X = the top event.

Regarding the F-V IM, it is used when an event contributes to the failure of the top event but is not necessarily the most critical one. Overall, this importance measure shows the contribution of the end events to the reliability of the relevant gate they participate. The F-V IM shows the ratio of the probability of occurrence of any cut set including event A and the probability of the top event. That is:

$$I_i^{FV}(A) = \frac{1- \cap_{j=1}^{m}[1-P\{M_{ij}(t)\}]}{1- R_s[r(t)]} \quad (4.12)$$

where:

I_i^{FV} = Fussell-Vesely importance measure

m_i = the number of minimal cut sets containing *i*

$\cap_{j=1}^{m}$ = minimal cut set

$M_{ij}(t)$= the j^{th} minimal cut set among those containing *i*, verified at time *t*.

R_s = system reliability

$r(t)$ = end event occurring at time *t*

The Cri IM considers the overall probability of the top event occurrence due to basic event A. Moreover, it modifies the Birnbaum importance measure by adjusting for the relative probability of basic event A to reflect how likely the event is to occur and how feasible it is to improve the top event/gate. Furthermore, it is defined as:

$$I_i^{cr}(A) = (P\{X|A\} - P\{|X|{\sim}A\} * \frac{P\{A\}}{P\{X\}}) \quad (4.13)$$

where:

$I_i^{cr}(A)$ = Criticality importance measure for event *A*

A = the event whose importance is being measured

$\sim A$ = the event did not occur

X = the top event

Moreover, in the case that the overall operational profile of a subject system or component is requested, it is useful to include the calculation of availability A_i in the entire assessment as well. This is given by the following equation:

$$A_i = 1 - Un \tag{4.14}$$

In this case Un is the respectful Unavailability of a given system or component, which if it follows the exponentially distributed failure rates λ attributed to it, is calculated as:

$$Un = e^{-\lambda t} \tag{4.15}$$

4.6 Fuzzy Set Theory (FST) in a Multi Attribute Decision Making (MADM) environment

As mentioned in §4.5, the application of FST in a MADM process can combine various different parameters which otherwise cannot be used together in the selection of the most appropriate maintenance approach for a given system or piece of equipment. This is because FST can examine a diverse group of parameters under one single decision support methodology. Especially in the case of the selection of the most appropriate maintenance approach for a given vessel/system out of a number of different alternatives/solutions, FST takes into account multiple experts decisions originating from different degrees of expertise (e.g. managerial, technical), having different experience levels (e.g. young ship officers to highly experienced technical managers) as well as persons having different training on the ship environment (e.g. highly trained chief engineers and captains to financial manager with little or no training at all on ship systems). FST captures all these aspects combining them into a common platform, mathematically and precisely modelled. Moreover, FST is a widely applied tool, especially in the Multi Attribute Decision Making (MADM) environment. In terms of the selection of the most appropriate maintenance approach as part of technical section of the novel RCBM strategy, FST is implemented following the methodological steps as shown in Olcer and Odabasi (2005). In this respect, the MADM approach consists of three major parts: the ranking, aggregation and finally the selection stage (Figure 4.9).

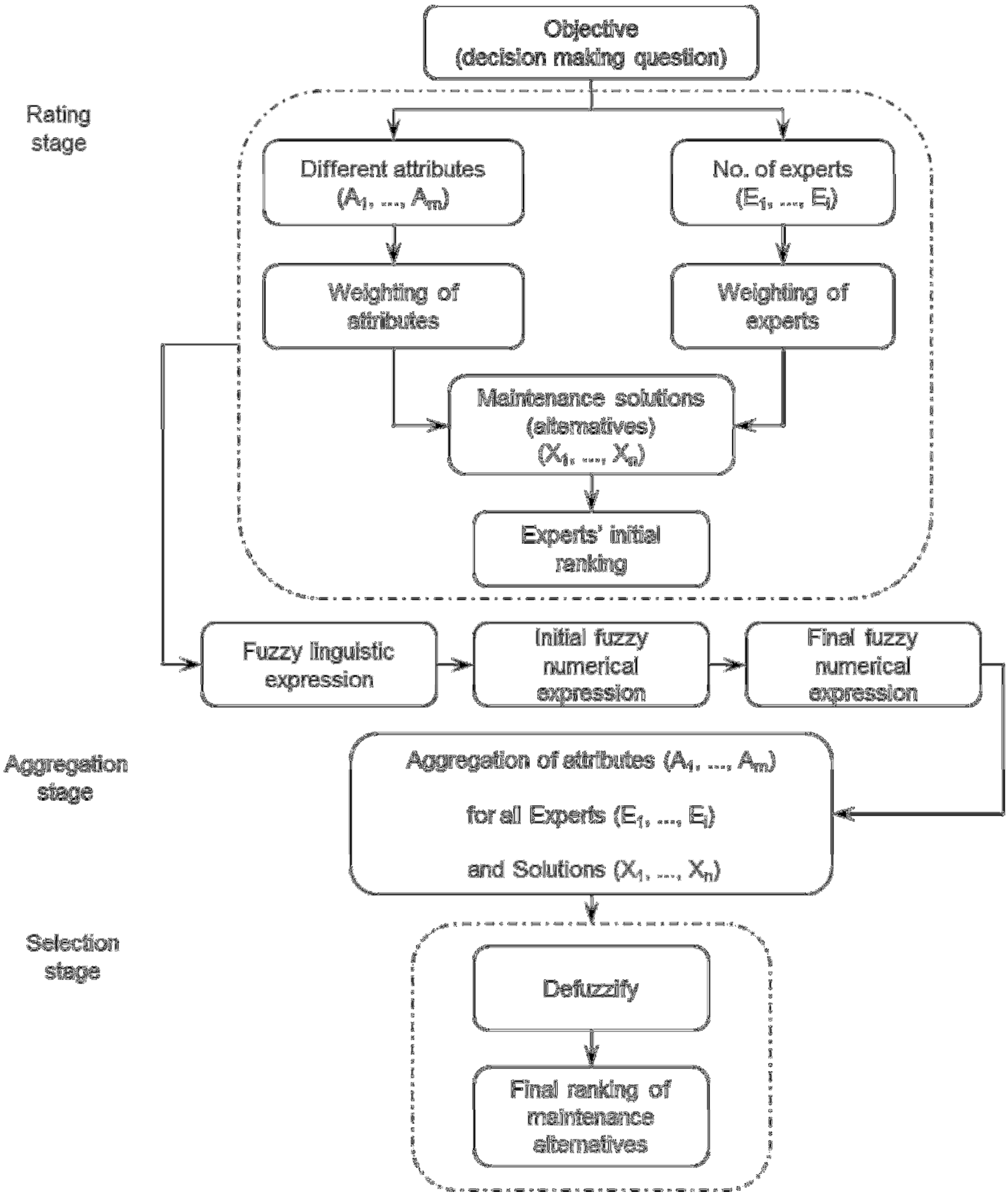

Figure 4.9 Suggested MADM approach for the maintenance problem of the ship DG system

As can be seen in Figure 4.9, the suggested MADM approach is initiated with the setting up process of the specific objective under which the decision-making will take place. That is the initial question that needs to be answered by a group of experts. Moreover, this is followed by the three distinctive stages, which form the core of the MADM approach; that is the rating, aggregation and selection stage. In the next paragraphs, each one of these stages are explicitly described followed by the specific application with regards to the selection of the most appropriate maintenance approach for the DG system of a given vessel.

4.6.1 Rating stage

The rating stage is the first part of the MADM approach. Initially, the specific attributes which are originally instructed by the decision maker as well as the specific number/group of experts that will participate in the MADM process are determined. Overall, there are two types of attributes which can be utilised: the subjective and objective ones. The differentiation is based on the fact that whenever an attribute is described with crisp (numerical) values, then it is defined as an objective attribute. That is because crisp values can be expressed in a similar numerical way for all experts involved (i.e. these values can be acknowledged as common and standard values). On the other hand, whenever an attribute is described in a vague (fuzzy) way including experts' subjective linguistic terms, then it is defined as a subjective attribute. Furthermore, both attribute types mentioned above can be also categorised according to the positive or negative linguistic value each attribute conveys. Therefore, they can be categorised as 'benefit' (positive linguistic meaning) or 'cost' (negative linguistic meaning). An example of benefit and cost type attributes are the 'maintenance efficiency' attribute, which is sorted as a benefit type of attribute while 'company investment' is categorised as a cost type attribute.

Following the above, each one of the attributes and the experts are assigned weighting factors (different or similar) according to the relevance of the experts to the objective in question. In the case of similar weighting factors among the experts, the group decision-making problem is of a homogeneous nature while when the experts' weighting varies, it is of a heterogeneous type. The alternatives (or solutions) for the maintenance type to be used in the subject case (ship DG system) are also provided at this stage. Subsequently, each expert provides his/her initial ranking on each alternative on the initial objective/question relevant to the various attributes. In other terms, he/she answers the questions deriving from the attributes of each solution (in this case maintenance type) and assigns crisp or linguistic terms (qualitative information) to them. This is performed by answering to a specific set of questions which are given by the facilitator of the decision making process in the first place. In this way, the initial decision matrix for the MADM selection is established.

What follows next is the transformation of the fuzzy linguistic expression of the experts' answers to the initial fuzzy numerical expression. This is achieved by employing a set of different Scales for transforming linguistic terms/answers to fuzzy numbers. The Scales used are the ones suggested by Chen and Hwang (1992), which propose a set of 8 different scales for the transformation of the fuzzy linguistic expressions to fuzzy numerical expressions. These Scales vary from the simple ones using just two linguistic terms (Scale 1-'medium' and 'high' linguistic values) to the more complicated ones using 13 different linguistic terms (Scale 8) (Table 4.1).

Following the above, the general formulas and mathematical relationship which describe a trapezoidal fuzzy number *A* and its membership function $\mu A\ (x)$ can be defined as:

$A = (\alpha_1, \alpha_2, \alpha_3, \alpha_4)$ and

$$\mu A\ (x) = \begin{cases} (x - a_4)\ /\ (a_2 - a_1), & for\ a_1 \le x \le a_2 \\ 1 & for\ a_2 \le x \le a_3 \\ (a_4 - x)\ /\ (a_4 - a_3) & for\ a_3 \le x \le a_4 \\ 0 & otherwise \end{cases}$$

where

$\alpha_1 \le \alpha_2 \le \alpha_3 \le \alpha_4$

Table 4.1 Linguistic terms used and their fuzzy transforming scales (Scale 1-8) (Chen and Hwang 1992)

	Scale Linguistic terms	1	2	3	4	5	6	7	8
1	None								(0, 0, 0.1)
2	Very Low			(0, 0, 0.1, 0.2)		(0, 0, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.2)	(0, 0.1, 0.2)
3	Low - Very Low							(0, 0, 0.1, 0.3)	(0, 0.1, 0.3, 0.5)
4	Low		(0, 0, 0.2, 0.4)	(0.1, 0.25, 0.4)	(0, 0, 0.3)	(0, 0.2, 0.4)	(0.1, 0.2, 0.3)	(0, 0.2, 0.4)	(0.1, 0.3, 0.5)
5	Fairly Low				(0, 0.3, 0.5)	(0.2, 0.4, 0.6)		(0.2, 0.35, 0.5)	(0.3, 0.4, 0.5)
6	More or less Low						(0.2, 0.3, 0.4, 0.5)		(0.4, 0.45, 0.5)
7	Medium	(0.4, 0.6, 0.8)	(0.2, 0.5, 0.8)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)		(0.4, 0.5, 0.6)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)
8	More or less High						(0.5, 0.6, 0.7, 0.8)		(0.5, 0.55, 0.6)
9	Fairly High				(0.5, 0.75, 1)	(0.4, 0.6, 0.8)		(0.5, 0.65, 0.8)	(0.5, 0.6, 0.7)
10	High	(0.6, 0.8, 1)	(0.6, 0.8, 1, 1)	(0.6, 0.75, 0.9)	(0.7, 1, 1)	(0.6, 0.8, 1)	(0.7, 0.8, 0.9)	(0.6, 0.8, 1)	(0.5, 0.7, 0.9)
11	High - Very High							(0.7, 0.9, 1, 1)	(0.5, 0.7, 0.9, 1)
12	Very High			(0.8, 0.9, 1, 1)		(0.8, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 1, 1)	(0.8, 0.9, 1)
13	Excellent								(0.9, 1, 1)

Based on what is mentioned so far, each expert E_k $(k = 1, 2, \dots, m)$ provides the answers to the questionnaire for each alternative with respect to the various attributes initially shown. Then, the trapezoidal fuzzy number $R_k = (\alpha_{k,} b_{k,} c_{k,} d_{k,})$ (with $0 \leq \alpha_k \leq b_k \leq c_k \leq d_k \leq m$) for each one of these answers is created to show the given answers in a fuzzy set format. At this point, it should be noted that trapezoidal fuzzy numbers are used for the subject case study as this is the most comprehensive approach to use fuzzy number sets and thus is employed by most practitioners in MADM problems. Accordingly, these are then transformed into standardised trapezoidal fuzzy numbers R_k^* (k = 1, 2,.., m) as follows:

$$R_k^* = (\alpha_k /m,\ b_k /m,\ c_k /m,\ d_k /m) = (\ \alpha_k^*, b_k^*, c_k^*, d_k^*) \tag{4.16}$$

where:

$0 \leq \alpha_k^* \leq b_k^* \leq c_k^* \leq d_k^* \leq 1$

In this case, m is the maximum value of the non-standardised trapezoidal fuzzy numbers given by the experts for the same attribute. Having concluded with the rating stage, the aggregation stage is described next.

4.6.2 Aggregation stage

At this stage, all the answers given by the experts for each one of the suggested alternatives concerning each single attribute used in the previous stage are aggregated. The latter is carried out in order to generate the set of fuzzy numbers for each one of the specific attributes for all alternatives that will be used in the defuzzification and selection stage. This is carried out as follows: initially, the degree of importance of each expert E_k $(k = 1,2, \dots, m)$ is we_k where:

$we_k \in [0, 1]$ and

$\sum_{k=1}^{m} we_k = 1$

Since the number of experts as well as their experience and expertise on the suggested alternatives may vary, different weighting factors are assigned to them. At first, the most significant expert is chosen among the group of persons involved in the decision making process and is assigned a factor equal to one ($re_k = 1$). Then, the rest of the experts are compared with him/her and a relative weighting factor is given to them too:

max $\{re_1, re_2, \dots, m\} = 1$ and
min $\{re_1, re_2, \dots, m\} > 0$

Then the degree of importance we_k is estimated as:

$$we_k = \frac{re_k}{\sum_{k=1}^{m} re_k} \tag{4.17}$$

Bearing the above in mind, the degree of agreement (or similarity function) S among the experts is determined as follows:

$$S(A,B) = 1 - \frac{|\alpha_1 - b_1| + |\alpha_2 - b_2| + |\alpha_3 - b_3| + |\alpha_4 - b_4|}{4} \tag{4.18}$$

where *A* and *B* two standardised trapezoidal fuzzy numbers with:
$A = (\alpha_1, \alpha_2, \alpha_3, \alpha_4)$,
$B = (b_1, b_2, b_3, b_4)$ and
$0 \le \alpha_1 \le \alpha_2 \le \alpha_3 \le \alpha_4 \le 1$
$0 \le b_1 \le b_2 \le b_3 \le b_4 \le 1$

It should be also mentioned that $S(A,B) = S(B,A)$.

After determining all the degrees of agreement among experts, the agreement matrix (*AM*) can be constructed as follows:

$$AM = \begin{bmatrix} 1 & S_{12} & \dots & S_{1v} & \dots & S_{1n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ S_{u1} & S_{u2} & \dots & \dots & \dots & S_{un} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ S_{m1} & S_{m2} & \dots & S_{mv} & \dots & 1 \end{bmatrix}$$

where:
$S_{uv} = S(R_u, R_v)$ if u ≠ v and
$S_{uv} = 1$ if u = v

The latter denotes that all the diagonal elements of the matrix are equal to one. Following, the average degree of agreement (*AA*) is calculated as the average degree of agreement $AA\ (E_u)$ of expert E_u (u =1, 2, ... M) by employing the Agreement Matrix (*AM*) of the problem, where:

$$AA(E_u) = \frac{1}{m-1} \sum_{\substack{v=1 \\ v \neq u}}^{m} S(X_{u,} X_v) \qquad (4.19)$$

Next the relative degree of agreement (*RA*) is estimated as well as the consensus degree coefficient (*CC*) of expert E_u (u =1, 2, ..., m), in which:

$$RA(E_u) = \frac{AA(E_u)}{\sum_{v=1}^{m} AA(E_u)} \qquad (4.20)$$

and

$$CC(E_u) = \beta\, we_k + (1 - \beta)\, RA(E_u) \qquad (4.21)$$

where

β = relaxation factor with $0 \leq \beta \leq 1$

β = 0, homogenous group of experts

In this case, the relaxation factor β is used in order to show the influence that the facilitator of the MADM problem conveys on the overall process. Subsequently, the aggregation result (R_{AG}) is measured as:

$$R_{AG} = CC(E_1) \otimes R_1 \oplus CC(E_2) \otimes R_2 \oplus \ldots CC(E_m) \otimes R_m \qquad (4.22)$$

where

$\otimes$: fuzzy multiplication operator

$\oplus$: fuzzy addition operator

After finalising the aggregation stage of the MADM process, the selection stage is introduced next. This is compiled by two separate sub-stages: the defuzzification and eventually the selection of the best alternative sub-stage, which are described in the following section.

4.6.3 Selection stage

As described above, the first step in the selection stage is the defuzzification. This is performed so as to transform the aggregated fuzzy trapezoidal numbers into crisp numbers, which can be then used in the final selection stage of the best alternative available. In order to carry out the above, the fuzzy scoring method is employed as described in Chen and Hwang (1992). Following this approach, the fuzzy maximising and minimising sets need to be determined first as follows:

$$\mu_{max}(x) = \begin{cases} x, & for\ 0 \leq x \leq 1 \\ 0, & otherwise \end{cases} \tag{4.23}$$

$$\mu_{min}(x) = \begin{cases} 1 - x, & for\ 0 \leq x \leq 1 \\ 0, & otherwise \end{cases} \tag{4.24}$$

Following the above, the right as well as the left scores of fuzzy number *B* ($\mu_R\ (B)$ and $\mu_L\ (B)$ respectively) are also estimated which assist in calculating the total score of fuzzy number *B*, which is:

$$\mu_T\ (B) = [\ \mu_R\ (B) + 1 - \mu_L\ (B)\ ]\ /\ 2 \tag{4.25}$$

where:

$$\mu_R\ (B) = \sup_x[\ \mu_B\ (x) \wedge \mu_{max}(x)\ ] \tag{4.26}$$

And

$$\mu_L\ (B) = \sup_x[\ \mu_B\ (x) \wedge \mu_{min}(x)\ ] \tag{4.27}$$

In this way, the defuzzification stage is now concluded, enabling the transmission to the next step of the selection stage of the MADM approach, which is the ranking sub-stage. In this case, the TOPSIS (Technique of Ordered Preference by Similarity to Ideal Solution) is used in the present study as shown next.

4.6.4 Ranking by using TOPSIS method

In addition to the presentation of the above methodological steps in order to achieve the implementation of the FST in a MADM problem, there is a point at which all the different alternatives need to be ranked accordingly. This is carried out by using the Technique of Ordered Preference by Similarity to Ideal Solution (TOPSIS) ranking method, which is described with more details in Appendix A. In order to carry out the TOPSIS ranking method, the normalised ratings are calculated first by using the vector normalisation technique for the r_{ji} element of the normalised decision matrix as follows:

$$r_{ji} = \frac{x_{ji}}{\sqrt{\sum_{j=1}^{N} x_{ji}^2}} \qquad (4.28)$$

where:

$j = 1,2,..., N$

$i = 1,2,..., K$

x_{ji} = value of alternative j with respect to attribute i

Then the weighted normalised ratings u_{ji} are calculated as the product of each row r_{ji} of the normalised decision matrix shown before by the weight w_i of each attribute as shown next:

$$u_{ji} = w_i \, r_{ji} \qquad (4.29)$$

where:

$j = 1,2,..., N$

$i = 1,2,..., K$

w_i = weight of ith attribute

In this case, the standard normalisation weight w_i is given by:

$$w_i = \frac{r_i}{\sum_{i=1}^{K} r_i} \qquad (4.30)$$

where:

$0 \leq w_i \leq 1$

$$\sum_{i=1}^{K} r_i = 1$$

$\{r_1, rw_2, ..., r_K\}$

$\{w_1, w_2, ..., w_K\}$

In the following steps, the imaginary ideal solution is identified; that is the positive (A^+) and negative (A^-) ideal solution respectively, which are defined as:

$$A^+(E_u) = \{ v_1^+, v_2^+, \ ..., v_i^+, ..., v_K^+\} \tag{4.31}$$

and

$$A^-(E_u) = \{ v_1^-, v_2^-, \ ..., v_i^-, ..., v_K^-\} \tag{4.32}$$

where:

$v_i^+ = \{\max v_{ji}, i \in J_1; \min v_{ji} \ i \in J_2\}$

$v_i^- = \{\min v_{ji}, i \in J_1; \max v_{ji} \ i \in J_2\}$

J_1=set of benefit attributes

J_2=set of cost attributes

The final ranking is performed by calculating the distance of each alternative from the ideal positive and negative values estimated in the previous step; that is the distance S_i^+ from the positive ideal value and the distance S_i^- from the negative ideal value. This is performed by using the following formulas:

$$S_i^+ = \sqrt{\sum_{i=1}^{K} (v_{ji} - v_i^+)^2} \tag{4.33}$$

$$S_i^- = \sqrt{\sum_{i=1}^{K} (v_{ji} - v_i^-)^2} \tag{4.34}$$

where:

$j = 1, 2, ..., N$

Finally, the overall distance (or similarity) of each alternative A_j from the positive ideal solution is estimated as:

$$C_j^+ = \frac{S_j^-}{S_j^+ - S_j^-} \tag{4.35}$$

where:

$0 < C_j^+ < 1$; j = 1, 2, ..., N

Ultimately, the best-ranked alternative is the one with the maximum C_j^+. In this case, if C_j^+ is close to one, then the alternative A_j is considered as ideal. On the contrary, if it is closed to zero, it is considered as non-ideal.

4.7 Chapter summary

In this Chapter, the novel maintenance framework with application in the maritime sector is suggested and described in detail. It is divided into two main parts. The first one presents and describes the novel Reliability and Criticality Based Maintenance (RCBM) framework. The above-mentioned framework combines the advantages of the TPM and RCM approaches with particular focus to the maritime sector attributes. In the second part of Chapter 4, the introduction of the detailed reliability and criticality analysis tools that are employed for the case studies of the thesis in hand are also demonstrated. These consist of the FMECA approach as well as the FTA tool being upgraded to employ static and dynamic gates to represent the system structure under consideration, thus transformed into the DFTA tool. In conjunction to DFTA, minimal cut set theory is also demonstrated in its application for the current selected case studies as well as the reliability IMs which validate the results of the DFTA approach. Moreover, the use of FST in the MADM maintenance problem is also established. Subsequently, the application of the RCBM strategy using the reliability and criticality tools already described is shown next in the case of the systems of vessel *"DSV A"* as well as the Diesel Generator (DG) system of a motor sailing cruise ship. Both of these case studies are described in the following Chapter.

5 CHAPTER 5-CASE STUDIES

5.1 Chapter outline

In this Chapter, the application of the initial technical aspect of the RCBM strategy is shown as it is described in the previous part of the present thesis. This includes the demonstration of how the reliability and criticality analysis can be applied to ships by performing a study on Diving Support Vessel "*DSV A*" and the DG system of a motor sailing cruise ship. Initially, the data acquisition and gathering process for the subject case studies is shown. In the first case study, the reliability and criticality analysis is demonstrated by employing the Dynamic FTA (DFTA) reliability tool with static and dynamic gates. In the case study of the DG system, the DFTA reliability tool is combined with the FMECA tool in order to further investigate the technical aspects of this system. Regarding DFTA, the boundary conditions of the examined systems are initially set-up assisting in the creation of the DFT modelling. Then, the DFT calculation and evaluation attributes are finalised in order to achieve the mentioned objectives of the analysis. In order to further scrutinise on the results of the DFTA, the Birnbaum, Fussell-Vesely and Criticality reliability Importance Measures (IMs) as well as the minimal cut set theory are used to provide in-depth examination of the results achieved in terms of the most critical end-events of each system. Following the above, dynamic 'SPARE' gates are introduced in the DFT structure in both case studies in order to represent the additional maintenance measures that will rectify and improve the reliability levels of each main system through time. Their influence on the change of the overall reliability is also investigated. Additionally, the FMECA tool is used to provide details on the different failure causes identified as well as the severity, frequency and eventually criticality of the components of the DGs. All these are described with details in the following sections.

5.2 Acquisition and gathering of data-field studies

In this section of Chapter 5 the acquisition and data gathering process is presented and explained in detail. The above process is a significant part for the implementation of the RCBM strategy as it forms the very initial stage on which the reliability and criticality assessment is performed. In this respect, a variety of different sources for collecting relevant failure data for various ship systems and components have been contacted in the first place. These include among others contacting personnel from both onshore and onboard maritime departments. More specifically, in the effort to collect the relevant data, onshore personnel such as technical managers and superintendent engineers from the technical departments of different shipping companies have been contacted as well as various visits and discussions with engineering officers of all levels (from chief to cadet engineers) and captains onboard ships have taken place. In the best of cases, maintenance managers of an operator of offshore vessels have been interviewed in order to address the data collection activity as well as identify the shortcomings of the existing maintenance management systems.

Moreover, the mentioned interviews have been expanded to include ship operators of different ships (e.g. crude oil, LNG ad LPG tankers, bulk carriers and dry cargo ships, container ships, RO-RO vessels, offshore supply vessels, cruise ships) in order to cover a wide range of the different sectors of the maritime industry. All the above have been realised mostly due the author's past contacts and good relationships with ship operators established along his professional career before and during the undertaking of the present thesis. In this respect, access to different computerised maintenance management systems (CMMS) has been given in some of the mentioned cases and field studies have been conducted in order to retrieve the mentioned data.

It has to be mentioned that the process for gathering the required data has been proven to be a laborious task for a number of reasons. Initially, the different maintenance management systems have been constructed to accommodate a variety of different parameters (e.g. actual raw failure data, running hours of equipment, surveys performed and general comments) which, according to the onboard personnel, they have been more confusing than helpful. In a specific case, the CMMS has been used as an electronic 'notepad' in which any kind of information was collected without proper screening and identification of the information that was actually needed (not even recording the actual failure rates or the mean time between failures of the failed system components). Furthermore in another case, there was ambiguity between the onshore and onboard personnel in terms of the need for such an electronic data gathering system, leading to the recording of unnecessary and eventually useless data. All the above confirmed the author's perception that the need for a structured maintenance recording system as well as the necessity for a new overall maintenance strategy as this is described in Chapter 4, is highly necessary.

However, there has also been a case in which a separate maintenance unit has been set-up as part of the overall technical department of a shipping company and where the raw data regarding failures of various components identified onboard a fleet of vessels have been recorded. Accordingly, it has been feasible to obtain such data for the purposes of the current research study, under the commitment that confidentiality is strictly adhered to. The latter also reveals another motive for ship operators not being so willing to distribute and consequently carry out further research into maintenance and data retrieval systems; that is due to confidentiality and commercial reasons. In this respect, a sample table of raw maintenance data from a computerised maintenance system is shown in Figure 5.1

Therefore, having obtained the so much needed raw data, the reliability and criticality assessment of different ship systems has been achievable as this is presented with further details in the following sections.

Cause code	Object			Number of failures	Mean time (days)
NONE	S	38.212.10.00	DECOMPRESSION CHAMBERS	7	92
OBSO	S	38.212.10.00	DECOMPRESSION CHAMBERS	2	244
NONE	S	38.212.90.00	CHAMBER DOMESTIC	2	244
COMP	S	38.213.00.00	BELL & SPHL	5	122
CONN	S	38.213.00.00	BELL & SPHL	2	244
MATP	S	38.213.00.00	BELL & SPHL	2	244
NONE	S	38.213.00.00	BELL & SPHL	4	149
COMP	S	38.213.60.00	SPHL	2	244
NONE	S	38.213.90.00	SPHL	2	244
COMP	A	38.213.80.01	LIFEBOAT HYPERBARIC	2	244
NONE	S	38.214.00.00	HANDLING	6	105
NONE	S	38.214.20.00	LAUNCH SYSTEMS	2	244
NONE	S	38.214.30.00	LIFT BEAMS	2	244
NONE	S	38.216.00.00	AIR SYSTEMS	2	244
NONE	S	38.216.40.00	AIR COMPRESSORS HP	2	244
NONE	A	38.216.40.01	COMPRESSOR AIR HP	2	244
CABL	S	38.218.00.00	ELECTRICAL COMMS AND CUTOUTS	2	244
COMP	S	38.218.00.00	ELECTRICAL COMMS AND CUTOUTS	5	122
NONE	S	38.218.00.00	ELECTRICAL COMMS AND CUTOUTS	4	149
CABL	S	38.218.40.00	COMMUNICATION	2	244
NONE	S	38.218.40.00	COMMUNICATION	2	244
COMP	S	38.218.60.00	INSTRUMENTATION	4	149
NONE	S	38.218.80.00	INSTRUMENTATION	2	244
COMP	S	38.400.00.00	SAFETY SYSTEMS	3	183
NONE	S	38.400.00.00	SAFETY SYSTEMS	6	105
COMP	S	38.410.00.00	SAFETY EQUIPMENT	3	183
NONE	S	38.410.00.00	SAFETY EQUIPMENT	6	105
COMP	S	38.413.00.00	FIREFIGHTING EQUIPMENT	2	244
COMP	S	38.413.60.00	FIRE AND GAS DETECTION	2	244
COMP	S	38.413.61.00	FIRE DETECTION SYSTEM	2	244
NONE	S	38.417.00.00	HATCHES AND DOORS	4	146
NONE	S	38.417.40.00	WATERTIGHT HATCHES	3	183
			Total	1226	184

Figure 5.1 Sample table of raw data from a computerised data management system of a ship (data courtesy of Company A)

5.3 Case study of *"DSV A"*

The first case study concerns a Diving Support Vessel (DSV). In this regard, "*DSV A*" belongs to class of vessels which were built in 1986 (Hell and Tebbutt, 1986). It is a multipurpose vessel used mainly for diving support services. Its operational profile also includes hyperbaric welding, flexible riser and umbilical lying, installation of heavyweight structures as well as providing support for trenching and diverless subsea equipment. In Figure 5.2 and Figure 5.3 the profile and the upper and main deck view of the subject vessel are shown.

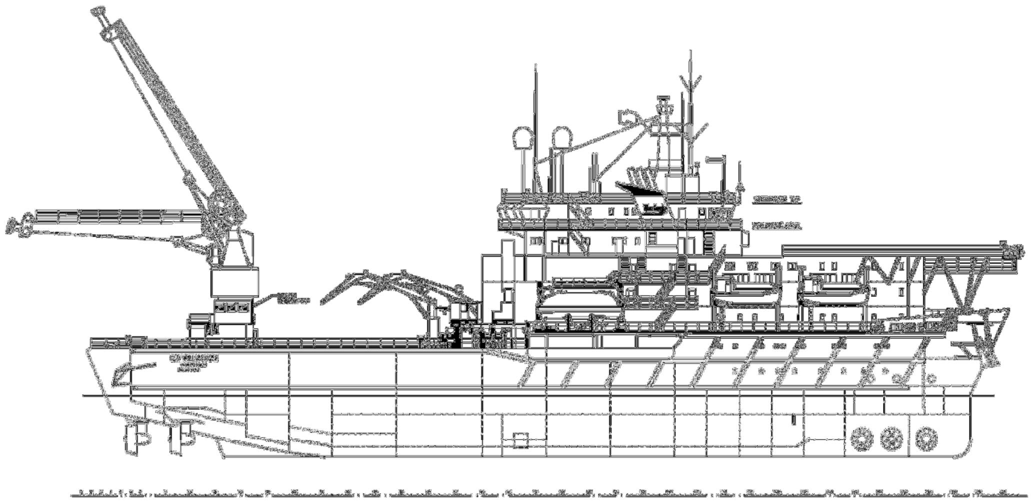

Figure 5.2 Profile view of "*DSV A*"

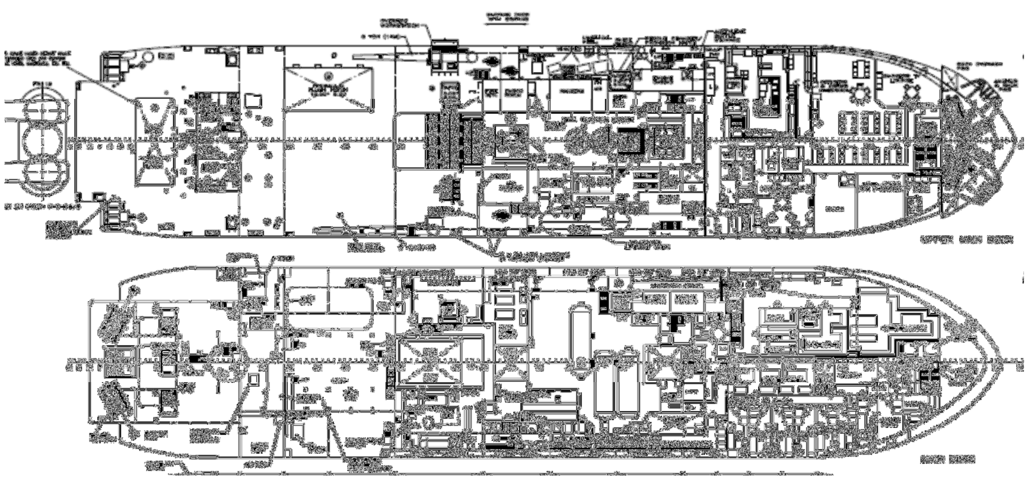

Figure 5.3 Upper and main deck view of "*DSV A*"

"*DSV A*" is a Dynamic Positioning (DP) 3 vessel with very good stabilising capability even in the harshest weather conditions (active and passive stabilizing systems providing only 1-2 degrees rolling motion in a sea state of 8 Beaufort scale). The vessel is equipped with two heavy duty cranes of maximum lifting capacity of 65/130 tons at 30 m radius and two light duty cranes with maximum lifting capacity of 10 tons at 20 m radius. The pair of the two heavy duty cranes can work either on a stand-alone basis or together as one heavy-lift crane. The vessel includes a centrally located working moonpool together with Remotely Operated Vehicles (ROVs), which can be deployed either from the moonpool or the sides of the ship, providing essential support in the offshore operational activities. Moreover, the principal characteristics of the vessel are presented in Table 5.1.

Table 5.1 Main characteristics of "*DSV A*"

Principal characteristics	
Year built	1989
Ship type	Diving Support Vessel (DSV)
Length overall	111.40 m
Length bp	100.40 m
Breadth moulded	22.50 m
Breadth extreme	24.00 m
Depth moulded	7.80 m
Draft max	7.26 m
GRT	9,158 tns
Engines	6 x 2,100kW each
Main cranage system	2 heavy duty cranes (65/130 tons)
	2 light duty cranes (under 10 tons)

5.3.1 Operational profile of "DSV A"

After having described the principal characteristics of the various systems of *"DSV A"*, it is important to address the exact operational profile of the subject vessel in order to achieve the overall picture of the importance of performing the reliability and criticality analysis. In this regard, *"DSV A"* operates worldwide serving the offshore oil and gas sector in the Gulf of Mexico, North Sea area and elsewhere in places where its multiple capabilities are required, especially the ones related to diving and subsea operations. In this case, the divers' compartments and the cranage facilities are preserved in excellent condition as well as the rest of the vessel's main systems which make up for the outstanding operational profile of the ship.

Based on these capabilities, the vessel can operate and perform extremely well in the demanding offshore sector taking into account the safety of working personnel and crew onboard, the protection of the environment, the asset itself, the achieved project deadlines as well as the cost of equipment used closely adhering to national and international rules.

5.3.2 Functional characteristics of "DSV A"

Regarding its functional characteristics, "*DSV A*" is powered by six 2,100 kW engines driving three azimuth thrusters used for main propulsion located at the aft part of the ship (one at the centre and one at each side) and three tunnel thrusters located at the bow. There are two engine rooms separated with watertight fire-insulated bulkheads providing 100% redundancy. The vessel is also supplied with a helideck and accommodation spaces for 139 persons in 76 cabins. The diving support system consists of a saturation diving system currently rated to 380 metres of seawater (msw). It is equipped with three 6-man Deck Decompression Chambers (DDC) and two 3-man diving bells. Both of the diving bells are of the conventional type (heave-compensated) although initially the second one was designed for mobile 'flying' type (self-propelled). The combination of the two diving bells allows divers to work and decompress at various depths either operating as two different working teams or as one working group with a back-up diving bell in the case of an emergency. In case of an emergency, a Self Propelled Hyperbaric Lifeboat (SPHL) is situated on the starboard side of the vessel which is linked with the DDC complex through a secured hatch way. The SPHL is actually a hyperbaric chamber in a lifeboat able to sustain a full crew of 18 divers under saturation. In addition, two places for a helmsman and a medical support member are included in the lifeboat outside the chamber for the safe transportation of the divers to a shore-based decompression unit.

5.3.3 Current maintenance practices for "DSV A"

On top of the above, the managing company follows modern methods regarding maintenance including keeping and updating a failure database in which all unexpected failures and planned maintenance tasks are collected assisting the top management team to schedule the maintenance works and dry-dockings. Additionally, the company employs some of the latest condition monitoring tools as well as invests in training of its crew and other working personnel so as to keep up with the latest maritime and offshore advancements. In this respect, condition monitoring tools are also employed in order to enhance the preventive maintenance plan followed onboard the vessel.

However, despite all the above-mentioned originalities, there are still some corrective maintenance tasks performed, which entail the potential risk of reducing the otherwise high performance ratio of the subject vessel and simultaneously may lead to additional expenses (e.g. the vessel might need to abandon the working field and return back to port after a few days or order for spare parts to be transported in the offshore location). Additionally, the online failure database includes duplicated entries in some cases, which render the system difficult to use in its full capability. This is also related to the continuous strive of the operating company to achieve superior results through the application of innovative tools and techniques, thus increasing the availability of the vessel and accordingly its market reputation.

5.3.4 System boundaries and data collection activity for "DSV A"

Bearing the above in mind and in order to initiate the reliability and criticality analysis of the various systems of "*DSV A*", a single DFT structure has been initially created including all the different systems to be analysed. This task has been carried out in an initial attempt to examine the whole ship as one single system and therefore investigate the reliability of the entire vessel with the use of DFTA. Following this procedure, a wide range of sub-systems have been examined such as:

- Vessel systems
  - Power plant
  - Electrical installation
  - Propulsion
  - Water system
  - Air system
  - Oil system
  - Lifting, hauling & anchoring
  - HVAC

- Diving system as part of the subsea systems
- Navigation & communication systems
- Safety systems

It is important to note that the partitioning and subsequently the construction of the DFT structure is initially carried out according to the coding that each system, sub-system and end-component is given in the original raw data format, that is the format used by the operator's maintenance management system . For example, *"DSV A"*, which is at the top of the list of the systems described, is coded as 38.000.00.00 and accordingly:

- *"DSV A":* 38.000.00.00
- Vessel systems: 38.100.00.00
- Engine No1: 38.111.11.01
- Engine No2: 38.111.11.02 etc.

In this way, the DFT structure consisted of more than 100 gates and 300 basic events. The computational process (computer hardware capacity and time available) in order to get the reliability results was most time consuming and ultimately not possible to achieve, even if the least demanding calculation method (cut sets in comparison to the exact calculation method) is used. To overcome this obstacle, it was decided to build independent DFTs for the various sub-systems of the entire vessel and evaluate their reliability and criticality index separately regarding each one of the specific systems mentioned. It was also decided to reduce the number of systems analysed because of the insufficient information to support a thorough analysis at this level. At this point, it needs to be mentioned that the particular system set-up was derived after several different 'runs' and 'trial-and-error' efforts were performed in modelling the DFT structure, also considering and referring to the technical expertise of the company's competent personnel. This in turn resulted in fine-tuning the suggested reliability and criticality investigation of the subject systems.

Bearing the above limitations in mind, the final breakdown and boundary conditions of the systems under consideration is shown in Figure 5.4.

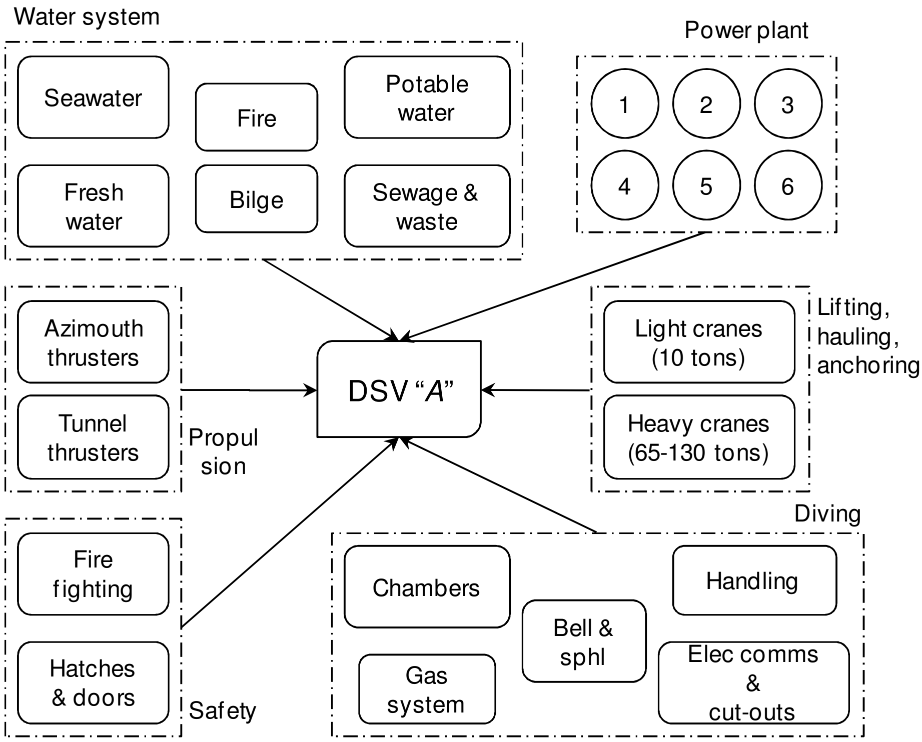

Figure 5.4 Breakdown of the systems of "*DSV A*" under consideration

As is shown above, the mentioned main systems examined are the following:

- Power plant system. It consists of two main sub-systems, E/R 1 and E/R 2 with three engines attributed to each one of them (Engines No1-3 for E/R 1 and Engines No 4-6 for E/R 2), which are responsible for the entire power generation of the vessel. This specific subdivision was followed having in mind the layout of the vessel and its DP 3 capability which requires two separate watertight as well as fire-proof compartments. At the final level of the FT structure, specific failure causes are used as inputs/end events (e.g. 'improper maintenance', 'corrosion' and 'component defect') which are then populated with numerical values from the Mean Time Between Failures (MTBF) Table provided by the managing company of the subject vessel. The same process regarding the inputs/end events for the rest of the main systems of *"DSV A"* is carried out as well.
- Propulsion system. It consists of the main sub-systems of azimuth and tunnel thrusters. Furthermore, azimuth thrusters are broken down into the thrusters located at the port, centre and starboard side of the aft part of the ship. On the other hand, tunnel thrusters are divided into the bow thrusters and the power packs.
- Lifting, Anchoring & Hauling (LA&H) system. This system is broken down into two categories. The first one concerns the light cranes (duties less than 10 tons) further

subdivided into crane A and B. The second one includes the heavy cranes (65/130 tons) also subdivided into main crane A and B.

- Water system. Water system includes the seawater; bilge; fire; fresh water; potable water; and sewage & waste sub-systems.
- Diving system. Diving system includes the Chambers; Bell & Self Propelled Hyperbaric Lifeboat (SPHL); handling; gas systems; and electrical communications & cut-outs.
- Safety system. This system includes the fire-fighting equipment and the hatches & doors sub-systems.

After finalising the modelling for all the systems and sub-systems identified, their components are populated with failure data originating from the actual operation of the vessel. The historical failure data have been gathered for a period of six years from the company that operates the vessel. The data are either directly fed into the main data collection system from the captain and chief engineer onboard the ship or have been collected from the reports that are brought back to the company's main office after the superintendent engineers' visits on board the ship. The maintenance department of the company is then responsible for entering them in the main electronic database system.

The data screening process involved studying the data sets and eliminating the ones that did not have any particular relation to the analysis. Such data include:

- 'None' category. In this case, data population included ordinary preventive maintenance actions such as replacement of equipment according to manufacturer's guidelines
- Duplication of data encoding and registration. This issue was identified during the detailed investigation of the data sets provided by the operating company. It was further crosschecked with the chief engineer of the vessel and eventually is one of the measures suggested for modification and improvement in terms of the recording system/maintenance management plan.

In this way, an overall number of 96 data points are used in addition to a number of 77 gates employed for all the different main systems. In Table 5.2 a part of the overall data set employed is shown while a complete and detailed table of the complete data set used in the thesis is presented in Appendix A.

Table 5.2 Part of the table for the MTBF used (29 out of 96 end-events) for different systems and components of *"DSV A"*

##	System	Component	Failure cause	MTBF (days)
1	Power plant	engine no1	comp	853
2			corr	853
3			imtc	365
4		engine no2	comp	853
5			corr	160
6			imtc	853
7	Propulsion	bow thruster fwd no1	fwt	426
8		bow thruster centre no2	fwt	640
9		bow thruster aft no3	fwt	512
10		azimuth thruster port no1	fwt	365
11			comp	160
12			ilub	853
13	Water	main cooling pumps	bloc	853
14			fwt	853
15		seawater vvs & pipework	corr	512
16			crac	853
17	LH&A	light cranes A	fwt	853
18			mecd	640
19		main crane A	cont	853
20			corr	640
21			matf	426
22	Diving	Chambers	cont	512
23			fwt	320
24			wrcm	853
25		sdc structure	comp	512
26			cont	853
27			corr	853
28	Safety	fire fighting equipment	comp	853
29			corr	512

Moreover, the explanation of the abbreviations for all failure modes used in the present case study is shown in Table 5.3.

Table 5.3 Explanation of abbreviations of failure causes

Abbreviation	**Explanation**
Comp	Component defect
Cont	Contamination
Conn	Connection defective
Corr	Corrosion
Crac	Cracked
Fwt	Fair wear and tear
Ilub	Insufficient lubrication
Imtc	Inappropriate maintenance
Matf	Material failure
Mecd	Mechanical damage
Wrcm	Wrong component

5.3.5 Development of DFTs for "DSV A"

After finalising the presentation of the components and the failures of the various sub-systems, the DFT modelling for each one of the systems mentioned is developed e.g. in the case of the Power plant system, its DFT structure is shown in Figure. 5.5. At this point it should be mentioned that the author carried out a visit onboard a sister vessel of *"DSV A"* while she was at dry-dock in order to better comprehend the systems involved in the present reliability and criticality assessment as well as gain crucial insight into the particular maintenance aspects of the subject vessel. Moreover, it was made possible to identify the operational capabilities of such systems and further discuss their functional requirements through informal interviews with the superintendent engineer and the principal officers of the vessel.

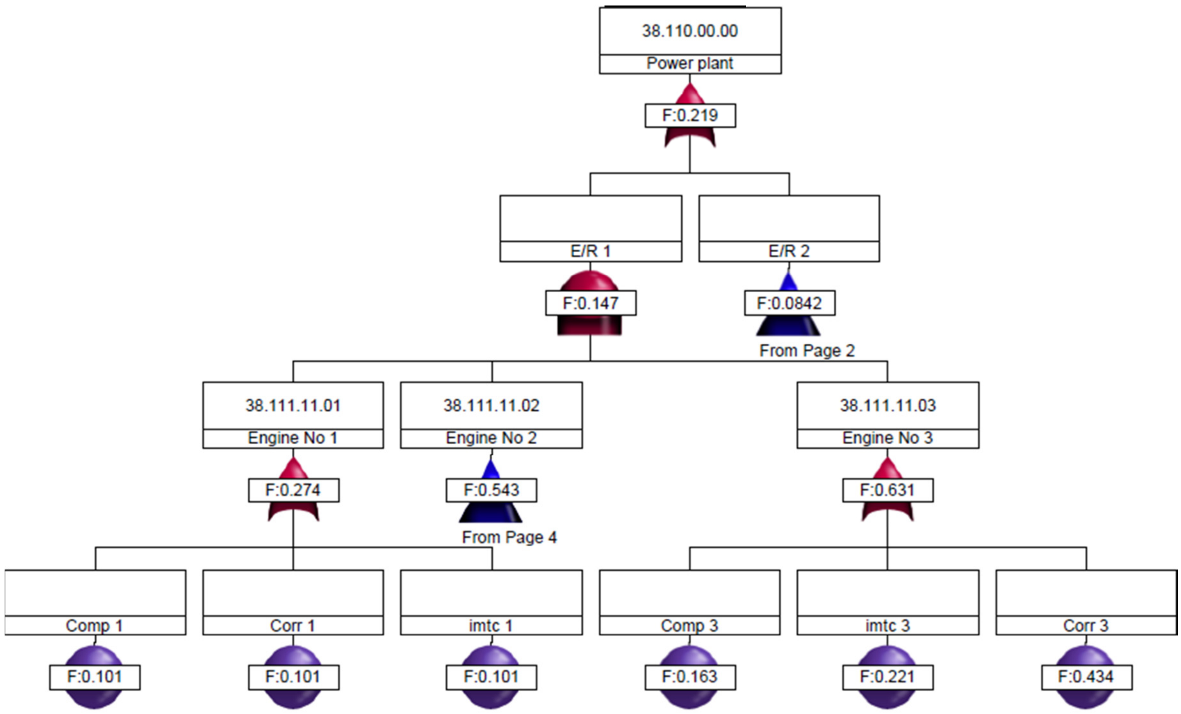

Figure 5.5 Part of the DFT structure for the power plant system of *"DSV A"*

As shown in Figure. 5.5, the Power plant system is interconnected with its sub-systems with a 'OR' gate, meaning that for the failure of the top gate (power plant system) to occur, all of the gates (sub-systems) in the lower level need to occur (fail to operate). Carrying on with the rest of the gates of this specific DFT, all the engines are modelled with 'OR' gates, showing that the failure of these gates occurs when any one of the lower level events (component failure, corrosion and inappropriate maintenance) occurs. Moreover, 'TRANSFER' gates are also used in order to enhance the graphical representation of the subject system (e.g. 'TRANSFER' gate used in the case of E/R 2 and engine No 2) further denoting that the DFT structure of the Power plant system is continued and is described with another DFT structure. Accordingly, the rest of the systems of *"DSV A"* are modelled based on the use of static and dynamic gates described in Chapter 4. In addition to the above, Appendix B shows the entire DFT structure including all the gates and events used for the present analysis.

After the final DFT structure is completed, the quantitative DFTA takes place in order to estimate the reliability and criticality results of the various systems and sub-systems. For this reason, an existing software platform which incorporates the reliability and criticality analysis tools as mentioned above is being used, thus enabling the assessment of the subject systems; this is the case of the Reliability Excellence (Relex) software, which is used to carry out the analysis (Relex 2009). Before starting with the presentation of the results for each case study, it is important to highlight the sequence followed in order to achieve the reliability and criticality outcomes of the analysis. This process is described in Figure 5.6.

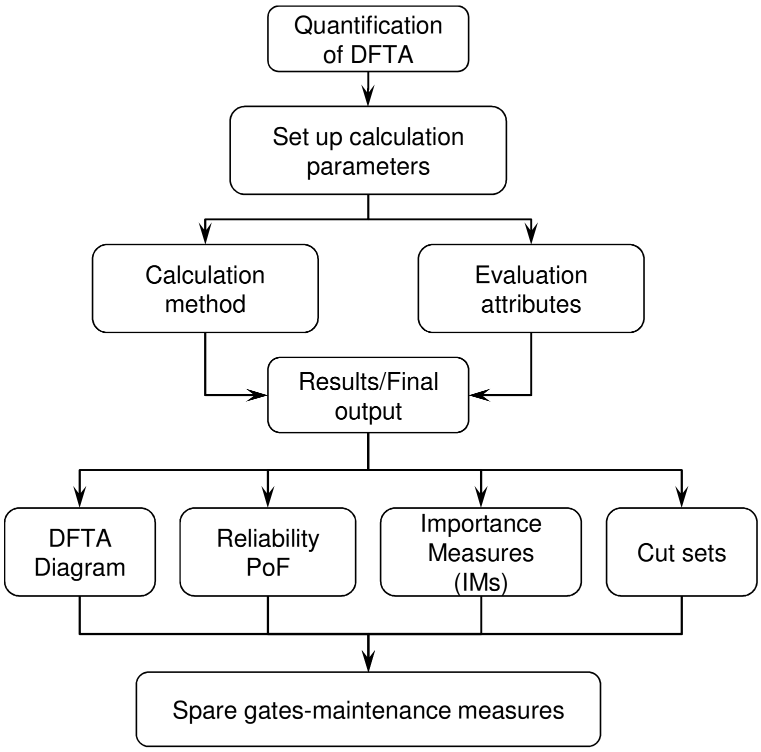

Figure 5.6 DFTA calculation process for *"DSV A"*

As shown above, the quantitative DFTA is initiated with the set-up of the calculation parameters. Initially, the Esary-Proschan calculation method is employed for the specific case study. This method, as described in the previous Chapter, is an approximation method. It employs cut sets in order to estimate the reliability and criticality results of the DFT and provides a considerable advantage compared to the exact calculation method in terms of timeliness and accuracy. The next step includes the formalisation of the evaluation attributes to be used such as the start and end-time of the calculation simulation as well as the number of data points selected. For the case of *"DSV A"* start time is set to zero while end time of the calculations is set to 30 months (which is similar to $2^{1/2}$ years). This time frame is chosen as the best suitable in order to simulate the time interval between two consecutive dry-dockings according to classification societies' rules and regulations during which failure rectifications or major planned maintenance can take place. The development of the reliability of each one of the main systems and sub-systems is studied in time intervals of two (2) months (time chosen based on good seamanship practice).

After obtaining the reliability and probability of failure results for the subject vessel, remedial measures are suggested so as to improve the current maintenance condition. This is demonstrated in the DFT structure as dynamic 'SPARE' gates, which are introduced for the various identified critical end-events (Figure 5.7). Following that, the reliability and probability of failure results of the main system and sub-systems are calculated once again in order to observe any improvements in the reliability index of the relevant systems examined. The DFT structure of *"DSV A"* including the use of 'SPARE' gates is shown in Appendix C.

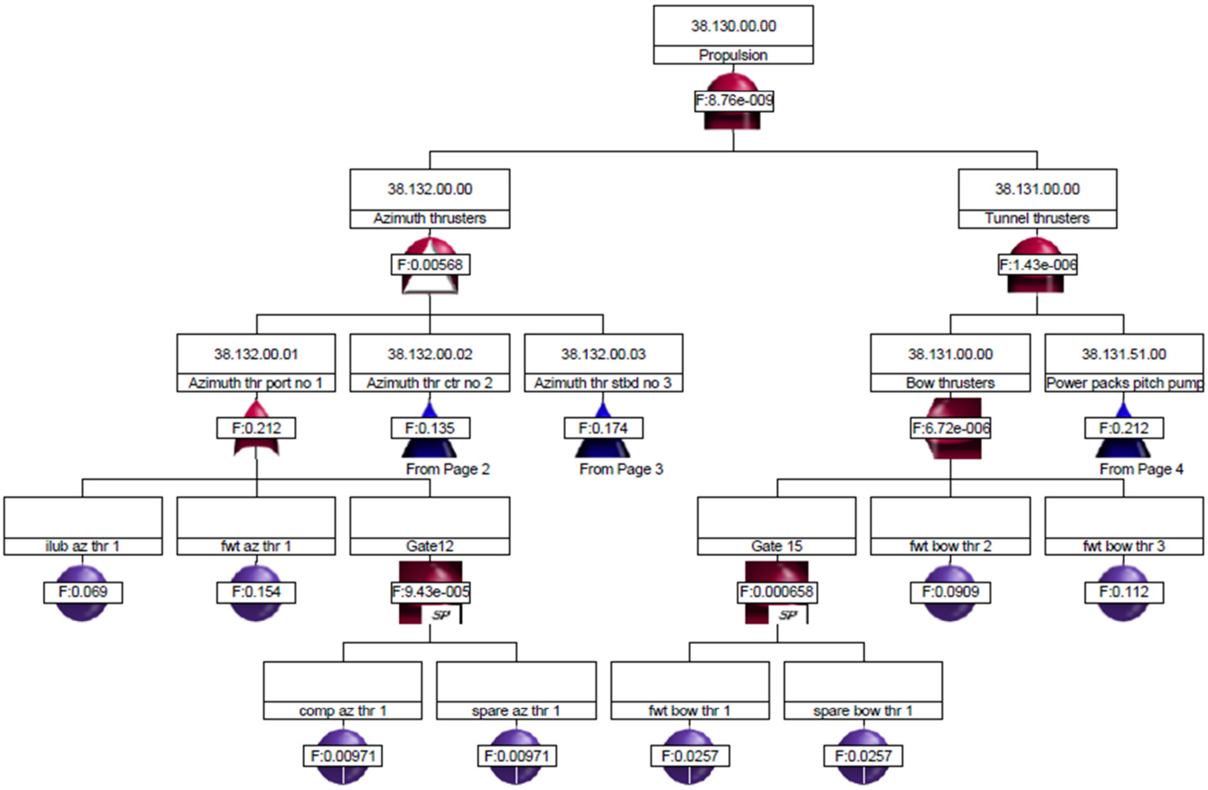

Figure 5.7 Employment of dynamic 'SPARE' gate in the FT structure of the propulsion system

In addition to the above, it is considered that it would be beneficial to calculate the overall reliability and availability of the vessel over a period of time before and after the introduction of the suggested maintenance measures so as to establish the influence of the proposed innovative maintenance strategy on the subject vessel. Therefore, the initial parameterisation and setting up of the DFT was conducted taking into account all the various vessel systems identified (Power plant, Propulsion, Lifting Anchoring & Hauling, Water, Diving, Safety). The aim is to derive the initial reliability and availability state of the mentioned systems, identify their most critical components, suggest maintenance measures and then examine their enhancing effect on the complete vessel as well. In this case, the reliability of the overall system is not feasible to achieve, as the various systems investigated are very different one from the other regarding their technical parameters, with different components examined for each one of them. Therefore, it would be inconsistent to attempt the inclusion of all systems under one major system (the entire vessel in this case) in order to examine its overall reliability. On the other hand, the assessment of the availability of the vessel before and after the implementation of the maintenance strategy is possible to achieve since, in this case, the availability can be examined with respect to the vessel's overall performance through time. On the other hand, with respect to the FMECA approach, it assists in examining the technical characteristics/aspects of the system under consideration and is more relevant to be used in the description of detailed micro-systems such as the Diesel Generator system in contrast to the various systems of *"DSV A"*. This is explicitly shown in the next sections in which the presentation of the case study of the DG system takes place.

5.4 Case study of DG system

In this section of Chapter 5, the application of the previously mentioned reliability and criticality methodology is presented regarding the case study of the Diesel Generator (DG) system of a motor sailing cruise ship. The main particulars of the subject vessel are shown in Table 5.4.

Table 5.4 Main particulars of the subject vessel

Year of Built	1990
Ship type	Motor sailing cruise ship
Main propulsion	Diesel-electric (4 diesel generators)
Masts	5
Capacity	308 passengers
Length	187.0 m (including bow sprit)
Breadth	20.0 metres
Draft	5.0 metres
Tonnage	14,745 GRT
Service speed	10-15 knots

5.4.1 *Operational profile of DG system*

This vessel is a motor sailing cruise ship which is employed in the cruise industry, sailing worldwide in areas of major touristic attractions (e.g. Caribbean Sea, Mediterranean Sea etc.). Her sailing pattern is customised according to the seasonal market requirements all around the year (i.e. summer season in the warm Mediterranean climate while changing destination in the winter months for the moderate weather of the Gulf of Mexico). The vessel is driven by a set of four DGs responsible for the main propulsion as well as the overall electrical supply load of the vessel. She is also equipped with three sailing masts, which are primarily used for recreational purposes, thus the characterisation of 'motor sailing cruise ship'. In Table 5.5 the main characteristics of the DG system are presented.

Table 5.5 DG characteristics

Total no of DG	4
Rated kW	2,280
Total HP	13,216
Engine rpm	750
Cylinder bore	320 mm
Cylinder stroke	350 mm
FO consumption	3 tonnes/24 hrs (normal conditions)

Moreover, Figure 5.8 describes the examined DG system in more detail. As is shown, it consists of five DGs, out of which DG 1-DG 4 are the main DGs providing the power supply for the entire ship operation. DG 5 is the emergency Diesel Generator which is one of the most critical items of the ship and can be used in emergency situations (e.g. providing emergency lighting in case of general black-out). The main DGs are located in pairs in the port and starboard side of the vessel respectively. Additionally, the way the DGs are related in order to connect to the electrical distribution system of the vessel is shown in Figure 5.8. The four DGs are connected through the main switchboard with two transformers, one for the 440V and one for the 220V electrical units. The 440V unit is used to provide the main propulsion of the ship through two propulsion units, propulsion unit 1 (port) and propulsion unit 2 (starboard). They are also capable of supporting the manoeuvrability of the ship with two thruster units, thruster unit 1 (aft) and thruster unit 2 (forward). The 220V electrical unit supports all the general power needs of the ship as well as the control panel (CP) board of the bridge, engine room, etc. As mentioned before, DG 5 (emergency DG) is responsible for the primary needs of the ship in the case of an emergency/unexpected event, in which case it can supply both the 440V and 220V electrical units with power for an amount of time.

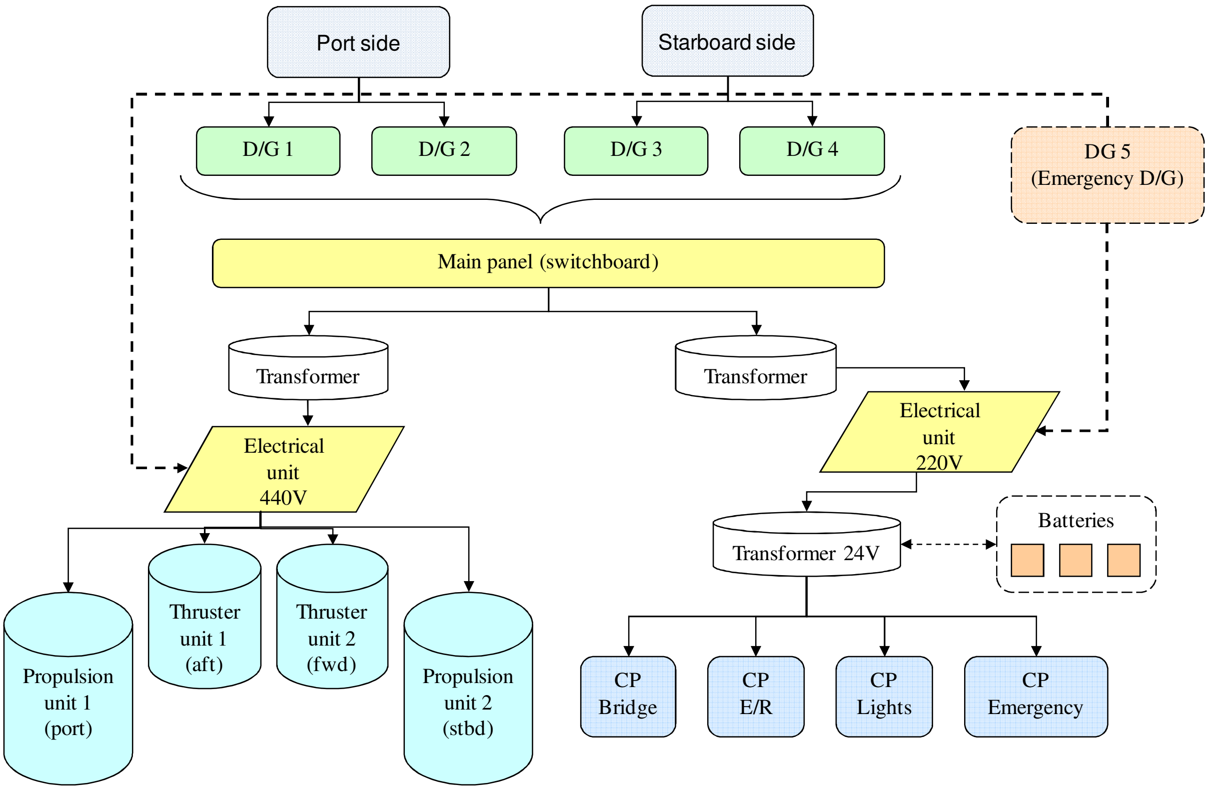

Figure 5.8 Layout of the overall Diesel Generator (DG) system for the subject motor sailing cruise ship

5.4.2 Current maintenance practices for the DG system

Being employed in the highly competitive maritime leisure industry, it is of paramount importance for the vessel to preserve its operational condition in exceptional levels so as to keep up with the industry standards set worldwide. Maintenance works are mostly carried out in a preventive/pre-planned way, meaning that the management team of this vessel tries to fulfil all the maintenance and repair works in a predetermined annual interval as well as minimise any potential equipment breakdowns and consequently any downtime occurring. In this respect, the reliability and criticality analysis of the maintenance characteristics of the DG system is of crucial importance for the preservation of excellent performance ratio of the ship. It can also assist in identifying the most critical items of the whole system so as to focus the maintenance work at specific components during the programmed maintenance interval which will further enhance the operability conditions of the ship.

5.4.3 System boundaries and data collection activity for the DG system

Furthermore, in order to understand the function of the DGs used in this case study, each one of them is divided in their own sub-systems (Figure 5.9). This is a very important step in order to start the reliability and criticality analysis and understand the core of its value. The central part of each DG is the main body/frame. Additional sub-systems include the fuel, air and lube oil (LO) system in addition to the electrical components and the miscellaneous equipment system. Each sub-system is further partitioned into its different components as shown below:

- Main body/frame: oil mist detectors, cylinder heads, governor, valves & fuel injectors and turbocharger (T/C)
- Fuel: fuel oil (FO) valves & piping, thermostatic valve circuit, filter autoclean and filter duplex
- Air: start limiter, air cooler & manifold and start air
- Electrical components: alternator and DG control panel
- Lube oil: lube oil (LO) valves & piping, glacier filter oil and duplex LO filter
- Miscellaneous: alarms, engine preheating unit, instruments and special tools

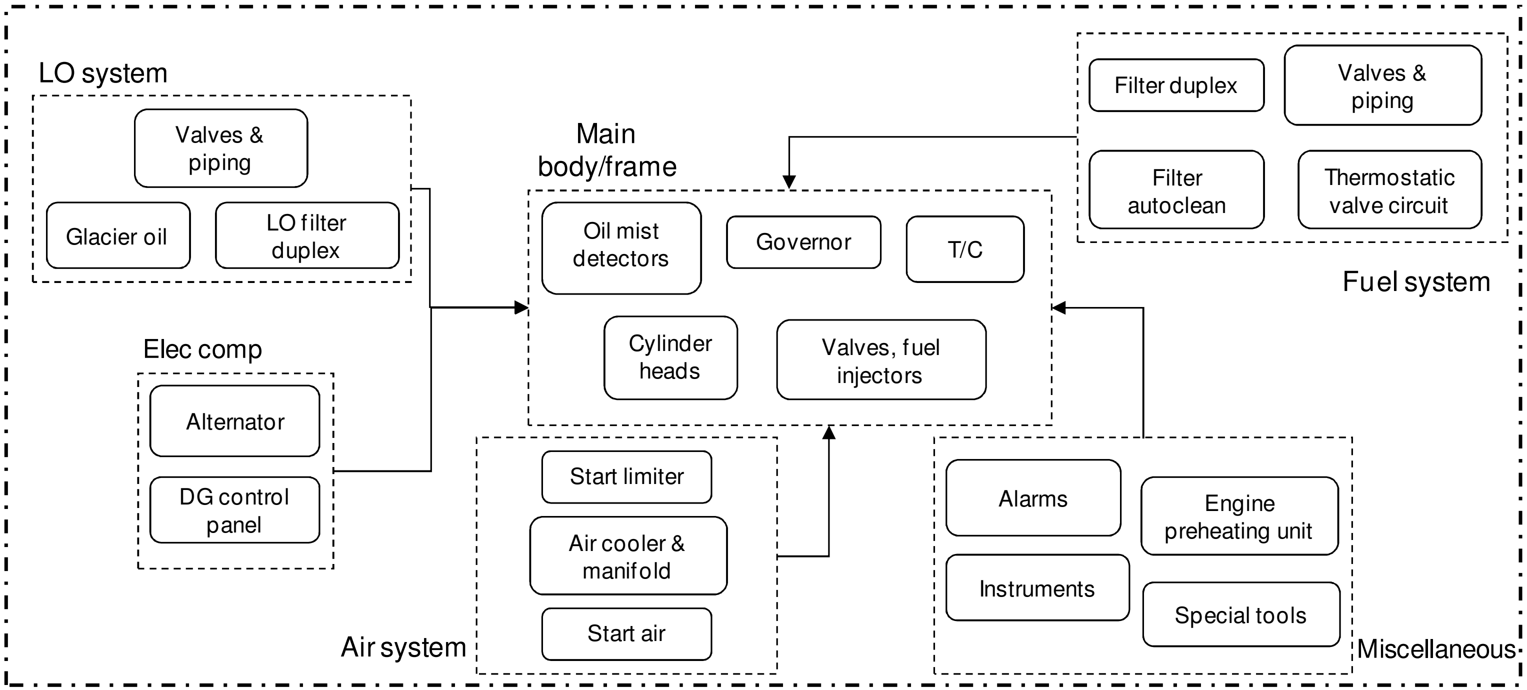

Figure 5.9 Boundary condition of the Diesel Generator showing the sub-systems and components used for the specific case study

On top of the above, as in every case study, it is of paramount importance to set up the correct foundations on which the application of the methodology mentioned in the previous Chapter is based. With this process, the ‘Garbage In-Garbage Out’ obstacle is avoided and the entire application is presented in a crystal-clear way. In this case, and in order to carry out the reliability analysis of the DG system, actual raw failure data have been provided by the operator of the vessel which are extracted from the online maintenance management system of the ship for a period of five years (2004 to 2009). As in the case of *“DSV A”*, it is deemed necessary to screen out the data that were duplicated or are not properly filled-in. That is due to either the deficit of the online system or improper fill-in process by the crew of the ship. The resulting remaining data include failures, underperforming and overhauling events. The final set of data used in the present case study including Mean Time Between Failures (MTBF) of the components described is shown in Table 5.6.

As is mentioned before, the data originate from the online maintenance system of the vessel, which shows when the function of each one of the components mentioned is lost during the period of five years. In order to keep the consistency for all the components of the DGs, it is decided to present the MTBF for all of the components of the various DGs even if these are not part of the initial raw data list. For example, in the case of the oil mist detectors of DG 1, DG 2 and DG 4, they present MTBF values of 8,296, 5,736 and 14,256 hours respectively. In the case of DG 3 ad DG 5 no such values (or else breakdowns, failures) are originally mentioned. Being on the conservative side, it is assumed that the MTBF for the oil mist detectors of these DGs is equal to the observation time, which is 5 years or else 43,800 hours meaning that the specific equipment performed well during the recorded period.

Table 5.6 Actual field data showing the Mean Time Between Failures (MTBF) in hours for the operation of all DGs

MTBF (hours) Components	DG 1	DG 2	DG 3	DG 4	DG 5 (Emergency)
Oil mist detectors	8,296.0	5,736.0	43,800.0	14,256.0	43,800.0
Cylinder heads	8,808.0	14,340.0	24,112.0	13,698.0	43,800.0
Governor	11,995.0	25,704.0	36,780.0	1,896.0	43,800.0
Valves, fuel injectors	43,800.0	43,800.0	5,592.0	43,800.0	43,800.0
Turbocharger	43,800.0	31,944.0	19,512.0	43,800.0	43,800.0
Fuel system valves & piping	2,208.0	29,436.0	2,208.0	29,736.0	43,800.0
Fuel filter autoclean	720.0	744.0	720.0	720.0	720.0
Fuel filter duplex	16,536.0	43,800.0	22,992.0	43,800.0	43,800.0
Thermostatic valve circuit	23,184.0	43,800.0	43,800.0	43,800.0	43,800.0
L/O system valves & piping	43,800.0	43,800.0	43,368.0	43,800.0	43,800.0
Filter glacier oil	16,896.0	16,848.0	40,032.0	16,698.0	43,800.0
Filter lube oil (duplex)	43,800.0	43,800.0	43,800.0	33,084.0	43,800.0
Start limiter	32,748.0	43,800.0	43,800.0	43,800.0	43,800.0
Start air system	43,800.0	8,048.0	43,800.0	43,800.0	43,800.0
Air cooler & manifold	7,488.0	43,800.0	43,800.0	43,800.0	43,800.0
Alternator	2,745.0	2,622.0	1,618.0	2,188.0	4,867.0
D/G control panel	43,800.0	43,800.0	43,800.0	43,800.0	18,494.0
Engine preheating unit	43,800.0	43,800.0	6,204.0	43,800.0	43,800.0
Alarms	13,608.0	43,800.0	43,800.0	43,800.0	43,800.0
Instruments	43,800.0	43,800.0	12,120.0	43,800.0	43,800.0
Special tools	7,512.0	43,800.0	43,800.0	43,800.0	43,800.0

After the identification of the various sub-systems and their components, the reliability and criticality study is presented. For this reason, the FMECA and FTA with static and dynamic gates are employed. These tools are explained in more detail in the following paragraphs starting with the presentation of the FMECA.

5.4.4 FMECA for the DG system

FMECA is also conducted in order to identify the most severe and frequent causes of the overall DG system failures. The FMECA table is a combination of:

- The failure events and their causes
- The local and global effects taking place
- The detection and prevention method applied
- The severity, frequency and criticality values
- The repair and unavailability times and
- Any additional remarks provided.

In the following Table, a small extract of the overall FMECA for the DG system is shown (Table 5.7). The full extent of the proposed FMECA is presented in Appendix H.

Table 5.7 Part of the FMECA table for the examined DG system

##	Failed item	Failure event	Failure cause	Effects		Detection method	Prevention method	Severity				Frequency				Criticality				Repair time	Unavailability	Remarks
				Local	Global			S	E	A	O	S	E	A	O	S	E	A	O			
1	Oil mist detectors	blocked	No vaccum (vaccum breaks), filter chocked, faulty, valve chocked/damaged	unable to detect oil mist	stop engine, explosion	failure alarm	regular "zero setting", calibration	D	D	D	D	2	2	2	2	D2	D2	D2	D2	1hr	1.5-2 hrs	replace by spare (at least one/dg)
2	Cylinder heads 1-6	leakage, overheating	cracks, faulty exhaust valves, improper combustion	high temp alarm, smoke detection/alarm	stop engine	high pressure/temp alarms	proper monitoring of oil, exhaust & water pipes	B	B	C	C	3	3	3	3	B3	B3	C3	C3	2 hrs	3-4 hrs	proper maintenance
3	Governor	erratic function	electronic/mechanical control failure	cannot operate/malfunction load share	stop engine	frequency meter, kilowatt meter	lub oil relenish, maintain electronic circuits	A	A	C	C	3	3	3	3	A3	A3	C3	C3	2 hrs	3 hrs	
4	Valves, fuel injectors	blocked valve and/or injectors	Lack of maintenance, poor fuel quality, fuel temperature not correcct, oil leakage on valve, not proper fuel injection/combustion	Load share for relevant cylinder, insufficient oil combustion, excessive smoke	Deferential temperature of exhaust gas	High deferential temperature indicated local or at control room monitors visual inspection	Overhauling/inspection and parts replacement according to manufacturer's instructions	B	B	C	C	3	3	3	3	B3	B3	C3	C3	1/2 hr	1 hr	spare fuel injectors ready for use
5	Turbocharger	bearing failure, seizure	lack of lubrication, excessive carbon deposits, cracked blades, inlet filter ckocked, not sufficient air pressure, surging	bearing damage, turbine damage	lower output, high fuel oil consumtion	high exhaust temp, reduced efficiency, low scavenge pressure (surging)	monitorong bearings, exhaust temp, scavenge pressure & temp	A	B	C	C	3	3	3	3	A3	B3	C3	C3	6hrs	cleaning with chemicals, etc - 12-24hrs	depending on turbine condition
6	Fuel system, valves, piping	Rupture of pipe, leakage, sludges/water in the line	poor quality diesel/HFO, cat fines, sludges (MDO)	oil spillage, hot spot creation	fire in E/R, genset failure, blackout	visual, loss of power, high temp deviation	good purification, filter cleaning, fuel treatment	D	D	D	D	2	3	3	3	D2	D3	D3	D3	1/2 hr	depending on situation	
7	Fuel filter autoclean	blocked	mechanism failure	low fuel oil pressure	blackout, loss of power	differential pressure alarm	draining of water/sludges	B	B	B	B	3	3	3	3	B3	B3	B3	B3	2 hrs	2.5 hrs	autoflush mechanism in place

In order to complete the FMECA, a criticality matrix is developed taking into account different severity and frequency categories. In this respect, various studies and procedures regarding FMECA and risk matrices have been reviewed in order to achieve the objectives of this study. For more details the reader is referred to the IMO FSA approach (2007), the marine risk assessment offshore technology report prepared by DNV for the UK HSE (DNV 2001), the delivered reports of the EU funded project SAFEDOR (Skjong et al 2005, Loer and Hammann 2007), the common BS/ISO 17776 standard for the petroleum and gas industries (BS/ISO 2002), the work of Jonkman et al (2003), the DNV recommended practice on risk management in marine and subsea operations (DNV 2003) and the ABS guidance notes on risk assessment applications for the marine and offshore oil and gas industries (ABS 2003b). Regarding the severity ranking, the different categories used in this study are presented in Table 5.8.

Table 5.8 FMECA severity categories and their ranking

Severity level	***Personnel safety(S)***	***Environmental impact (recovery time) (E)***	***Asset integrity (A)***	***Operation (O)***
A (minor)	no injury	no damage/contamination	negligible damage < £5k	minimal operation loss
B (marginal)	minor injury (first aid)	minor damage/spillage, good effect of control measures (a few days)	minor damage £5k - 20k	short operation loss (few hours)
C (major)	multiple minor injuries, major injury	major damage/pollution, low effect of control measures (a few days to a month)	localised damage £20k - 100k	minor replacement needed (1-2 days)
D(critical)	multiple major injuries	critical damage/pollution, minimal effect of control measures (more than a month)	major damage £100k-1MM	major repair needed (operation loss 1 day-week)
E (catastrophic)	1 fatality or more	Significant environmental impact, massive pollution (more than a year)	damage > £3 MM, total loss	total operation loss (> 1 month)

In these terms, severity is examined in four distinctive affected areas: personnel safety (S), Environmental impact (E), Asset integrity (A) and overall Operation (O). These are ranked into five categories according to the impact occurred: A (minor), B (marginal), C (major), D (critical) and E (catastrophic). At this point, it is important to mention that each one of the different severity levels is created bearing in mind the IMO FSA approach (2007) in terms of the categories for the severity effects on human safety as well as the effects on ships. For instance, the ‘minor’ and ‘marginal’ severity levels in the FMECA approach developed herein refer to the minor or single injuries according to the IMO FSA approach. The same severity category corresponds to local equipment damage (in terms of the ship/asset itself) which also indicates a minor financial damage in the range of £5-20k and minimal operation loss of a few hours. On the other extremity, the severity level ‘catastrophic’ used in the present FMECA corresponds to the top IMO FSA severity category with one or more fatalities in terms of human safety while the effects on the ship/asset are in the range of ‘total loss’. The financial burden for the latter is £3MM, which agrees with the value set by IMO for having a pre-set financial value for a single fatality as well. Moreover, the FMECA severity table has been instructed so as to retain the equivalency of the severity status across the four different categories (e.g. Personnel safety severity level E (catastrophic) of 1 fatality is equal to Asset integrity severity level of damage of 3 million pounds sterling). It is also assumed that one major injury is equal to 10 minor injuries while one fatality is equal to 10 major injuries.

In terms of the frequency ranking, it is similarly divided into five categories: 1 (extremely unlikely), 2 (remote), 3 (occasional), 4 (probable) and 5 (very frequent). Frequency levels are considered in terms of a fleet of vessels bearing in mind that the ship life is assumed to be 25 years. For example, the frequency level of an event occurring once in the lifetime of a fleet of 40 vessels is estimated as:

Frequency = 1 / (40 vessels * 25 years lifespan) = 0.0001 (extremely unlikely event-level 1)

Based on the above, the various probability levels, their description as well as the quantitative probability ranking are showed in Table 5.9.

Table 5.9 FMECA frequency levels

Level	*Ranking*	*Description*	*Quantification*
1	extremely unlikely	1 event/10,000 vessel-years (app. once in the lifetime of a fleet of 40 vessels)	1.000E-04
2	remote	1 event/1000 vessel-years (app. once in the lifetime of several similar vessels)	1.000E-03
3	occasional	1 event/100 vessel-years (once in a ship's lifetime)	1.000E-02
4	probable	1 event/10 vessel-years (a few times during a ship's lifetime)	1.000E-01
5	very frequent	several events/vessel-year (app. once every 2-3 months)	1

Bearing all the above in mind, the criticality matrix is developed in order to provide the various criticality levels for the specific case study. Overall, criticality ranking is identified as the outcome of severity of consequence and frequency of the mentioned consequences. In Table 5.10, the suggested criticality matrix is presented showing the four separate areas of criticality ranking.

Table 5.10 FMECA criticality matrix

		Frequency				
		1	**2**	**3**	**4**	**5**
Severity	**A**	A1	A2	A3	A4	A5
	B	B1	B2	B3	B4	B5
	C	C1	C2	C3	C4	C5
	D	D1	D2	D3	D4	D5
	E	E1	E2	E3	E4	E5

As shown, four risk levels have been created (low, moderate, significant and high) and are described and moreover explained below (Table 5.11):

- Level 1: Low (negligible criticality)
- Level 2: Moderate (tolerable criticality)

- Level 3: Significant (tolerable criticality with specific measures in place to prevent/mitigate the end-results)
- Level 4: High (intolerable criticality)

Table 5.11 FMECA criticality index Table

Level 1	negligible criticality
Level 2	tolerable criticality
Level 3	tolerable, specific measures in place
Level 4	intolerable criticality

At this point it is important to mention that wherever the severity level *'E' (catastrophic)'* is identified, it is considered as intolerable criticality level. Especially in the case of the *Personnel safety* category, even if the probability of occurrence is *extremely unlikely* (that means overall ranking *E1*, so *minor criticality* category), it is still considered as *High (intolerable criticality)* category since it involves one or more fatalities occurring. The criticality matrix is developed in such a way so as to demonstrate the various levels involved in the case study presented herein. In this way, the most critical components are identified which provide support in the preparation of the DFT structure that follows.

5.4.5 Development of DFTs for DG system

In order to start the DFTA, the DFT diagram is initially created based on the steps mentioned above. In this respect, Figure 5.10 shows the DFT structure of the entire DG system.

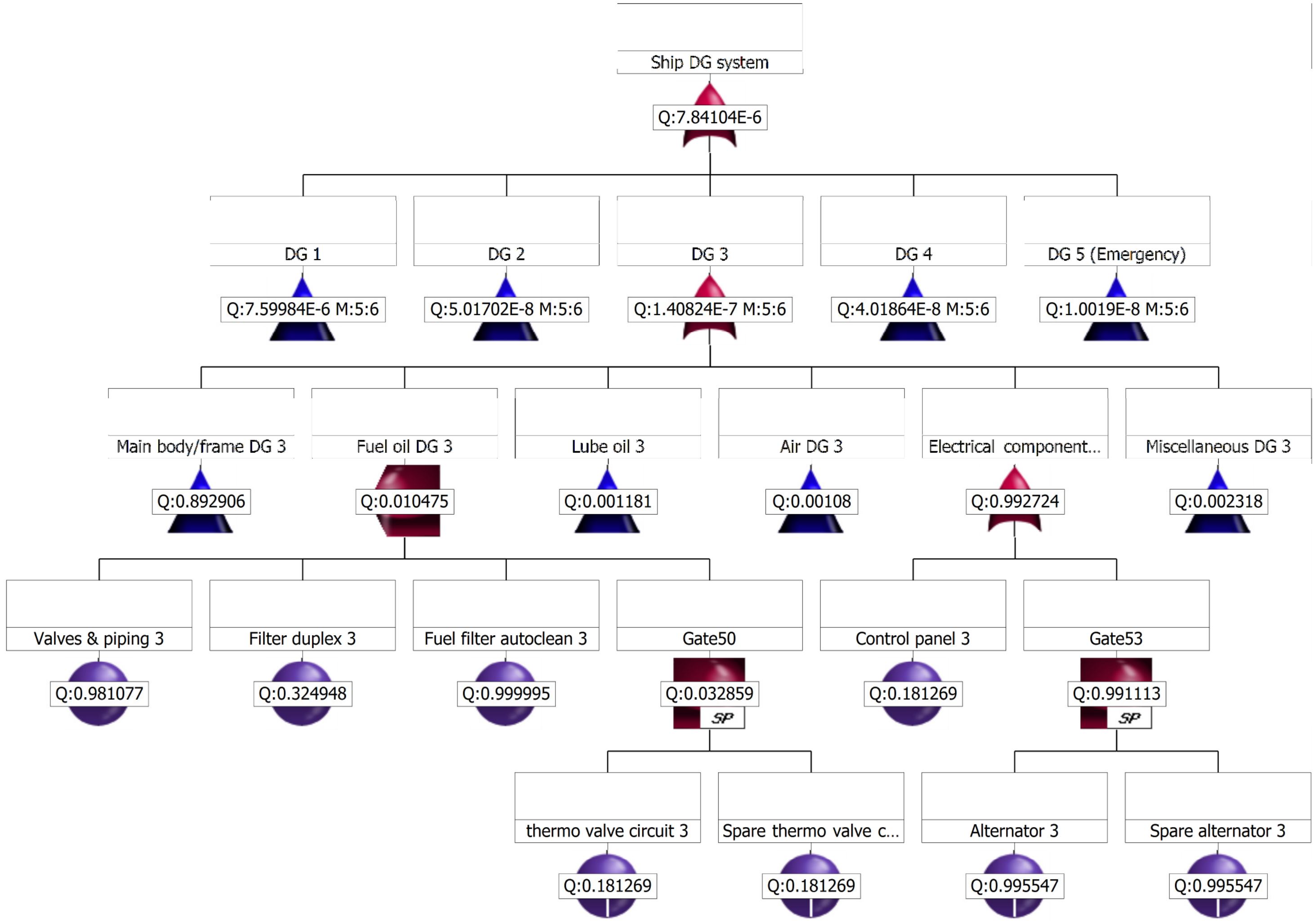

Figure 5.10 Dynamic Fault Tree structure of the entire DG system

As is shown above, the DG system is represented by an ‘OR’ gate meaning that the failure of any of the Diesel Generators may lead to the failure of the entire DG system. Then, each one of the individual DGs is described as in the case of DG 3 with a five out of six ‘VOTING’ gate meaning that for this specific DG to fail, the outcome of five out of six sub-systems needs to be negative (failed). This specific gate is used as all the sub-systems (main body/frame, fuel oil, lube oil, air and electrical components) are equally important for the failure of the main sub-system (top gate) apart from one of them which is the miscellaneous sub-system. Following this, each one of the DFT structure of the sub-systems is described in its own discrete way as is shown in the next paragraph.

Starting with the main body/frame of each DG, this is described with an ‘OR’ gate, directly depending on the failure of its components (or otherwise depending on the basic events such as the oil mist detectors and the rest of the components). The fuel oil sub-system is represented by a ‘Sequence enforcing’ (‘SEQ’) gate. The basic events of this sub-system are positioned in order from left to right according to their MTBF. This means that the lowest MTBF value is placed on the left side of the sequence of the events followed by the event with the immediate higher value. This occurs as the failure of the events which will influence the failure of this sub-system will start from the one having the lowest MTBF. Next, the lube oil sub-system is described by using a ‘Priority AND’ (‘PAND’) gate. Once more, the basic events which are included in this gate are positioned from left to right based on their MTBF value (lower to higher value) as the event with the lowest MTBF value will be the first to fail/occur. The air sub-system is described with and ‘AND’ gate as each one of its components need to fail for the air system to fail. For the electrical components sub-system, an ‘OR’ gate is employed for describing the interrelation between the alternator and the control panel of each DG. Finally, for the miscellaneous gate, an ‘AND’ gate is also used to define the modelling of this sub-system. This is carried out as such because the basic events comprising this gate may also function as stand-alone components, therefore not depend on each other to fail and thus make the top gate fail as well.

After finalising the DFT modelling and in continuation of the original set-up, the quantitative DFTA takes place (Figure 5.11).

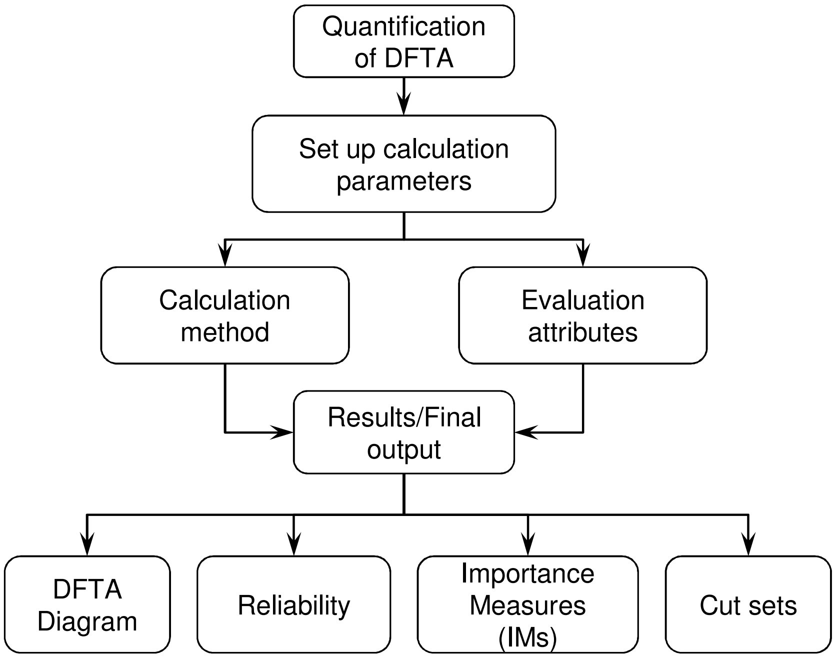

Figure 5.11 DFTA calculation process for the DG system

In order to estimate the reliability and criticality results of the main system (entire DG system) as well as of the individual DGs, Relex software is used to carry out the probabilistic calculations (Relex 2009). The same procedure is followed for the DFTA as in the case of *"DSV A"*. The quantitative DFTA is initiated with the set-up of the calculation parameters. The calculation method is selected (Esary-Proschan calculation method) for the same reasons as in the case of the *"DSV A"*. The evaluation attributes used in this case study are: start time is set to zero while end time is set to five years (43,800 hours). This set-up is chosen in order to examine the reliability of the DG system at the end of a period when a major repair and maintenance sequence of works may occur (Special Survey requirements according to the guidelines of classification societies). The development of the reliability of each one of the main systems and sub-systems is studied in time intervals of three (3) months (in order to simulate the quarterly reporting maintenance intervals). In this way, the results of the DFTA are obtained regarding the final DFT diagram, the reliability through time of the entire DG system as well as of the individual DGs and finally the IMs and the cut sets for each one of the Diesel Generators. The details of the DFT structure of the entire DG system are presented in Appendix E.

After obtaining the results of the reliability analysis and defining the most critical components for each one of the DGs, 'SPARE' gates are used in order to address the issue of the introduction of additional maintenance measures so as to improve the condition of the overall and individual DG system. As mentioned before, dynamic ‘SPARE’ gates may represent spare parts, stand-by equipment, etc. which will enhance the reliability results of the system examined. In this case study, an example of the use of ‘SPARE’ gates is shown in the DFT structure of DG 4 (Figure 5.12). All the additional ‘SPARE’ gates which are used for the rest of the DGs are shown in detail in Appendix F. The above are better described in the following Chapter in which the implementation of the mentioned reliability tools are presented.

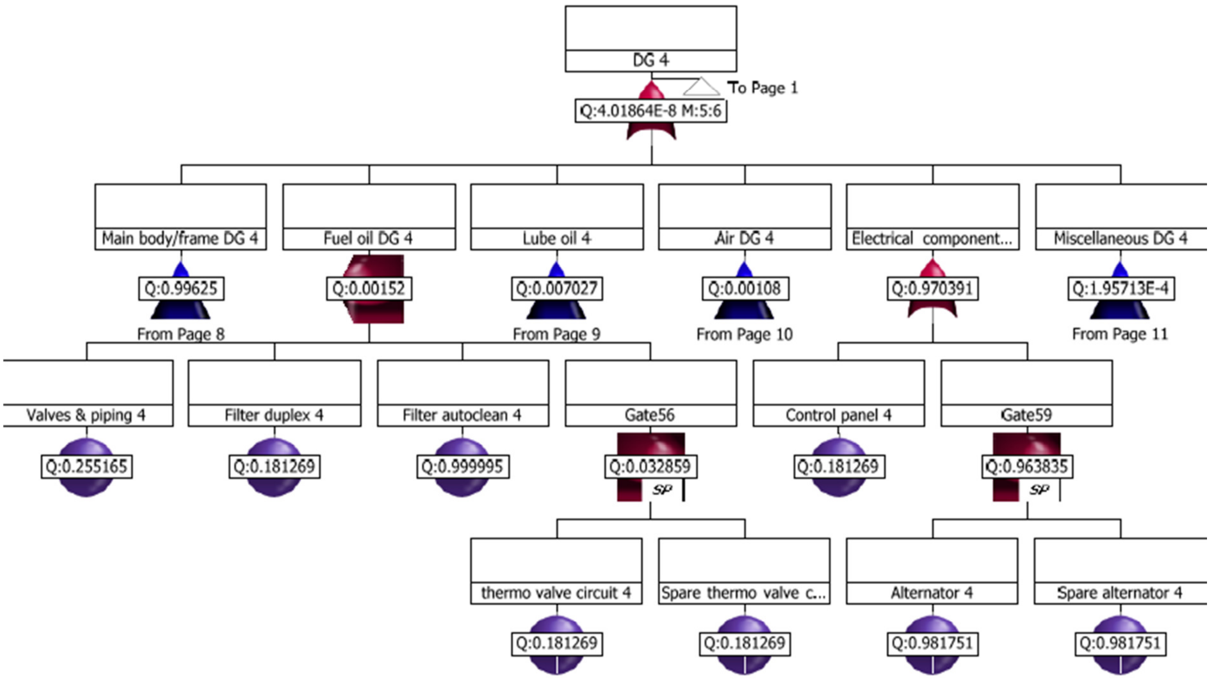

Figure 5.12 \dynamic Fault Tree structure of the ship DGs system including the use of ‘SPARE’ gates

5.5 Chapter summary

In this Chapter, the initial setup for the application of the reliability and criticality analysis tools as part of the RCBM strategy is demonstrated in detail. The selection of two case studies is carried out in order to demonstrate the applicability of the above in terms of the main systems and sub-systems of *“DSV A”* as well as of the DG system of a motor sailing cruise vessel. In the first case, the DFTA tool is used employing static and dynamic gates in conjunction with the application of minimal cut set theory and reliability importance measures so as to examine the reliability and criticality of the ship’s systems. In the second case, the study is initiated with the FMECA tool with a purpose-built criticality matrix in order to provide more insight into the reliability of the DG system of the vessel under consideration. Then the DFTA is also applied so as to assess the reliability and criticality levels of the main system and sub-systems. In both cases, the original maintenance data stemming from the computerised maintenance databases of the subject vessels are used, illustrating the actual repair and maintenance condition of the ships over a period of years. Having set up the initial information for performing the reliability and criticality assessment of the mentioned ship systems, the results of the suggested analysis are explicitly shown and explained with more details in Chapter 6 and Chapter 7 following next.

6 CHAPTER 6-RELIABILITY RESULTS OF *“DSV A”*

6.1 Chapter outline

In this Chapter, the results of the application of the RCBM strategy in the maritime industry are demonstrated. More specifically, the reliability and criticality analysis of Diving Support Vessel *“DSV A”* is described in details. At first, the reliability and criticality analysis performed on the main systems and sub-systems of *“DSV A”* and the appropriate maintenance measures to be considered in order to enhance the reliability of these systems are implemented and the results are presented.

The main systems include the Power plant, Propulsion, Water systems as well as the Lifting, Anchoring & Hauling, Diving and Safety systems. Initially, the reliability results over time of each one of the main systems as well as the Probability of Failure (PoF) of their sub-systems are presented. Then the Birnbaum (Bir), Criticality (Cri) and Fussell-Vesely (F-V) Importance Measures (IMs) are demonstrated. The cut sets for all the systems which assist in identifying the most critical components of the subject vessel are presented as the next step. Moreover, remedial measures regarding the specific critical items/components with their failure causes for each specific system and sub-system are shown and further explained. This is achieved in terms of the introduction of ‘SPARE’ gates in the Dynamic Fault Tree (DFT) structure for each main system examined while their reliability index is calculated once again in order to investigate their improvement. Based on the results obtained with this approach, further suggestions and discussion for each one of the systems examined takes place.

6.2 Introduction

In terms of presenting and examining the results of the reliability and criticality analysis of *“DSV A”*, it must be mentioned that the reliability results for each main system and sub-system are shown as a development of their reliability index (in percentiles). The threshold for good operational reliability is set to 90% of the original reliability index for all the mentioned systems based on discussions with representatives from the shipping company (technical manager, superintendent engineer and chief engineers). The results for the sub-systems will be shown as the Probability of Failure (PoF) progress. This is done in order to obtain a better representation of the sub-systems development through the simulation time. The good operational threshold in this case is set to 10% for the same reasons as mentioned above.

In the case of the presentation of the reliability IMs, it should be reminded that each one of them (Birnbaum-Bir, Criticality-Cri and Fussell-Vesely-F-V IMs) denotes different characteristics of the examined main system. As described in the methodology Chapter (Chapter 4), the Bir IM is used to identify which end-event/component needs further improvement related to the rest of the events in the same system/DFT. Cri IM is applied when one needs to identify which end-event/component is more likely to occur and is at the same time critical to the top event/system. Last but not least, Fussell-Vesely IM is used when one needs to determine which end-event/component may contribute to the failure of the main system without being critical. This happens when a minimal cut-set, which contains the subject event, occurs. In addition to the above, a further clarification is essential concerning the 'component' level in the IMs tables presented next. The latter is the one which reflects the 'end-event/component' in the DFT modelling structure. Apart from the above it should be mentioned that the IMs are used in a way so as to present the ranking of the failures of the components no matter how big or small their values might be thus presenting differences in the values observed for each one of them.

Regarding the cut set results, these assist in the identification of the potential ways/sets that the failure of the top event may occur. The top ranked cut sets lead to the identification of the minimal cut sets, which is the shortest way that the failure of the top event will take place thus identifying the events that cause failure to happen. The prioritisation of the minimal cut sets for each system with the combination of IMs mentioned before lead to the identification of the suggested maintenance/rectification measures, which are then represented by 'SPARE' gates and events. In some systems the number of cut sets created may be tens or even hundreds depending on the modelling structure of the DFT as well as the number of dynamic gates used to represent the relationships among different gates. For this reason and for economy of space, the first ten cut sets of each main system of *"DSV A"* are presented in this case study.

So far the different steps of carrying out the reliability analysis of *"DSVA"* are presented by performing the reliability calculation results, the IMs and the cut-sets for all the main systems and sub-systems examined. The above steps are performed with the aim of identifying the most critical events for each system and the ones that contribute the most on the failure of the top event. The next stage in the present analysis is to suggest improvement measures through the introduction of 'SPARE' gates and events and examine the upgrading of the reliability of each system at the same time frame (simulation time) as examined before. In this respect, the present study also investigates which specific 'SPARE' gate introduced in the initial DFT contributes more to the enhancement of the reliability of the main system. This is determined by exploring the results of the reliability IMs overall and more specifically the Criticality as this one denotes not only which end-events of the DFT are more important among each other but also show the contribution they have in the overall increase of the reliability of the main system. Nonetheless, the Birnbaum and Fussell-Vesely IMs are also taken into account while conveyed with a lower weighting factor.

At this point, it is important to mention that 'SPARE' gates and events represent the maintenance measures, which may lead to the enhancement of each system. More specifically, this could be the introduction of spare parts, redundant/stand-by equipment, additional preventive maintenance measures, more frequent inspection intervals, engaging condition monitoring tools either on a temporary or a permanent manner (one-off condition monitoring inspections by contractors or investing on permanently installed devices on equipment) and modifications in the original design. The above alternatives depend on the specific condition of the equipment/component in question as well as on the reliability results that are derived for each individual system. Summarising, 'SPARE' gates and events suggest further commitment of the company towards understanding and coping with maintenance procedures. As mentioned in section §5.3, the various systems of *"DSV A"* which have been identified are investigated furthermore are the following:

- Power plant
- Propulsion
- Lifting, Anchoring & Hauling (LA&H)

- Water
- Diving
- Safety

6.3 Reliability calculation results for the Power plant system

In this section, the reliability calculation results for the Power plant system of *"DSV A"* are presented next.

6.3.1 Reliability results for the Power plant system

Starting with the first system, the reliability curves of the Power plant system together with the two main sub-systems of E/R 1 and E/R 2 are shown in Figure 6.1. The introduction of E/R 1 and E/R 2 is performed in order to represent the different engine room compartments that this vessel operates as a result of its DP 3 capability. It should be mentioned that the reliability results for each main system and main sub-system are shown as a development of their reliability index (in percentile). As mentioned before, the threshold for good operational reliability is set to 90% of the original reliability index for all the mentioned systems based on discussions with experts and representatives from the shipping operator including a technical manager, a superintendent engineer and a chief engineer.

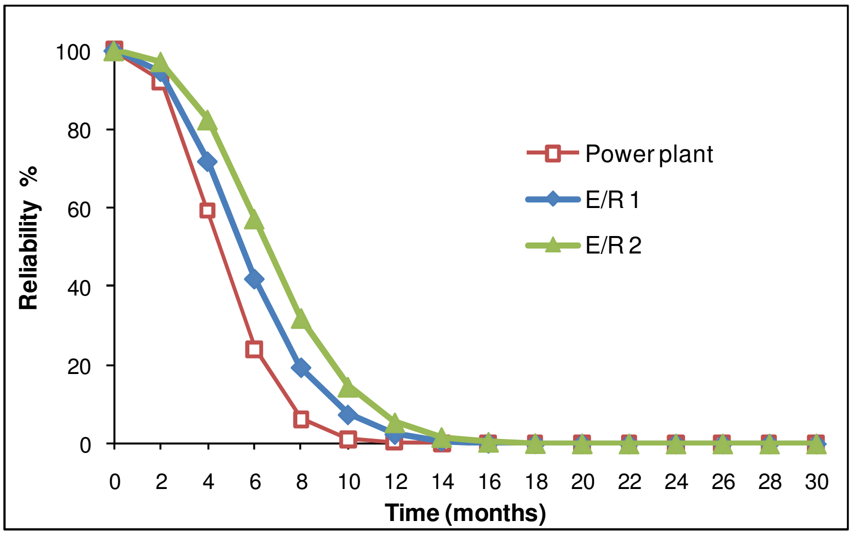

Figure 6.1 Reliability results for the Power plant system and the E/R 1 and E/R 2 main sub-systems

As shown in Figure 6.1, the overall reliability of the Power plant system retains its operational capability for a period of a few months and then starts deteriorating quite fast reaching its lowest level after 10 months of operation. The threshold for good operational state is reached after only three months of operation of this system. The reliability for the E/R 1 and E/R 2 main sub-systems is similarly low as mentioned before for the main system (3 to 4 months for 90% reliability index). It should be noted that the low reliability figures do not necessarily indicate that the systems or sub-systems remain out of operation as the crew on board always deals with any malfunctions that might be presented beforehand. The reliability results in this case reflect the margin of improvement that can be performed on every main system and sub-system if additional maintenance measures are implemented as will be discussed in section §6.3.5 of the present Chapter.

Additionally, in order to study the Power plant system in depth, further analysis is carried out examining the results for the PoF of engines 1-3 for E/R 1 and 4-6 for E/R 2 (Figures 6.2-6.3). The results for the sub-systems are shown as a PoF progress in order to obtain a better insight of the sub-systems development through time. The good operational threshold in this case is set to 10% after supplementary discussions and engagement of experts' judgement from the shipping operator of the vessel has been provided.

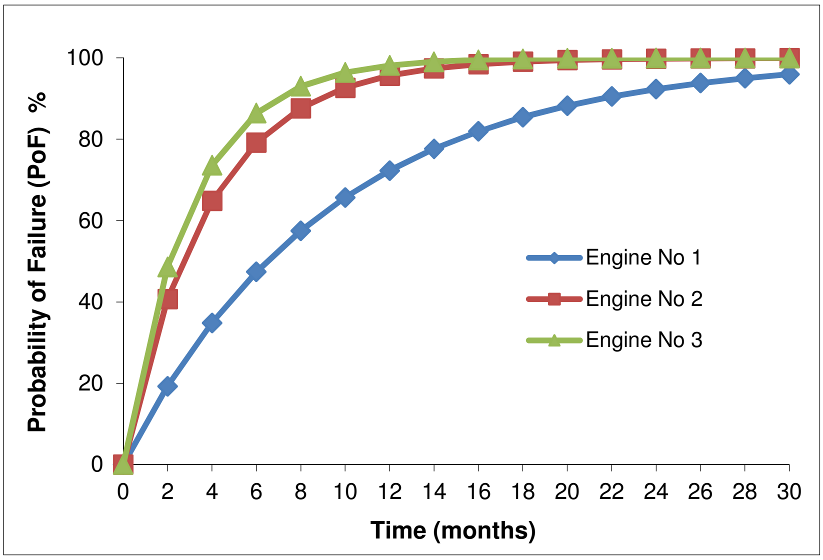

Figure 6.2 Probability of failure results for engines no 1, 2 and 3 of E/R 1sub-system

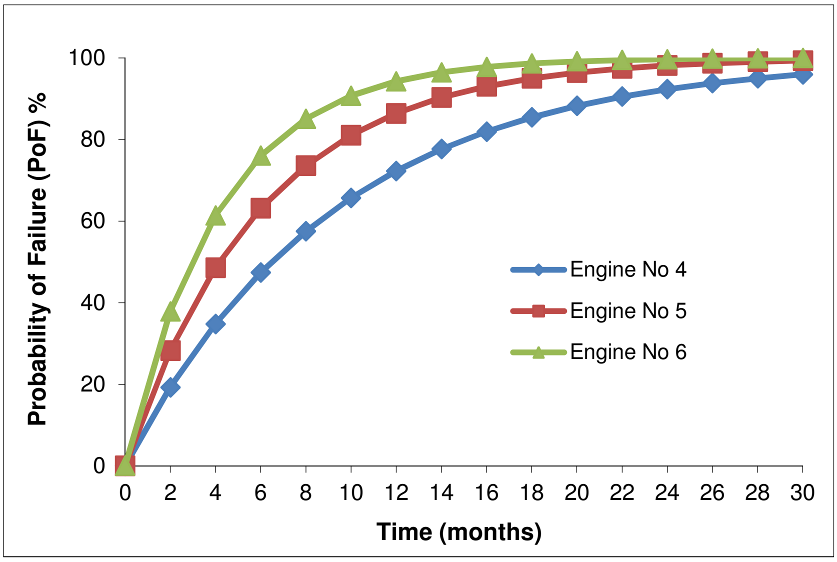

Figure 6.3 Probability of failure results for engines no 4, 5 and 6 of E/R 2 sub-system

Regarding the PoF analysis of each one of the six engines of the vessel, they show better results than the entire Power plant system but after some point they gradually reduce their reliability index as well. In more details, engines no 2 and no 3 present the highest PoF results (PoF increasing to 40% after two months of operation) while engine no 1 shows better performance results (PoF of 40% after five months of operation). Nevertheless, the PoF for all three engines is gradually increasing and it reaches the unwanted low region of results quite quickly, a case which will be dealt with in the next Chapter when additional measures will be introduced. In this case, ‘SPARE’ gates and events are added in the FT structure in order to examine the level of improvement of the deteriorating condition of all ship engines.

From Figure 6.3 it is also observed that the condition of engines no 4, no 5 and no 6 is similar to the one described before for engines no 1-3. Engines no 5 and no 6 are deteriorating faster than engine no 4 (PoF of 30%, 40% and 20% respectively) after only two months of operation. Moreover, this means that the mentioned engines are not maintained in the optimum way and thus there is the possibility of the crew interfering through corrective maintenance tasks in order to address potential flaws in the operation of the subject engines. At this point is should be mentioned that, as in the case of the entire Power plant system, the low reliability results for all engines do not mean that the engines remain out of operational capacity while working. The present analysis reflects the PoF index of all engines so as to pinpoint the worst operating sub-system and furthermore investigate the underlying factors for the worst performing items of equipment (or otherwise end-events of the FT structure). This is shown in detail by employing the Birnbaum, Criticality and Fussell-Vesely IMs. In addition to the above, the excess in the capacity of diesel generators, which concerns all six engines of the Power plant system, means that additional maintenance work can be carried out on the engines without having all DGs operating thus, no disruption in the standard vessel operations. However more details on the failures of the engines of the Power plant system as well as maintenance measures to address the low PoF are presented in §6.3.4.

6.3.2 Reliability IMs results for the Power plant system

At first, the IMs for the main Power plant system are presented in Tables 6.1-6.3. Initially, the Birnbaum IM is shown followed by the Criticality and Fussell-Vesely IM.

Table 6.1 Birnbaum IM for the Power plant system

##	Event	Birnbaum	##	Event	Birnbaum
1	Comp 1	34.878%	10	Corr 3	15.162%
2	Corr 1	34.878%	11	imtc 3	14.544%
3	imtc 1	34.878%	12	Comp 3	14.381%
4	Comp 4	20.502%	13	Comp 5	14.197%
5	Corr 4	20.502%	14	imtc 5	14.197%
6	imtc 4	20.502%	15	Corr 5	14.114%
7	Corr 2	19.417%	16	Corr 6	10.581%
8	Comp 2	17.866%	17	imtc 6	10.541%
9	imtc 2	17.866%	18	Comp 6	10.457%

Table 6.2 Criticality IM for the Power plant system

##	Event	Criticality	##	Event	Criticality
1	Corr 2	38.538%	10	Comp 5	10.578%
2	Corr 3	30.093%	11	imtc 5	10.578%
3	Comp 1	16.149%	12	Comp 4	9.493%
4	Corr 1	16.149%	13	Corr 4	9.493%
5	imtc 1	16.149%	14	imtc 4	9.493%
6	imtc 3	14.685%	15	Corr 5	8.560%
7	Corr 6	11.984%	16	Comp 2	8.272%
8	Comp 3	10.715%	17	imtc 2	8.272%
9	imtc 6	10.644%	18	Comp 6	7.791%

Table 6.3 Fussell-Vesely IM for the Power plant system

##	Event	Fussell-Vesely	##	Event	Fussell-Vesely
1	Corr 2	49.242%	10	imtc 5	14.273%
2	Corr 3	38.329%	11	imtc 6	14.045%
3	Comp 1	24.072%	12	Comp 4	13.388%
4	Corr 1	24.072%	13	Corr 4	13.388%
5	imtc 1	24.072%	14	imtc 4	13.388%
6	imtc 3	19.499%	15	Corr 5	11.617%
7	Corr 6	15.754%	16	Comp 2	11.487%
8	Comp 3	14.389%	17	imtc 2	11.487%
9	Comp 5	14.273%	18	Comp 6	10.364%

As is shown above, the most important events according to the Bir IM are the component failure ('comp'), corrosion ('corr') and inappropriate maintenance ('imtc') of engine no 1 (in E/R 1). 'Comp' denotes the failure of engine components that are overstressed or the fact that there is a fault in the initial design of the specific component. Corrosion refers to the corroded surfaces appearing in the cylinder heads or the pistons of the engine from SO_x gases. 'Imtc' denotes the wrong maintenance carried out by the maintenance crew (possibly a 3rd party) or the crew on board the ship which lead to failures and component replacements. The next most important events that need to be rectified in order to increase the reliability of the Power plant system are these of engine no 4 which belong in the E/R 2 compartment. Regarding the ranking of the most important events according to the Cri and F-V IMs, it is interesting to notice that they consist of the same events. It is clear that in both cases the same events affect the engines in the same way starting with 'corr' of engine 2 and engine 3 followed by 'comp' and 'corr' of engine 1. The commonality among all three different measures is that 'corr' is still one of the top failure causes for the Power plant system.

Moreover, it is important to notice that the percentage of the all the main failure causes in all three IMs are in the range of 30% to 40%. This result designates that the identified failures and corresponding sub-systems are highly critical for the function of the Power plant system. Thus, immediate maintenance measures need to be addressed for the subject sections of this ship system which are also further investigated in the following section so as to discover the specific failure attributes of each one of the engines involved. Additionally, the IMs identified above can be additionally justified when a further analysis is performed regarding the identification of the IMs of the two main sub-systems which comprise the Power plant system (main sub-system of E/R 1 and E/R 2). In Tables 6.4-6.5 the results of their reliability IMs are shown.

Table 6.4 Birnbaum, Criticality and Fussell-Vesely IMs for E/R 1 sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	Comp 1	38.083%	26.263%	35.854%
2	Corr 1	38.083%	26.263%	35.854%
3	imtc 1	38.083%	26.263%	35.854%
4	Corr 2	21.201%	13.453%	73.344%
5	Comp 2	19.508%	62.676%	17.110%
6	imtc 2	19.508%	13.453%	17.110%
7	Corr 3	16.555%	48.942%	57.089%
8	imtc 3	15.881%	23.883%	29.042%
9	Comp 3	15.703%	17.427%	21.431%

Table 6.5 Birnbaum, Criticality and Fussell-Vesely IMs for E/R 2 sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	imtc 4	24.027%	28.886%	34.761%
2	Corr 4	24.027%	28.886%	34.761%
3	Comp 4	24.027%	28.886%	34.761%
4	Comp 5	16.638%	32.189%	37.060%
5	imtc 5	16.638%	32.189%	37.060%
6	Corr 5	16.541%	26.048%	30.165%
7	Corr 6	12.401%	36.467%	40.905%
8	imtc 6	12.354%	32.389%	36.468%
9	Comp 6	12.255%	23.709%	26.911%

As shown, according to the Birnbaum IM, ‘comp’, ‘corr’ and ‘imtc’ are the most important failure events for the E/R 1 sub-system (38.083% respectively), which at the same time are the top identified events for the overall Power plant system (see Table 6.1). In this respect, the Bir IM denotes that the ‘comp’, ‘corr’ and ‘imtc’ failure events for the E/R 1 sub-system need further improvement compared to the rest of the end-events of E/R 1. According to the Criticality IM for E/R 1, ‘comp’ of engine no 2 is the most critical failure (62.676%) followed by ‘corr’ of engine no 3 (48.942%). For the F-V IM for E/R 1, ‘corr’ of engines no 2 and no 3 are the most important ones (73.344% and 57.089% respectively). As observed, there is a difference in the initial ranking of the end-events when the Cri IM results are compared to the Bir and F-V IM ones. In this case, the Cri IM results identify which end-event is more likely to occur and at the same time is critical to the operation of E/R 1. Supplementary to the Cri IM results, the F-V IM results identify the end-events which contribute in the criticality of the operation of E/R 1 but are not initially identified as critical events by themselves. In this case, the end-events/failures pertaining to hidden mishaps of the specific system (E/R 1) are also specified, thus advancing the value of the criticality analysis performed in the present study.

In addition to the above, the reliability IMs for the main sub-system of E/R 2 (Table 6.5.) also demonstrates the correlation among the IMs of E/R 2 and the Power plant system. According to this, Engine no 4 is the most important one of all according to the Bir IM (IM values of 24.027%) while 'corr' and 'imtc' of engine no 6 and 'comp' and 'imtc' for engine no 5 are the three most critical according to the Cri and F-V IMs. For the same reasons as mentioned above, it is also observed that there is a difference in the results of the reliability IMs when identifying the most critical end-events for E/R 2, which is explained by the very definition of each IM. At this point it should be also mentioned that this part of the analysis will further assist the present study when additional maintenance measures will be suggested so as to overcome the identified critical events by introducing 'SPARE' gates and events in the FT structure.

6.3.3 Cut set results for the Power plant system

At first, the cut set results of the Power plant system are shown in Table 6.6 followed by the cut sets of the E/R 1 and E/R 2 sub-systems in Tables 6.7-6.8. In them, the cut set events are mentioned starting from the most likely to occur as well as its order showing the number of events participating in the specific cut set.

Table 6.6 Cut set results for the Power plant system (10 out of 54)

##	Cut set events	Order	PoOcc
1	Comp 1, Corr 2, Corr 3	3	1.904%
2	Corr 1, Corr 2, Corr 3	3	1.904%
3	imtc 1, Corr 2, Corr 3	3	1.904%
4	imtc 1, imtc 3, Corr 2	3	0.969%
5	Corr 1, imtc 3, Corr 2	3	0.969%
6	Comp 1, imtc 3, Corr 2	3	0.969%
7	imtc 1, Comp 3, Corr 2	3	0.715%
8	Corr 1, Comp 3, Corr 2	3	0.715%
9	Comp 1, Comp 3, Corr 2	3	0.715%
10	Corr 1, imtc 2, Corr 3	3	0.444%

For the overall Power plant system, the sequence of events that influence the reliability of this system to a higher degree than the others is the component failure of engine no 1 and corrosion of engine no 2 and engine no 3. The next most influential set of events is the one comprising the corrosion failure of engines no 1, no 2 and no 3. The third cut set path in Table 6.6 is the inappropriate maintenance of engine no 1, corrosion of engine no 2 and engine no 3. In this way, the measures that will be presented in the next section of this Chapter focus on how to minimise this problem mentioned in the Power plant system. It should be also mentioned that the actual PoOcc values for the mentioned cut set results of the Power plant system are very low (highest values of almost 2%). This denotes that the probability of occurrence of the specific combination of cut sets is not very probable to occur. Nevertheless, it is important to be reminded that the failure as well as the identification of the criticality of the individual end-events does influence the reliability level of the top system. It is also worthwhile observing that the cut sets appearing in Table 6.6 do not include any events from E/R 2 (engines no 4, no 5 and no 6). This shows that the engines in E/R 1 is most imperative to be improved compared to the ones in E/R 2. This is due to corrosion problems identified in the operation of the specific engines of "*DSV A*", which also influence the operability of their components (e.g. valves, injectors, sealing and rings). This is more obvious when examining separately the cut sets of E/R 1 and E/R 2 shown in Tables 6.7-6.8.

Table 6.7 Cut set results for the E/R 1 sub-system (10 out of 27)

##	Cut set events	Order	PoOcc
1	Comp 1, Corr 2, Corr 3	3	1.904%
2	Corr 1, Corr 2, Corr 3	3	1.904%
3	imtc 1, Corr 2, Corr 3	3	1.904%
4	imtc 1, imtc 3, Corr 2	3	0.969%
5	Corr 1, imtc 3, Corr 2	3	0.969%
6	Comp 1, imtc 3, Corr 2	3	0.969%
7	imtc 1, Comp 3, Corr 2	3	0.715%
8	Corr 1, Comp 3, Corr 2	3	0.715%
9	Comp 1, Comp 3, Corr 2	3	0.715%
10	Comp 1, imtc 2, Corr 3	3	0.444%

As mentioned before for the overall Power plant system, corrosion is one of the major problems of E/R 1 (first set of Comp 1, Corr 2, Corr 3 followed by the second cut set of Corr 1, Corr 2, Corr 3 and the third most important one of imtc 1, Corr 2, Corr 3).

Table 6.8 Cut set results for the E/R 2 sub-system

##	Cut set events	Order	PoOcc
1	imtc 4, imtc 5, Corr 6	3	0.408%
2	imtc 4, Comp 5, Corr 6	3	0.408%
3	Corr 4, imtc 5, Corr 6	3	0.408%
4	Corr 4, Comp 5, Corr 6	3	0.408%
5	Comp 4, imtc 5, Corr 6	3	0.408%
6	Comp 4, Comp 5, Corr 6	3	0.408%
7	imtc 4, imtc 5, imtc 6	3	0.364%
8	imtc 4, Comp 5, imtc 6	3	0.364%
9	Corr 4, imtc 5, imtc 6	3	0.364%
10	Corr 4, Comp 5, imtc 6	3	0.364%

In the case of E/R 2 sub-system the first three cut sets identified mostly concern corrosion issues in engine no 6 (first set of imtc 4, imtc 5, Corr 6, second cut set of imtc 4, comp 5, Corr 6 and third one of Corr 4, imtc 5, Corr 6). Inappropriate maintenance (imtc) of engine no 4 and component failure (comp) of engine no 5 are also among the top failure causes for the sub-system of E/R 2.

So far, the identification of the most critical items of the Power plant system has been carried out by employing the different reliability IMs (Bir, Cri and F-V) as well as the cut sets estimation. What follows next is to suggest maintenance measures which will enhance the quality and reliability results of the main system. This is achieved with the introduction of 'SPARE' gates, as is shown in the next section.

6.3.4 'SPARE' gates – Discussion and suggestions for the Power plant system

As presented in the previous sections §6.3.1-6.3.3 of Chapter 6, the Power plant system displayed overall low reliability results as well as its sub-systems (i.e. E/R 1 and E/R 2) after a short period of operation time. In order to examine the exact reasons for this behaviour, reliability IMs as well as minimal cut sets have been deployed. In this respect, the most critical items/components, failure causes and maintenance measures identified for E/R 1 and E/R 2 respectively are shown in Figure 6.4.

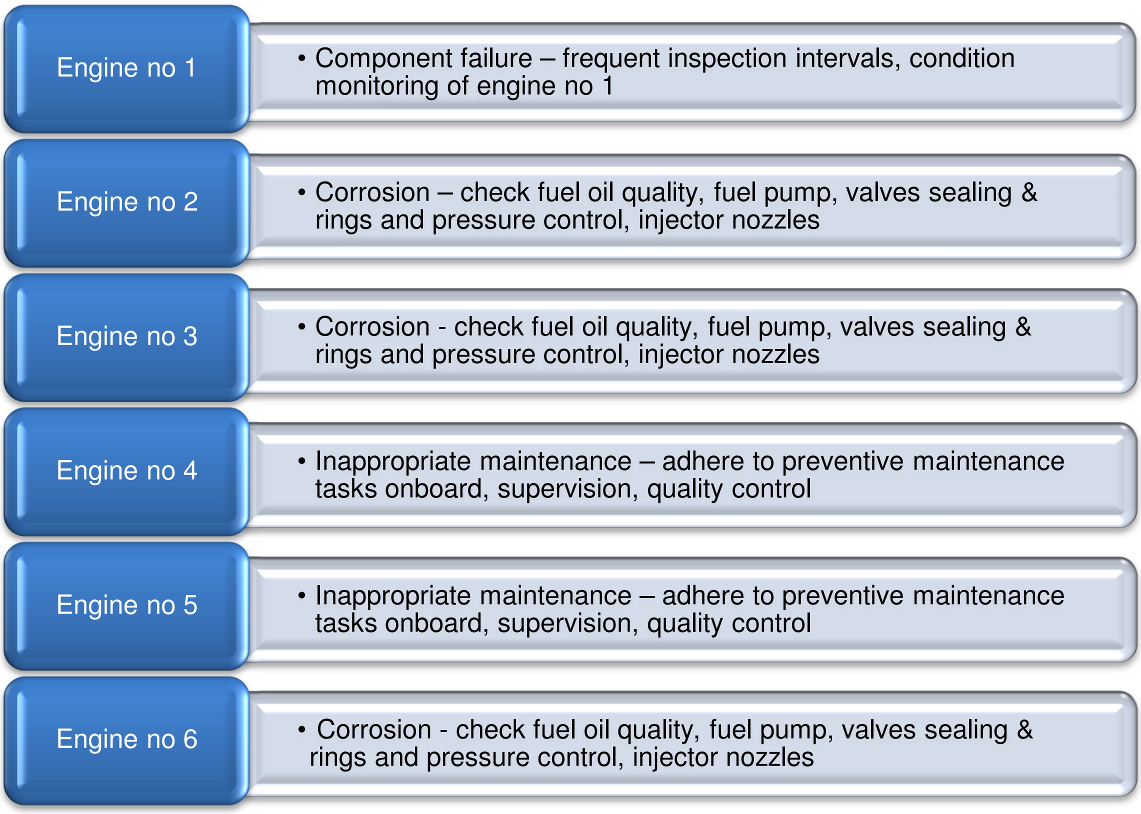

Figure 6.4 Most critical items/components, failure causes and maintenance measures suggested for the Power plant system

Regarding E/R 1, the most critical items identified are ‘component failure’ for engine no 1 as well as ‘corrosion’ for engine no 2 and no 3. With respect to ‘component failure’ (pre-lubricating oil pump electric motor failure), an initial step towards enhancing the condition of engines no 1 and no 2 is the prioritisation of the maintenance intervals for the electric motor carried out by the crew onboard the vessel as well as advise for inspections according to the preventive maintenance plan in order to address this cause of failure. Based on the results of the inspection plan, further investigation may be needed by means of condition monitoring equipment either in a regular/interval basis (sub-contractors involved to examine the root causes of component failure) or monitoring equipment permanently installed so as to obtain continuous monitoring of the components in place. The above may also include the combination of crew training courses so as to achieve the full benefits of condition monitoring techniques. Additionally, the supply of hand-held condition monitoring equipment (e.g. infrared cameras, ultrasonic equipment for vibration monitoring) for regular use during the daily routine operations of the ship can be suggested although an initial capital expenditure should be also expected. For engines no 2 and no 3 (‘corrosion’ failure), this can be dealt with by further inspection in terms of a number of potential causes which contribute to this defect. As a first level, an initial measure should be to check the fuel oil quality by using fuel oil additives to improve fuel oil dispersion. At a second level, checking of the relevant machinery parts used such as the fuel pump (check pressure on fuel pump to see if there are any gas leaks or improper sealing of the valves and rings) or the fuel injectors (malfunctioning of the injector nozzle) to identify and rectify any anomalies presented.

In the case of E/R 2, 'inappropriate maintenance' is the dominant failure cause for engines no 4 and no 5. In this case, it is more than evident that the maintenance effort which is directed towards the subject engines is inadequate. Bearing this in mind, the maintenance sequence suggested can be subject to two different levels of measures. The first one includes the marine crew onboard the ship and the ordinary preventive maintenance tasks they carry out on a routine basis during which more specific instructions and training from the company's side are needed to ensure timely and appropriate/high quality maintenance and repair works. In the specific case of E/R 2, the increase in the PoF for the subject engines only after a few months of operation urges the employment of further close monitoring of the condition of the engines and if deemed necessary, immediate corrective actions to be taken. At a second level, in the case that no direct maintenance tasks are required, maintenance and repair works may be performed by an external subcontracted maintenance crew during a regular dry-docking period or Special/Intermediate survey. In this case, a supervision team from the company's side including active involvement of a superintendent engineer and/or other engineering crew members (i.e. Chief Engineer, 2nd Engineer) may be appointed to ensure that the repair and maintenance works are carried out according to the quality and technical specification details and procedures of the company, especially during maintenance works taking place in the dry-dock during the Intermediate and Special Surveys of the vessel. In terms of the 'corrosion' issues for engine no 6, the alternative maintenance sequence should include measures similar to the ones applied for engine no 3. In this respect, checking of the fuel oil quality is an initial measure which can be followed by more frequent inspections regarding the relevant machinery equipment and components (e.g. sealing rings, fuel injectors and valves).

Having the above in mind, 'SPARE' gates are introduced in the DFT structure, which represent the additional maintenance measures mentioned before in order to enhance the reliability results of the system examined. All the above suggestions are demonstrated in terms of the comparison of the reliability results before and after the application of 'SPARE' gates for the Power plant system overall as well as for the relevant sub-systems, that is E/R 1 and E/R 2 (Figures 6.5-6.7).

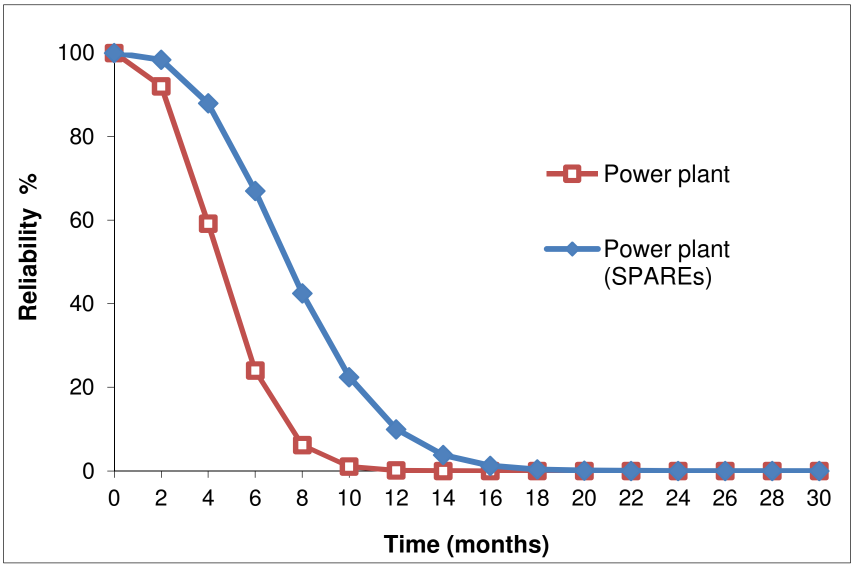

Figure 6.5 Comparison of reliability results of Power Plant system before and after the introduction of 'SPARE' gates

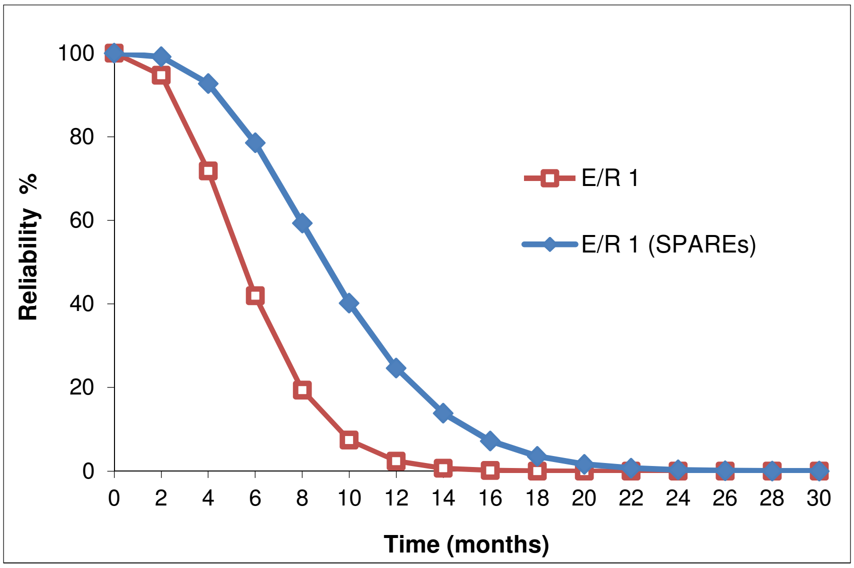

Figure 6.6 Comparison of reliability results of E/R 1sub-system before and after the introduction of 'SPARE' gates

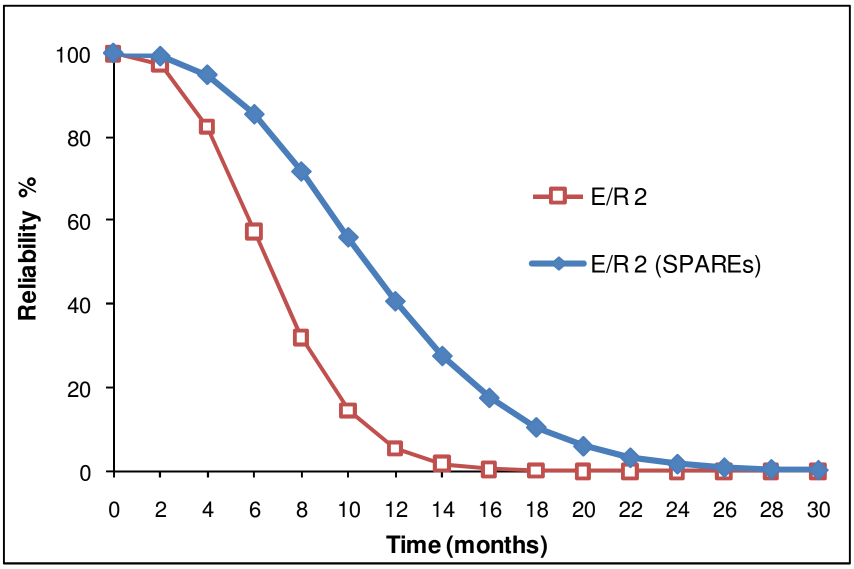

Figure 6.7 Comparison of reliability results of E/R 2 sub-system before and after the introduction of 'SPARE' gates

As is observed, the reliability results for all three systems examined are improved after the introduction of 'SPARE' gates. In more detail, the reliability of the overall Power plant system has increased its high reliability capacity to five months of operation. Moreover, regarding E/R 1 and E/R 2, their reliability results also retain a high operational level of 90% from an initial three month time up to seven months after the introduction of 'SPARE' gates and events. As observed, the improvement in the results after the use of 'SPARE' gates is not as high as expected. However, the Power plant system is maintained to very high standards due to the continuous efforts of the company and the crew onboard (the actual downtime of the overall system is estimated as just a few days per year). Nonetheless, the reliability and criticality analysis carried out in this study has demonstrated the areas and components that are critical for the operation of the Power plant system as well as measures which can preserve and moreover enhance its operational profile by minimising further critical failures. Overall it can be concluded from the above analysis that the Power plant system is identified a critical system for the operation of *"DSV A"*, thus necessitating maintenance measures implemented according to the criticality based maintenance strategy suggested before. Bearing the above in mind, the reliability calculation results for the Propulsion system are presented next.

6.4 Reliability calculation results for the Propulsion system

In this section, the reliability calculation results for the Propulsion system of *"DSV A"* are presented. As mentioned in section §5.3, the Propulsion system is responsible for the main propulsion needs of the vessel as well as for its initial and constant positioning at a certain sea area in which diving and other underwater works are carried out.

6.4.1 Reliability results for the Propulsion system

The reliability results of the main Propulsion system as well as for the Azimuth thrusters and Tunnel thrusters' sub-systems are shown in Figures 6.8 and 6.9.

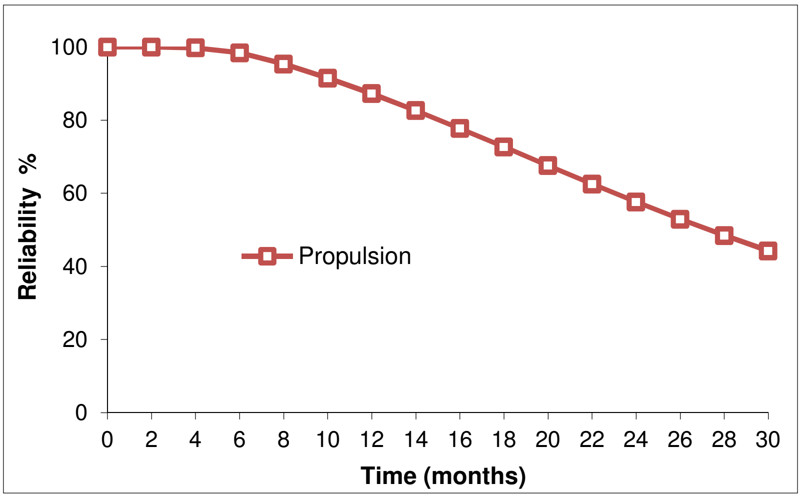

Figure 6.8 Reliability results for the Propulsion system

As shown, the reliability of the entire system maintains a 90% reliability level after 10 months of operation and then decreases to 40% at the end of the simulation time of 30 months ($2^{1/2}$ years) of operation. Compared with the Power plant system, the Propulsion system demonstrates much healthier reliability behaviour. This is also better demonstrated when examining the PoF of its sub-systems; that is the azimuth and tunnel thrusters' sub-systems shown in Figure 6.9.

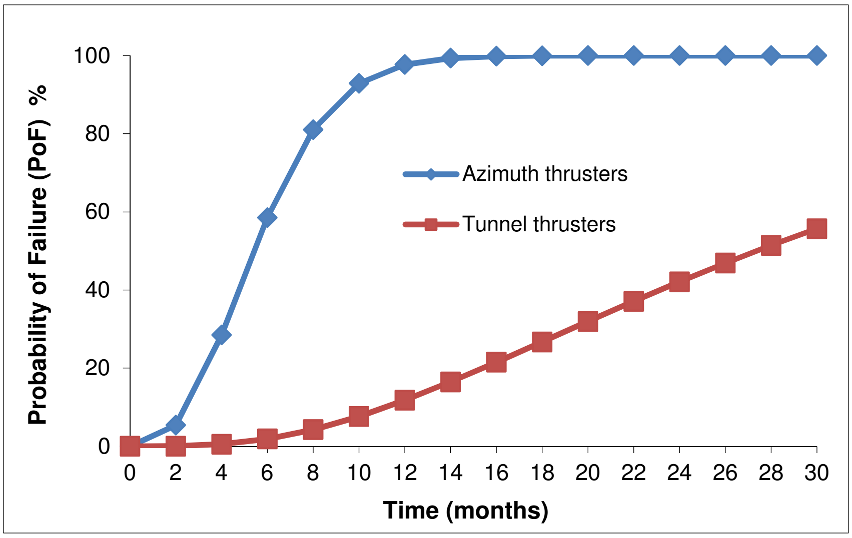

Figure 6.9 Probability of failure results for the sub-systems of azimuth and tunnel thrusters

Regarding the azimuth thrusters, the PoF pattern increases exponentially in the first few months of simulation time (0-8 months) while after that it gets stabilised and is almost constant for the rest of the simulation time. On the contrary, in the case of the sub-system of the tunnel thrusters, the PoF presents much better results until a time point of 14 months (PoF 20%). After that point, it increases gradually and reaches a maximum value (PoF 60%) at the end of the 30 month period. Once more, it should be noted that the crew on board the vessel carries out corrective maintenance so as to preserve the good operational condition of the propulsion system whilst it must also be appreciated that at this stage the increased PoF of the two sub-systems do not necessitate the vessel to dry-dock or undertake major corrective action. Additionally, in order to examine the specific failure causes for the subject systems, the reliability IMs and cut set results are employed as shown next.

6.4.2 Reliability IMs results for the Propulsion system

In this section, the results of the reliability IMs for the Propulsion system as well as for the sub-systems of the azimuth thrusters and tunnel thrusters are shown (Tables 6.9-6.11).

Table 6.9 Birnbaum IM for the Propulsion system

##	Event	Birnbaum	##	Event	Birnbaum
1	fwt bow thr 2	0.033%	9	fwt pitch pp	0.007%
2	fwt bow thr 3	0.027%	10	comp pitch pp	0.007%
3	fwt bow thr1	0.023%	11	comp azi thr3	0.006%
4	comp az thr 2	0.014%	12	ilub az thr 3	0.006%
5	fwt az thr 2	0.014%	13	fwt az thr 3	0.006%
6	ilub az thr 2	0.014%	14	fwt az thr 1	0.006%
7	matf pitch pp	0.007%	15	comp az thr 1	0.006%
8	mecd pitch pp	0.007%	16	ilub az thr 1	0.005%

Table 6.10 Criticality IM for the Propulsion system

##	Event	Criticality	##	Event	Criticality
1	fwt bow thr1	100.000%	9	ilub az thr 2	31.567%
2	fwt bow thr 3	100.000%	10	fwt az thr 1	27.807%
3	fwt bow thr 2	100.000%	11	fwt az thr 3	21.920%
4	comp azi thr3	62.436%	12	fwt pitch pp	21.870%
5	comp az thr 1	57.662%	13	matf pitch pp	16.583%
6	comp pitch pp	41.945%	14	mecd pitch pp	16.583%
7	comp az thr 2	31.567%	15	ilub az thr 3	13.443%
8	fwt az thr 2	31.567%	16	ilub az thr 1	12.426%

Table 6.11 Fussell-Vesely IM for the Propulsion system

##	Event	Fussell-Vesely	##	Event	Fussell-Vesely
1	fwt bow thr1	101.102%	9	ilub az thr 2	33.701%
2	fwt bow thr 3	101.102%	10	fwt az thr 1	28.820%
3	fwt bow thr 2	101.102%	11	fwt pitch pp	22.836%
4	comp azi thr3	64.313%	12	fwt az thr 3	22.787%
5	comp az thr 1	59.359%	13	matf pitch pp	17.336%
6	comp pitch pp	43.595%	14	mecd pitch pp	17.336%
7	comp az thr 2	33.701%	15	ilub az thr 3	14.002%
8	fwt az thr 2	33.701%	16	ilub az thr 1	12.924%

As can be seen in the case of the Bir IM, the 'fwt' of bow thrusters no 2, no 3 and no 1 are the predominant failure events that need to be rectified followed by 'comp', 'fwt' and 'ilub' of azimuth thruster no 2. 'Fwt' denotes the wear and tear of motors, valves or efficiency losses of the bow thrusters while 'matf' includes the defective component breakdown that might occur during the operation of the ship. By 'comp' the failure of internal parts, bolts and nuts is indicated whilst 'ilub' refers to insufficient lubrication, meaning that a leak may be present in azimuth thruster no 2 which consumes more lube oil per unit than required. For the Cri and F-V IMs of the Propulsion system, the 'fwt' of bow thrusters no1, no 3 and no 2 are the most significant and are more likely to occur in the first place. The similarity in the ranking of the different events for both the Cri and F-V IMs can be explained as both these IMs have similar way of estimating the most critical equipment in a FT structure as explained in the methodology Chapter (Chapter 4).

Moreover, as observed in Tables 6.9-6.11 regarding the exact values of the different IMs, the Bir IM presents very low results (in the range of 0.033%) while on the contrary the Cri and F-V IMs show much higher ones (in the range of 10% to100%). This is due to the specific nature of the different IMs as explained in section §4.5.2.3. In other words, the Bir IM shows how much the improvement of each specific end-event may contribute to the escalation of the reliability of the overall Propulsion system. Since the Bir results are very low (almost zero), the occurrence of the specific individual failures will not influence the failure of the Propulsion system. Nevertheless, in this case it is more suitable to investigate the Cri and F-V IMs which both assist by estimating the components that are more critical for the specific system as well as the ones that are more likely to occur and contribute to the failure of the overall system. More details about the most important components of the azimuth and tunnel thrusters are shown in Tables 6.12-6.13.

Table 6.12 Birnbaum, Criticality and Fussell-Vesely IMs for the azimuth thrusters' sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	ilub az thr 2	23.317%	29.643%	34.205%
2	comp az thr 2	23.317%	29.643%	34.205%
3	fwt az thr 2	23.317%	29.643%	34.205%
4	comp azi thr3	10.446%	60.997%	65.276%
5	fwt az thr 3	10.209%	21.122%	23.129%
6	ilub az thr 3	10.159%	12.916%	14.212%
7	comp az thr 1	9.655%	56.380%	60.248%
8	fwt az thr 1	9.494%	26.915%	29.251%
9	ilub az thr 1	9.411%	11.964%	13.117%

Table 6.13 Birnbaum, Criticality and Fussell-Vesely IMs for the tunnel thrusters' sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	fwt bow thr 2	0.523%	100.000%	115.390%
2	fwt bow thr 3	0.423%	100.000%	115.390%
3	fwt bow thr1	0.356%	100.000%	115.390%
4	comp pitch pp	0.107%	39.205%	49.756%
5	fwt pitch pp	0.098%	18.669%	26.063%
6	mecd pitch pp	0.095%	13.839%	19.786%
7	matf pitch pp	0.095%	13.839%	19.786%

As can be observed for the azimuth thrusters' sub-system, the Bir IM shows that the azimuth thruster no 2 is the most important one with failure causes of 'ilub', 'comp' and 'fwt' being highly ranked followed by the azimuth thruster no 3. The same events are less important for the Cri and F-V IMs as the 'comp' of azimuth thruster no 3 and no 1 are the predominant ones (about 60% and 56% respectively for the Cri IM and 65% and 60% for the F-V IM). Regarding the tunnel thrusters' sub-system, 'fwt' of thrusters no 2, no 3 and no 1 are the most significant and need to be dealt with more attention followed by the pitch pump of the power-packs according to all three of the IMs. This accordance reflects that the 'fwt' of the bow thrusters is the most significant event in terms of both needing improvement compared to the other events, criticality significance for the sub-system and also contributes more to the failure of the bow thrusters sub-system. It should be also noted the 'not logical' importance figures of more than 100% for the F-V IM are present due to the calculation method employed for this specific IM (using cut sets) which at some point may show results higher than 100%.

6.4.3 Cut set results for the Propulsion system

Regarding the Propulsion system, its cut set results are shown in Table 6.14 followed by the ones of its sub-systems, the azimuth and tunnel thrusters (Tables 6.15-6.16). The cut sets of the Propulsion system are of the seventh order, meaning that seven events participate in each cut set.

The minimal cut set for this system (which is the top ranked cut set of this list) is a combination of events from both the azimuth and tunnel thrusters and more specifically the component failure and fair, wear and tear of the thrusters (minimal cut set of comp az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, comp pitch pp, comp azi thr3, comp az thr 1). That means that these failure events need to be addressed first with proper maintenance measures in order to observe better reliability results for the entire system. As observed, the PoOcc figures are very low (almost zero). This means that although the specific sequence of end-events is most probable to occur compared to the rest of the combinations of the various end-events for the specific system (Propulsion system), it is however not so important to happen overall. In other words, the Propulsion system is reliable enough to carry out its functions and the maintenance strategy implemented by the shipping company is robust enough to ensure such operations.

Table 6.14 Cut set results for the Propulsion system (10 out of 108)

##	Cut set events	Order	PoOcc
1	comp az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, comp pitch pp, comp azi thr3, comp az thr 1	7	0.00020%
2	fwt az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, comp pitch pp, comp azi thr3, comp az thr 1	7	0.00020%
3	ilub az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, comp pitch pp, comp azi thr3, comp az thr 1	7	0.00020%
4	ilub az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, fwt pitch pp, comp azi thr3, comp az thr 1	7	0.00010%
5	comp az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, fwt pitch pp, comp azi thr3, comp az thr 1	7	0.00010%
6	fwt az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, fwt pitch pp, comp azi thr3, comp az thr 1	7	0.00010%
7	comp az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, fwt az thr 1, comp pitch pp, comp azi thr3	7	0.00010%
8	fwt az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, fwt az thr 1, comp pitch pp, comp azi thr3	7	0.00010%
9	ilub az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, fwt az thr 1, comp pitch pp, comp azi thr3	7	0.00010%
10	fwt az thr 2, fwt bow thr1, fwt bow thr 2, fwt bow thr 3, matf pitch pp, comp azi thr3, comp az thr 1	7	0.00010%

Table 6.15 Cut set results for the azimuth thrusters' sub-system (10 out of 27)

##	Cut set events	Order	PoOcc
1	comp az thr 2, comp azi thr3, comp az thr 1	3	0.694%
2	fwt az thr 2, comp azi thr3, comp az thr 1	3	0.694%
3	ilub az thr 2, comp azi thr3, comp az thr 1	3	0.694%
4	ilub az thr 2, fwt az thr 1, comp azi thr3	3	0.337%
5	comp az thr 2, fwt az thr 1, comp azi thr3	3	0.337%
6	fwt az thr 2, fwt az thr 1, comp azi thr3	3	0.337%
7	ilub az thr 2, fwt az thr 3, comp az thr 1	3	0.246%
8	comp az thr 2, fwt az thr 3, comp az thr 1	3	0.246%
9	fwt az thr 2, fwt az thr 3, comp az thr 1	3	0.246%
10	ilub az thr 1, fwt az thr 2, comp azi thr3	3	0.151%

For the azimuth thrusters' sub-system, a combination of the component failure (comp) of the three azimuth thrusters is the top ranked cut set while the same failure cause also participates in two out of three events for the second most important cut set (fwt az thr 2, comp azi thr3, comp az thr 1). These results also agree with the cut set results of the overall Propulsion system. This is where the maintenance efforts need to be focused in order to improve the reliability results of this sub-system.

Table 6.16 Cut set results for the tunnel thrusters' sub-system

##	Cut set events	Order	PoOcc
1	fwt bow thr1, fwt bow thr 2, fwt bow thr 3, comp pitch pp	4	0.024%
2	fwt bow thr1, fwt bow thr 2, fwt bow thr 3, fwt pitch pp	4	0.012%
3	fwt bow thr1, fwt bow thr 2, fwt bow thr 3, matf pitch pp	4	0.009%
4	fwt bow thr1, fwt bow thr 2, fwt bow thr 3, mecd pitch pp	4	0.009%

For the tunnel thrusters' sub-system, the cut set order is four which means that four events participate in the cut set structure. The minimal cut set in this case comprises the 'fair, wear and tear' (fwt) of bow thrusters 1-3 with the addition of the 'component failure' of the pitch pump. This ranking also agrees with the cut set results of the main Propulsion system and signifies the importance of the specific failure events on the specific components of this system, which will be further addressed in the next section with the introduction of 'SPARE' gates. Moreover, as observed in both Tables 6.15 and 6.16, the values of the cut set events are very low (in the range of 0.02%), which agrees and moreover verifies the very low PoOcc for the subject sub-systems in comparison to the main Propulsion system. In this respect, it is obvious that the azimuth and tunnel thrusters perform satisfactorily and that the shipping company preserves these systems in very good functional condition for the operation of the vessel.

6.4.4 'SPARE' gates – Discussion and suggestions for the Propulsion system

As described in the sections §6.4.1-6.4.3 of this Chapter, the results regarding the reliability of the Propulsion system have led to the identification of the most critical components and failure causes for the subject system respectively. The above together with the maintenance measures suggested for the enhancement of the reliability results of the Propulsion system are summarised in Figure 6.10.

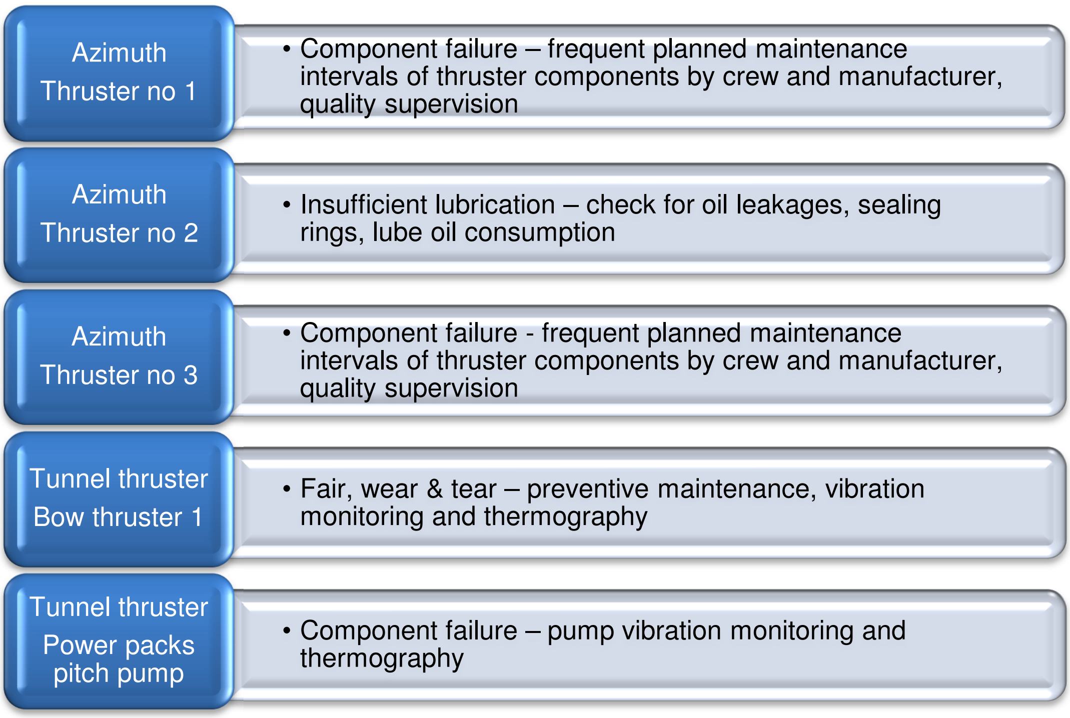

Figure 6.10 Most critical items/components, failure causes and maintenance measures suggested for the Propulsion system

Regarding the azimuth thrusters sub-system, the predominant failure cause is the 'component failure' for azimuth thrusters no 1 and no 3. In this case, the failures of the specific thrusters are identified as the failure of the coupling of the pump which can be dealt with careful and more frequent inspections based on a scheduled maintenance routine so as to prevent excessive breakdowns in the components of thrusters no 1 and no 3. For azimuth thruster no 2, 'insufficient lubrication' needs to be further investigated so as to determine the specific initiating failure events. Examples of these may refer to local leakage of lube oil, not appropriate or sufficient sealing rings used, lube oil consumption per unit more than explicitly needed.

For the tunnel thrusters sub-system, the most critical item identified is bow thruster no 1 and more specifically ordinary 'fair, wear & tear'. In this case, there are also two levels at which maintenance measures can improve the condition of the specific bow thruster. Initially, a stringent visual inspection may be carried out by the crew of the ship more regularly in order to investigate any usual anomalies in the operation of the bow thruster and its machinery as well as carry out regular internal cleaning and inspection. Next, more thorough checks can be performed by employing more sophisticated tools such as condition monitoring systems including vibration monitoring, thermography, etc. At this point it should be mentioned that the tools used for checking the condition of the thruster will not solve any failures by themselves as efficient utilisation of the measurements/data collected, it also requires training of the crew for effective application of these techniques so that appropriate maintenance action and schedule can be adopted. This requires the commitment of the top management for initial capital expenditure and a preparatory period in order to achieve the desired results.

In the case of the 'component failure' of the power packs pitch pump, similar measures as mentioned before in the case of the azimuth thrusters can be also implemented. More specifically, additional inspection may be carried out by competent engineers and spare parts that may be to address this issue. The extent of the inspection performed can be addressed by the marine crew onboard the vessel. In terms of more extended and complicated maintenance tasks needed a maintenance sub-contractor or even specialised technicians from the manufacturer's side may intervene to rectify the failures identified before.

Moreover, having identified the most critical end-events in the DFT for the Propulsion system, 'SPARE' gates are introduced in order to simulate the additional measures suggested as part of the maintenance strategy developed herein. The results of these measures with regards to the improvement of the reliability index of the Propulsion system are presented in Figure 6.11 along with the comparison to the previous condition of the same system.

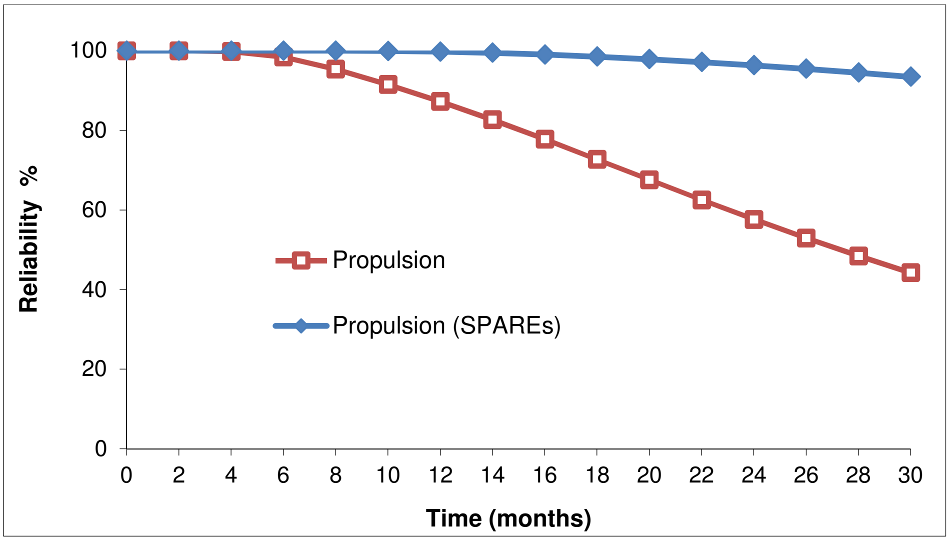

Figure 6.11 Comparison of reliability results of Propulsion system before and after the introduction of 'SPARE' gates

The 'SPARE' gates introduced represent the improvement in the 'component failure' azimuth thrusters no 1 and no 3 as well as the 'insufficient lubrication' of azimuth thrusters no 2. Regarding the tunnel thrusters' sub-system, 'SPARE' gates include remedial maintenance measures in terms of the 'fair, wear and tear' of bow thruster no 1. The 'SPARE' gates for the 'component failure' of the azimuth thrusters consider the additional checks carried out by competent engineers and spare parts that can be used to address this issue. Regarding the 'SPARE' gates for the tunnel thrusters, they refer to the use of a condition monitoring system (i.e. vibration monitoring, thermography, etc.). As can be seen, there is a significant improvement in the reliability results of the Propulsion system. By addressing the main failure causes as identified from the reliability and criticality analysis, the Propulsion system retains good reliability performance (above 90%) for almost the entire period examined (30 months). This means that the Propulsion system is able to operate sufficiently within the operating period between two consecutive dry-dockings as part of the Class Society guidelines that the vessel is registered with.

6.5 Reliability calculation results for the Lifting, Anchoring & Hauling (LA&H) system

In this section, the reliability calculation results for the Lifting, Anchoring & Hauling system of *"DSV A"* are presented next. As mentioned in section §5.3.4, the LA&H systems consists of two sub-systems: the Heavy and Light cranes respectively which are responsible for the overall lifting functions of the subject vessel.

6.5.1 Reliability results for the Lifting, Anchoring & Hauling system

In this section of the thesis, the reliability results of the Lifting, Anchoring & Hauling system are shown in Figure 6.12 while the PoF results of the sub-systems of Heavy cranes and Light cranes are presented in Figure 6.13.

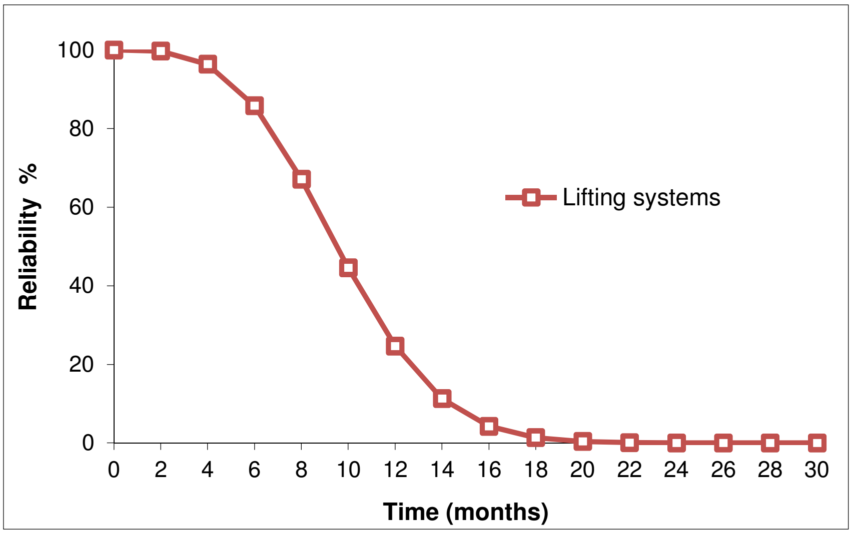

Figure 6.12 Reliability results for the Lifting, Anchoring & Hauling system

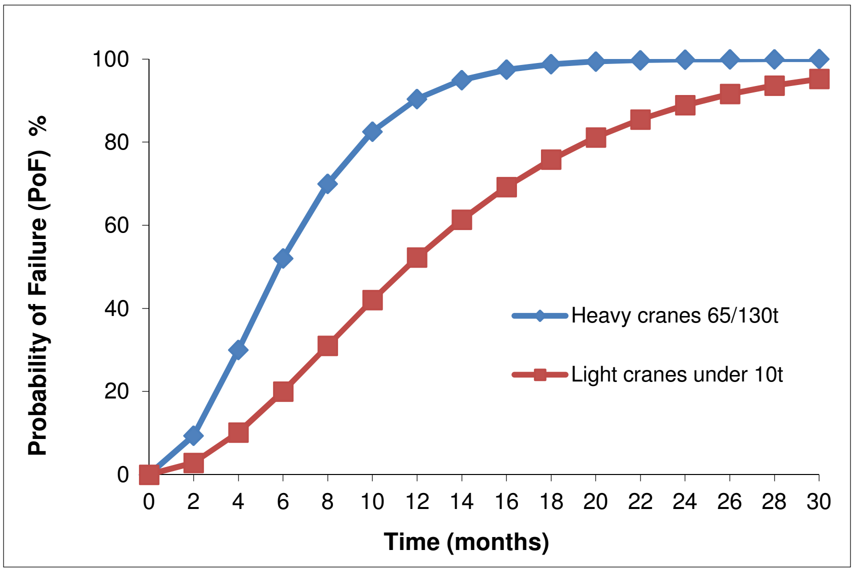

Figure 6.13 Probability of failure results for the sub-systems of Heavy and Light cranes

As may be seen in Figure 6.12, the reliability of the Lifting, Anchoring & Hauling system starts deteriorating after a few months of its operation and reaches the minimum value after 18 months of operation. For the sub-system of heavy cranes (Figure 6.13)., the PoF results show good performance of the heavy cranes up to 3 months (PoF 10%) and then their overall performance starts getting worse till they reach the minimum value after 14 months. In continuation to the above, the PoF of the light cranes sub-system achieves better results (PoF 10% after 5 months) and in contrast to the heavy cranes sub-system, it reaches the minimum value at the end of the simulation time (30 months). Considering the results of the two sub-systems above, it is obvious that the heavy duty cranes need further investigation in order to trace the most critical events which affect its reliability and consequently the reliability of the overall Lifting, Anchoring & Hauling system. This is performed by investigating the results for the reliability IMs as shown in the next section.

6.5.2 Reliability IMs results for the Lifting, Anchoring & Hauling system

In this section, the reliability IM results for the Lifting, Anchoring & Hauling system are shown in Tables 6.17-6.19. Then the results for the sub-systems of the heavy duty cranes (65/130 tons) and light duty cranes (10 tons) are presented next (Tables 6.20-6.21).

Table 6.17 Birnbaum IM for the Lifting, Anchoring & Hauling system

##	Event	Birnbaum	##	Event	Birnbaum
1	mecd light crane A	5.298%	6	corr main crane A	2.931%
2	fwt light crane A	5.289%	7	cont main crane A	2.929%
3	fwt light crane B	4.706%	8	matf main crane B	2.580%
4	mecd light crane B	4.692%	9	corr main crane B	2.574%
5	matf main crane A	2.937%	10	cont main crane B	2.574%

Table 6.18 Criticality IM for the Lifting, Anchoring & Hauling system

##	Event	Criticality	##	Event	Criticality
1	fwt light crane B	60.375%	6	mecd light crane B	37.406%
2	mecd light crane A	55.319%	7	corr main crane A	30.609%
3	matf main crane B	44.856%	8	corr main crane B	26.880%
4	matf main crane A	44.498%	9	cont main crane B	26.880%
5	fwt light crane A	42.161%	10	cont main crane A	23.346%

Table 6.19 Fussell-Vesely IM for the Lifting, Anchoring & Hauling system

##	Event	Fussell-Vesely	##	Event	Fussell-Vesely
1	fwt light crane B	62.056%	6	mecd light crane B	38.563%
2	mecd light crane A	57.058%	7	corr main crane A	31.300%
3	matf main crane B	45.709%	8	corr main crane B	27.455%
4	matf main crane A	45.422%	9	cont main crane B	27.455%
5	fwt light crane A	43.561%	10	cont main crane A	23.896%

As is obvious from Tables 6.17-6.19, ‘mecd’ and ‘fwt’ of light crane A and light crane B are the most important for the Lifting, Anchoring & Hauling system according to the Bir IM. The Cri and F-V IMs present the same ranking for the ranking of the top events (‘fwt’ of light crane B, ‘mecd’ of light crane A, ‘matf’ of main crane B and ‘matf’ of main crane A). In this case, ‘mecd’ refers to damaging of crane A from overloading while ‘fwt’ is related to the usual deterioration of the this crane which means that more frequent inspections need to be performed and further investigation to be carried out so as to be more specific on the failure causes for the light cranes. On the other hand, 'matf' concerns the wire rope, winch, hydraulics or material failures of safety devices. In order to observe the condition of the heavy and light cranes more in depth, the IMs for the two sub-systems are mentioned below (Tables 6.20-6.21).

Table 6.20 Birnbaum, Criticality and Fussell-Vesely IMs for the heavy cranes (65-130 tons) sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	matf main crane A	36.874%	37.486%	49.381%
2	corr main crane A	35.788%	25.071%	34.028%
3	cont main crane A	35.236%	18.845%	25.979%
4	matf main crane B	33.036%	38.530%	49.693%
5	corr main crane B	31.785%	22.267%	29.848%
6	cont main crane B	31.785%	22.267%	29.848%

Table 6.21 Birnbaum, Criticality and Fussell-Vesely IMs for the Light cranes (10 tons) sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	mecd light crane A	24.098%	52.940%	58.004%
2	fwt light crane A	23.896%	40.078%	44.283%
3	fwt light crane B	21.514%	58.067%	63.085%
4	mecd light crane B	21.201%	35.559%	39.202%

In the case of the heavy cranes sub-system, 'matf' of crane A is the event that can be further enhanced according to Bir IM. This is followed by 'corr' and 'cont' of the same crane. 'Matf' and 'corr' are failures referring to the material failure of heavy duty crane A and the corrosion existing in the same crane. On the other hand, 'cont' refers to the oil contamination used in crane A with water or solid parts. In this case, removing the existing oil is carried out and new oil is filled in. For the Cri IM 'matf' of crane B and crane A is more critical and its improvement can add more value to the overall improvement of the heavy duty cranes sub-system. This also coincides with the F-V IM regarding the priority that the different failures should be addressed having in mind the minimisation of the contribution of individual events in the occurrence of the top event/sub-system of main cranes.

For the light cranes sub-system (Table 6.21), light crane A is more critical than light crane B with 'mecd' and 'fwt' first in the ranking index regarding the Bir IM. For the Cri and F-V IMs the most important events are the 'fwt' of light crane B and 'mecd' of light crane A.

Once again, it is important to mention that the differentiation of the results regarding the importance of the different end-events/failures of the various components may vary from IM to another IM. This is the case for the Bir and Cri and F-V IMs as they are presented for the heavy and light duty cranes. This is due to the specific definition of these reliability measures, which assist the analyst in identifying the most critical equipment/failures for the subject systems. In this regard, the Bir IM identifies the end-events which are most important compared to the rest end-events and thus can develop the reliability of the main system examined. However, this does not mean that the specific end-events are also the most serious ones for the operation of the subject systems. The latter is performed by investigating and giving more attention to the Cri and F-V IMs, which show which end-events can influence and improve most the reliability of the system under investigation. Overall it can be concluded that the most important components and failures for the mentioned heavy and light duty cranes are the ones that are identified by the high percentage values of the mentioned components as shown in Tables 6.20 and 6.21.

6.5.3 Cut set results for the Lifting, Anchoring & Hauling system

In the case of the Lifting, Anchoring & Hauling system and its sub-systems (heavy cranes 65/130 tons and light cranes of 10 tons), the cut set results are presented in Tables 6.22-6.24.

Table 6.22 Cut set results for the Lifting, Anchoring & Hauling system

##	Cut set events	Order	PoOcc
1	mecd light crane A, fwt light crane B, matf main crane A, matf main crane B	4	0.092%
2	fwt light crane A, fwt light crane B, matf main crane A, matf main crane B	4	0.070%
3	mecd light crane A, fwt light crane B, corr main crane A, matf main crane B	4	0.063%
4	mecd light crane A, mecd light crane B, matf main crane A, matf main crane B	4	0.057%
5	mecd light crane A, fwt light crane B, corr main crane B, matf main crane A	4	0.055%
6	mecd light crane A, fwt light crane B, cont main crane B, matf main crane A	4	0.055%
7	mecd light crane A, fwt light crane B, cont main crane A, matf main crane B	4	0.048%
8	fwt light crane A, fwt light crane B, corr main crane A, matf main crane B	4	0.048%
9	fwt light crane A, mecd light crane B, matf main crane A, matf main crane B	4	0.044%
10	fwt light crane A, fwt light crane B, corr main crane B, matf main crane A	4	0.042%

As shown, the material failure of the cranes as well as the fair, wear and tear is present in the top cut sets. Each cut set in this case comprises four events (4^{th} order cut set) meaning that a sequence of these four events leads to the deterioration of the reliability of the Lifting, Anchoring & Hauling system. In practical terms, the cut set results indicate the combination of specific end-events whose failure will lead to the quickest failure of the system examined thus enabling the prioritisation of the maintenance sequence. Next, the cut set results of the heavy and light cranes are shown in Tables 6.23-6.24.

Table 6.23 Cut set results for the heavy cranes (65/130 tons) sub-system

##	Cut set events	Order	PoOcc
1	matf main crane A, matf main crane B	2	4.244%
2	corr main crane A, matf main crane B	2	2.925%
3	cont main crane B, matf main crane A	2	2.549%
4	corr main crane B, matf main crane A	2	2.549%
5	cont main crane A, matf main crane B	2	2.233%
6	corr main crane A, cont main crane B	2	1.757%
7	corr main crane A, corr main crane B	2	1.757%
8	cont main crane A, cont main crane B	2	1.341%
9	cont main crane A, corr main crane B	2	1.341%

The cut set results of the heavy cranes presented in Table 6.23 above, are of the second order with material failure of the cranes being the most frequent event shown. This is followed by the corrosion failure of the heavy cranes.

Table 6.24 Cut set results for the light cranes (10 tons) sub-system

##	Cut set events	Order	PoOcc
1	mecd light crane A, fwt light crane B	2	2.158%
2	fwt light crane A, fwt light crane B	2	1.648%
3	mecd light crane A, mecd light crane B	2	1.341%
4	fwt light crane A, mecd light crane B	2	1.024%

The cut sets of the light cranes are of the second order (two events in each cut set) as well. In this case, the mechanical damage and the fair, wear and tear is the top present events showing the accordance and the influence they have on the main system. As mentioned before, the investigation of the cut set results supplements the evaluation of the most critical equipment and failures for the two sub-systems, which is achieved through the use of the reliability IMs. As a consequence, this, leads to the introduction of maintenance improvement measures in the form of SPARE gates as is shown next.

Concluding with the analysis of the PoOcc results of the cut set events, it can be seen that in all three Tables above (6.22-6.24), the values are quite low (in the range of 0.09% to 4%). This denotes that the probability of occurrence of the specific sequence of events for the subject sub-systems is very low to occur. Practically, the shipping company and the officers onboard the vessel should not consider the components and their failures stemming from these cut sets but focus more on the results of the IMs as mentioned before.

6.5.4 'SPARE' gates - Discussion and suggestions for the Lifting, Anchoring & Hauling system

Based on the above results presented in sections §6.5.1-6.5.3 of Chapter 6, the most critical items/components, failure causes and maintenance measures suggested for the Lifting, Anchoring & Hauling system are demonstrated in Figure 6.14.

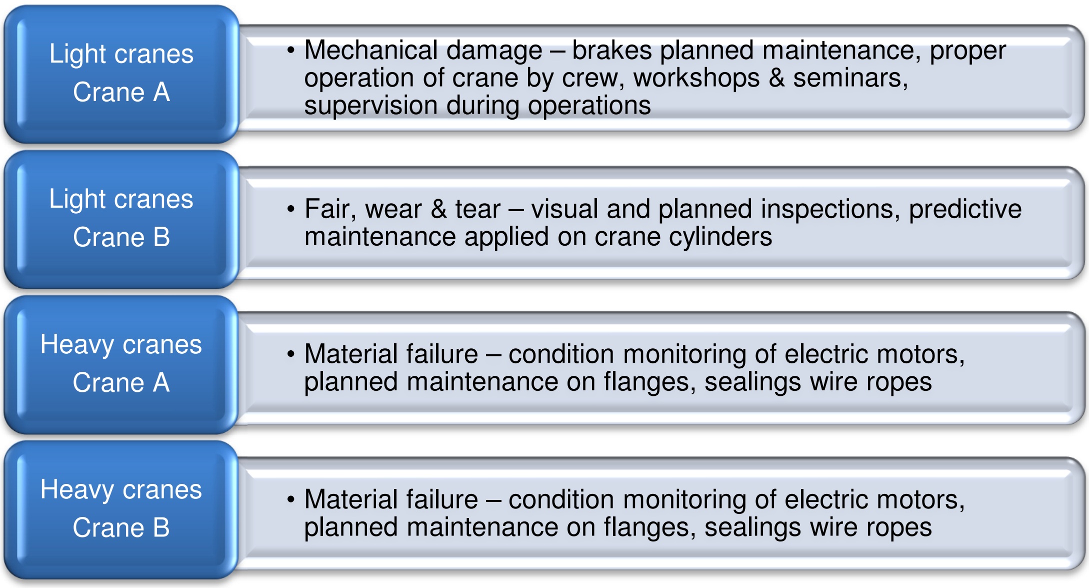

Figure 6.14 Most critical items/components, failure causes and maintenance measures suggested for the Lifting, Anchoring & Hauling system

In this case, the two main sub-systems are examined; that is the sub-system of the light cranes (10 tons) and the sub-system of the heavy cranes (65/130 tons). For the light cranes, the 'mechanical damage' of light crane A is the most critical failure and item respectively. The latter refers to the brake system of the crane, which did not function as required due to the pump failure used for controlling the brakes of the crane. Regarding the above, this can be dealt with carrying out more frequent inspection intervals for the crane and thus preventive maintenance measures implemented. This comes in addition to the feedback attained from the operator of the vessel about inappropriate use of the light duty cranes which indicates that the proper procedures for using this type of crane are not followed as per the industry and company’s guidelines and recommendations (Lifting Operations and Lifting Equipment Regulations-HSE 2010). This can be also dealt with enhanced operational performance implemented by the crew of the vessel and better use of the equipment of the light cranes. Moreover, the lifting operations engineer/superintendent onboard the vessel should address this issue in the actual daily sequence of operations. It is also suggested that the company provides seminars, workshops or additional in-house training.

In addition to the above, the second most critical item and failure cause for the case of light cranes sub-system is the ‘fair, wear and tear’ of light crane B. The ‘fwt’ can deal with a number of preventive and predictive maintenance actions. At an initial stage, regular inspection and rectification of any failure initiation signs of any part of light crane B should be performed by the maintenance crew onboard the ship so as to be able to stop any damage occurring in the first place. These tasks may include a regular visual inspection as part of the daily maintenance routine onboard the ship, proactive involvement of maintenance and repair tasks to a small extent according to the crew capabilities and subsequent reporting in the centralised maintenance database (PMS or CMMS) if further maintenance and repairs are required so as to prioritise and schedule potential repair works carried out when the vessel is alongside or in the dry-dock.

For the heavy duty cranes sub-system, both cranes A and B experience failures originating from the material degradation of their components. In this case, the heavy duty cranes are crucial for the successful operation of the vessel and the entire crane sub-system is one of the most important elements of it. In this respect, it is not unusual that the main cranes suffer from material failure in some of their components (e.g. electric motor failure, leaking flanges of the hydraulic system of the crane, wire rope erratic operation). In this respect, condition monitoring equipment can be installed to observe the condition of items such as wire ropes, winches and load sensors on a daily basis. The degradation of the heavy duty cranes can be dealt with more frequent inspections (preventive maintenance implemented). Another measure that can be implemented is by using either destructive (wire rope testing) or non-destructive techniques (ultrasonic measurements) in order to enhance the operation of both cranes. The above are introduced in the form of ‘SPARE’ gates as shown next (Figure 6.15).

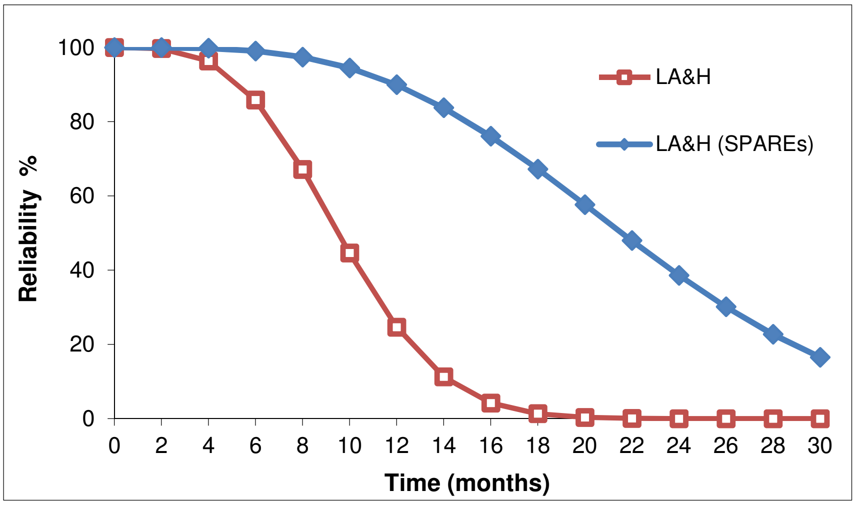

Figure 6.15 Comparison of reliability results of the LA&H system before and after the introduction of 'SPARE' gates

In this case, the 'SPARE' gates for the light cranes address the 'fair, wear and tear' of light crane B and the 'mechanical damage' of light crane A. As already mentioned, the 'fwt' can be dealt with condition monitoring measures suggested before in addition to the correct use of equipment and training of crew. The 'mecd' can be dealt with better operational performance from the side of the operators of the respective cranes and better use of the mentioned equipment. For the heavy cranes the 'SPARE' gates concentrate on changes in the 'material failure' of both cranes B and A. As is also observed, with the implementation of such maintenance actions, the reliability of the system is increased significantly from 5 months of good operational results up to 12 months of high operation profile. The LH&A system also retains its performance in higher results than in the previous operating condition overall (80% reliability after 15 months in comparison to very low reliability levels in the previous condition).

6.6 Reliability calculation results for the Water system

In this section of the thesis, the reliability calculation results for the Water system of *"DSV A"* are presented.

6.6.1 Reliability results for the Water system

The results for the Water system as well as for its sub-systems of seawater, bilge, fire, fresh water, potable water and sewage & waste are presented in Figures 6.16-6.18.

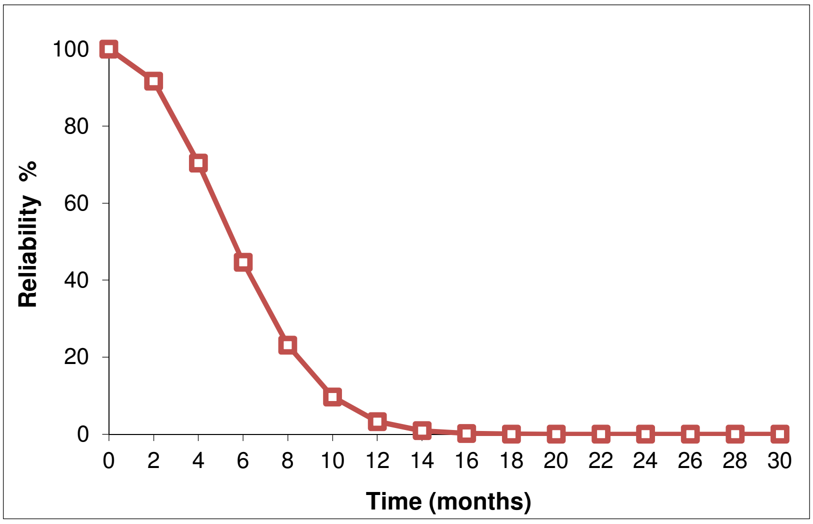

Figure 6.16 Reliability results for the Water system

As observed, the reliability of the Water system shows good results (above 90%) up to 3 months of operation and then starts decreasing rapidly until it reaches the lower figure of its reliability after 14 months. The reliability results for this main system over time are better explained if the PoF results are also examined as shown in Figures 6.17 and 6.18.

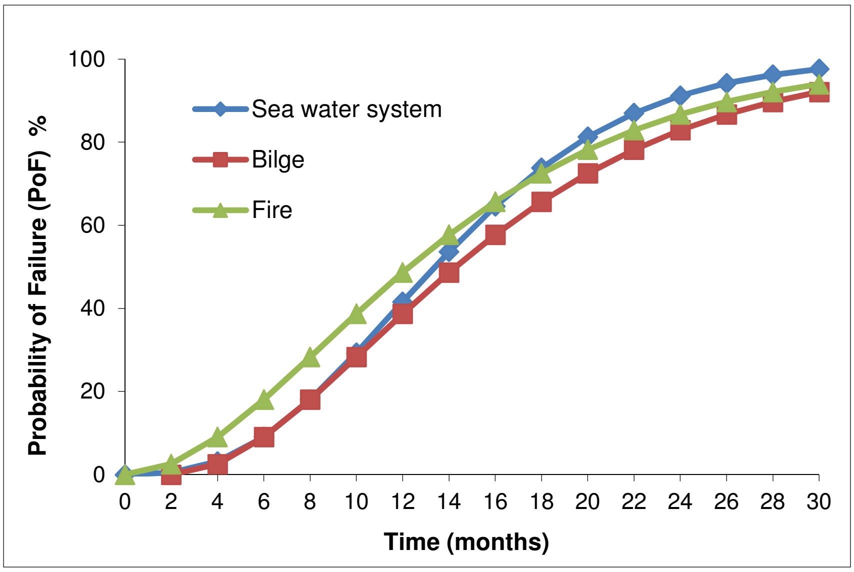

Figure 6.17 Probability of failure results for the sub-systems of sea water, bilge and fire

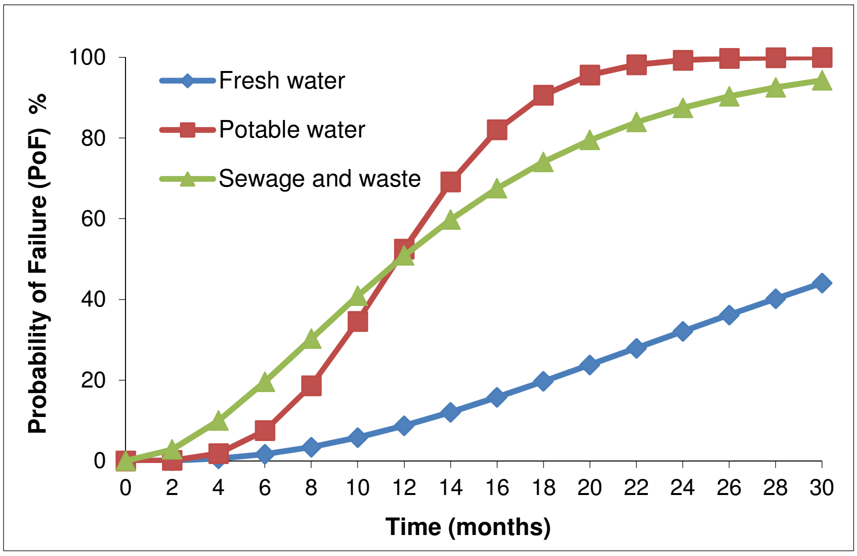

Figure 6.18 Probability of failure results for the sub-systems of fresh water, potable water and sewage and waste

In Figure 6.15 the PoF results for the seawater, bilge and fire sub-systems are shown following a similar failure pattern with exponentially distributed results until the end of the simulation time of 30 months. The three sub-systems slightly differ in the time point they overpass their PoF threshold, which is set to 10% of the initial values (6 months for sea water and bilge sub-systems and 5 months for the fire one). In this case it is interesting to further investigate the underlying factors for the similar trend in the results of these sub-systems, which is to be shown in the section presenting the reliability IMs for each sub-system of the main water system.

For the fresh water, potable water and sewage and waste, Figure 6.18 presents the PoF results. As shown, the fresh water sub-system has the least PoF (10% after 12 months) and reaches its highest failure value (PoF 40%) after 30 months. Potable water is the second most reliable sub-system in this graph with acceptable PoF level after 7 months and minimum value of 90% at the end of the simulation period. Sewage and waste PoF level is lower than the other sub-systems mentioned previously (10% at 4 months) while it shows lower PoF value at the end of the 30 month period than the potable water.

6.6.2 Reliability IMs results for the Water system

Next, the IMs for the Water system are presented in Tables 6.25-6.27. The Birnbaum IM is presented first followed by the Criticality and Fussell-Vesely IMs.

Table 6.25 Birnbaum IM for the Water system

##	Event	Birnbaum	##	Event	Birnbaum
1	cont sew tr	18.026%	16	fwt cath pr	2.279%
2	bloc sew tr	18.026%	17	corr cath pr	2.279%
3	corr sew tr	16.240%	18	corr tks	1.113%
4	corr emer pp	14.293%	19	bloc heat exch	0.845%
5	corr bilge pp rec	14.293%	20	fwt water tr	0.805%
6	corr fire pp	14.293%	21	fwt pp	0.805%
7	mecd bilge pp	14.293%	22	corr pp	0.805%
8	fwt emer pp	14.242%	23	cont water tr	0.805%
9	fwt fire pp	14.242%	24	corr vvs	0.637%
10	mecd bilge pp rec	14.242%	25	cont vvs	0.637%
11	corr bilge pp	14.242%	26	fwt circ pp	0.576%
12	bloc main cool pp	2.993%	27	mecd fresh water	0.474%
13	fwt main cooling pp	2.993%	28	corr fressh water	0.474%
14	corr sw vvs	2.286%	29	cont fresh water	0.474%
15	crac sw vvs	2.283%			

Table 6.26 Criticality IM for the Water system

##	Event	Criticality	##	Event	Criticality
1	corr sew tr	21.904%	16	fwt main cooling pp	2.480%
2	cont sew tr	19.679%	17	crac sw vvs	1.892%
3	bloc sew tr	19.679%	18	corr vvs	1.020%
4	corr emer pp	15.603%	19	fwt circ pp	0.922%
5	corr bilge pp rec	15.603%	20	bloc heat exch	0.922%
6	corr fire pp	15.603%	21	corr tks	0.922%
7	mecd bilge pp	15.603%	22	fwt water tr	0.879%
8	fwt emer pp	11.804%	23	fwt pp	0.879%
9	fwt fire pp	11.804%	24	corr pp	0.667%
10	mecd bilge pp rec	11.804%	25	cont water tr	0.667%
11	corr bilge pp	11.804%	26	corr fressh water	0.639%
12	corr sw vvs	3.083%	27	cont vvs	0.528%
13	fwt cath pr	2.488%	28	mecd fresh water	0.517%
14	corr cath pr	2.488%	29	cont fresh water	0.393%
15	bloc main cool pp	2.480%			

Table 6.27 Fussell-Vesely IM for the Water system

##	Event	Fussell-Vesely	##	Event	Fussell-Vesely
1	corr sew tr	24.523%	16	fwt main cooling pp	2.732%
2	cont sew tr	22.186%	17	crac sw vvs	2.080%
3	bloc sew tr	22.186%	18	corr vvs	1.116%
4	corr emer pp	17.459%	19	fwt circ pp	1.005%
5	corr bilge pp rec	17.459%	20	bloc heat exch	1.005%
6	corr fire pp	17.459%	21	corr tks	1.005%
7	mecd bilge pp	17.459%	22	fwt water tr	0.962%
8	fwt emer pp	13.254%	23	fwt pp	0.962%
9	fwt fire pp	13.254%	24	corr pp	0.730%
10	mecd bilge pp rec	13.254%	25	cont water tr	0.730%
11	corr bilge pp	13.254%	26	corr fressh water	0.698%
12	corr sw vvs	3.385%	27	cont vvs	0.577%
13	fwt cath pr	2.732%	28	mecd fresh water	0.565%
14	corr cath pr	2.732%	29	cont fresh water	0.429%
15	bloc main cool pp	2.732%			

From Tables 6.25-6.27 above, it is obvious that the sewage treatment plant is the most significant component of the Water system. All three IMs verify this outcome, even if they present small differences in the ranking of the most important failure cause (contamination, blockage and corrosion). The corrosion of the pumps is the next most significant failure cause, which is for the emergency pump, the reciprocating bilge pump as well as the fire pump. Mechanical damage and fair, wear and tear are the next failure causes that decrease the reliability of this system. It is obvious that in the case of the Water system there are many different failure events contributing to the reduction of its reliability. This issue will be addressed in the next section with the introduction of 'SPARE' gates and events by suggesting specific maintenance measures. Supplementary to the above and in order to address the significance of the components of the sub-systems of the Water system, their reliability IMs are presented in Tables 6.28-6.33. At first, the IMs results for the seawater sub-system are shown next.

Table 6.28 Birnbaum, Criticality and Fussell-Vesely IMs for the seawater sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	fwt main cooling pp	3.250%	49.382%	50.099%
2	bloc main cool pp	3.250%	49.382%	50.099%
3	corr sw vvs	2.482%	61.374%	62.062%
4	crac sw vvs	2.479%	37.672%	38.135%
5	fwt cath pr	2.474%	49.527%	50.099%
6	corr cath pr	2.474%	49.527%	50.099%

As can be seen, the ‘fwt’ and ‘bloc’ of the main cooling pump are the major events for the Bir IM followed by the ‘corr’ and ‘crac’ of the seawater valves. This partially agrees with the ranking regarding the Cri and F-V IMs, as the ‘corr’ of the seawater valves is first in the list followed by the ‘fwt’ and ‘bloc’ of the main cooling pumps. In this regard, the ‘corr’ of the seawater valves are the most critical failures and end-events for increasing the reliability of this sub-system while it can be also further enhanced according to the Bir IM.

Table 6.29 Birnbaum, Criticality and Fussell-Vesely IMs for the bilge sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	mecd bilge pp	15.196%	54.529%	57.387%
2	corr bilge pp	15.196%	41.250%	43.565%
3	corr bilge pp rec	15.143%	54.529%	57.387%
4	mecd bilge pp rec	15.143%	41.250%	43.565%

For the bilge sub-system, the three reliability IMs agree in terms of the most significant event. In this case the mechanical damage of the bilge pump is the most important failure event identified followed by the corrosion of both the bilge pump and the reciprocating pump as well. In this respect, the identified failures and components according to the three IMs denote that immediate attention should be focused on the subject equipment and maintenance measures should be addressed for them as it will be further explained in the following sections in which repair and maintenance tasks will be addressed for the entire Water system.

Table 6.30 Birnbaum, Criticality and Fussell-Vesely IMs for the fire sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	corr fire pp	15.196%	54.529%	57.387%
2	corr emer pp	15.196%	54.529%	57.387%
3	fwt fire pp	15.143%	41.250%	43.565%
4	fwt emer pp	15.143%	41.250%	43.565%

In the case of the fire sub-system, there is also agreement amongst the three IMs in terms of the ranking of the criticality and importance of the end-events. As shown above, the components that can be furthermore improved and also enhance the reliability of this sub-system are related to corrosion problems identified.

Table 6.31 Birnbaum, Criticality and Fussell-Vesely IMs for the fresh water sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	corr tks	1.213%	100.000%	100.000%
2	bloc heat exch	0.921%	100.000%	100.000%
3	fwt circ pp	0.627%	100.000%	100.000%

The fresh water sub-system comprises only three events which have (to a more or less degree) same importance for the operation of this sub-system. The most significant one is the corrosion of the ballast tanks, since the ballast tanks are one of the most sensitive part of the seawater system.

Table 6.32 Birnbaum, Criticality and Fussell-Vesely IMs for the potable water sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	fwt pp	0.877%	56.884%	56.884%
2	fwt water tr	0.877%	56.884%	56.884%
3	cont water tr	0.877%	43.183%	43.183%
4	corr pp	0.877%	43.183%	43.183%
5	corr vvs	0.694%	65.951%	65.951%
6	cont vvs	0.694%	34.117%	34.117%
7	corr fressh water	0.516%	41.284%	41.284%
8	mecd fresh water	0.516%	33.416%	33.416%
9	cont fresh water	0.516%	25.368%	25.368%

Regarding the potable water sub-system, major similarities and small differences among the three IMs are observed. More specifically, the key event according to the Bir IM is the fair, wear and tear of the potable water pump, which is the second most important event in the case of the Cri and F-V IMs. It is important to notice once again that the Bir IM specifies which end-event and subsequently component is most important compared to the rest of the end-events in the same sub-system, no matter of the high or low actual values this may have. It should be also mentioned that the Bir IM is a supplementing measure of the importance of this sub-system and that more attention should be focused on the Cri an F-V importance measure as these are the ones that actually identify which component of the subject system is more influential to it. In terms of the latter IMs, the corrosion of the valves is the most important event, also mentioned in the Bir IM. On the other hand, there is agreement with regards to the subsequent most significant events in all three IMs. These are the ‘fwt’ and the ‘cont’ of the water treatment plant as well as the corrosion of the potable water pump, which is also an expected failure cause for this equipment.

Table 6.33 Birnbaum, Criticality and Fussell-Vesely IMs for the sewage & waste sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	cont sew tr	26.789%	66.530%	65.780%
2	bloc sew tr	26.789%	59.658%	65.780%
3	corr sew tr	24.317%	59.658%	72.526%

In the case of the sewage & waste sub-system, which is also a small part of the main Water system of *"DSV A"*, there are small differences among the various events for all three IMs. 'cont' of the sewage treatment plant is the top ranked event followed by blockage and corrosion of the same treatment plant. In this case, the 'cont' of the sewage treatment plant is prioritised first while the 'corr' of the sewage treatment plant can be also improved but it is not as critical for the reliability of the entire sub-system as the definition of the F-V IM suggests.

6.6.3 Cut set results for the Water system

In this part of the analysis of the case study of *"DSV A"* the cut set results of the Water system are presented in Table 6.34.

Table 6.34 Cut set results for the Water system (10 out of 44)

##	Cut set events	Order	PoOcc
1	bloc sew tr, corr sew tr	2	1.021%
2	cont sew tr, corr sew tr	2	1.021%
3	corr emer pp, corr fire pp	2	0.827%
4	mecd bilge pp, corr bilge pp rec	2	0.827%
5	bloc sew tr, cont sew tr	2	0.827%
6	fwt emer pp, corr fire pp	2	0.627%
7	corr emer pp, fwt fire pp	2	0.627%
8	mecd bilge pp, mecd bilge pp rec	2	0.627%
9	corr bilge pp, corr bilge pp rec	2	0.627%
10	corr bilge pp, mecd bilge pp rec	2	0.476%

As can be observed, the blockage and the corrosion of the sewage treatment plant are the events present in the first cut set (second order). The sewage treatment plant is also present in the second cut set showing the dependence of the Water system on this component within the overall system. It should be mentioned that the first ten cut set results for the Water system are of the second order (which means that these are the quickest to occur) while there are also other cut sets which are of the third or even fourth order (containing three and four events respectively) down the list with all the cut set results examined. The aim of this part of the case study is to examine the cut set events that will eventually lead to the failure of the top event the soonest. This is the reason why the first ten cut sets are mentioned in the Table above. The cut set results for the major sub-systems are presented in Tables 6.35-6.39.

Table 6.35 Cut set results for the sea water sub-system

##	Cut set events	Order	PoOcc
1	bloc main cool pp, corr sw vvs, corr cath pr	3	0.071%
2	bloc main cool pp, corr sw vvs, fwt cath pr	3	0.071%
3	fwt main cooling pp, corr sw vvs, corr cath pr	3	0.071%
4	fwt main cooling pp, corr sw vvs, fwt cath pr	3	0.071%
5	bloc main cool pp, crac sw vvs, corr cath pr	3	0.043%
6	bloc main cool pp, crac sw vvs, fwt cath pr	3	0.043%
7	fwt main cooling pp, crac sw vvs, corr cath pr	3	0.043%
8	fwt main cooling pp, crac sw vvs, fwt cath pr	3	0.043%

The sea water sub-system includes cut sets of the third order with the blockage of the main cooling pump, the corrosion of the seawater valves as well as the corrosion of the cathodic protection contributing to the occurrence of the first cut set. The blockage of the main cooling pump and the corrosion of the seawater valves are also present in the second cut set which is logical since these are the main items that experience failures in practical terms as they are always in contact with sea water.

Table 6.36 Cut set results for the potable water sub-system (10 out of 24)

##	Cut set events	Order	PoOcc
1	corr fresh water, fwt pp, fwt water tr, corr vvs	4	0.012%
2	mecd fresh water, fwt pp, fwt water tr, corr vvs	4	0.010%
3	corr fressh water, fwt pp, cont water tr, corr vvs	4	0.009%
4	corr fressh water, corr pp, fwt water tr, corr vvs	4	0.009%
5	mecd fresh water, fwt pp, cont water tr, corr vvs	4	0.008%
6	mecd fresh water, corr pp, fwt water tr, corr vvs	4	0.008%
7	cont fresh water, fwt pp, fwt water tr, corr vvs	4	0.008%
8	corr fressh water, corr pp, cont water tr, corr vvs	4	0.007%
9	corr fressh water, fwt pp, fwt water tr, cont vvs	4	0.006%
10	cont fresh water, corr pp, fwt water tr, corr vvs	4	0.006%

For the potable water sub-system, the fourth order cut sets show that corrosion is the primary failure cause (‘corr fresh water, fwt pp, fwt water tr, corr vvs’) followed by fair, wear and tear of various items such as the fresh water pump and the water treatment plant. Finally, the results of the cut sets for the bilge, fire and the sewage & waste sub-systems are presented in Tables 6.37-6.39.

Table 6.37 Cut set results for the bilge sub-system

##	Cut set events	Order	PoOcc
1	mecd bilge pp, corr bilge pp rec	2	0.827%
2	corr bilge pp, corr bilge pp rec	2	0.627%
3	mecd bilge pp, mecd bilge pp rec	2	0.627%
4	corr bilge pp, mecd bilge pp rec	2	0.476%

Table 6.38 Cut set results for the fire sub-system

##	Cut set events	Order	PoOcc
1	corr emer pp, corr fire pp	2	0.827%
2	corr emer pp, fwt fire pp	2	0.627%
3	fwt emer pp, corr fire pp	2	0.627%
4	fwt emer pp, fwt fire pp	2	0.476%

Table 6.39 Cut set results for the sewage & waste sub-system

##	Cut set events	Order	PoOcc
1	bloc sew tr, corr sew tr	2	2.158%
2	cont sew tr, corr sew tr	2	2.158%
3	bloc sew tr, cont sew tr	2	1.757%

For the bilge sub-system, the first cut set includes the mechanical damage of the bilge pump and the corrosion of the reciprocating bilge pump as primary failure events followed by the corrosion of the bilge pump and that of the reciprocating bilge pump. For the fire sub-system, corrosion is the primary participant in the cut set results (first cut set of ‘corr emer pp, corr fire pp’ and second cut set of ‘corr emer pp, fwt fire pp’). The results for the sewage & waste sub-system show the blockage and the corrosion of the sewage treatment plant as the major participating events. Overall, it can be said that the main failure causes appearing at the top of the list for the cut set results of all the sub-systems of the Water system are related to corrosion which is consistent with the experienced problems/failures of such systems in practice as verified by the superintendent and chief engineers as well as from the hands-on experience of the author of the present thesis. Overall, it needs to be reminded that the cut set results indicate the specific combination of end-events that shows the quickest way of failure of each sub-system, no matter of how small or high this probability may be. On the other hand, the low results regarding the PoOcc of the sub-systems examined above denote that the probability of these cut sets occurring is very low and thus the criticality of the specific events occurring in the specific order are not of the highest importance. Moreover, the maintenance tasks allocated to them should derive from the thorough examination of the reliability IMs instead.

6.6.4 'SPARE' gates - Discussion and suggestions for the Water system

For the Water system, there are a number of sub-systems examined such as the seawater, bilge, fire, fresh water, potable and sewage & waste water ones. Regarding the above, the most critical items as well as their failure cause has been investigated as a result of the criticality analysis performed in the previous sections of this Chapter (§6.6.1-6.6.3). In this respect, the aforementioned results regarding the most critical items/components, failure causes and maintenance measures suggested for the Water system are presented in Figure 6.19.

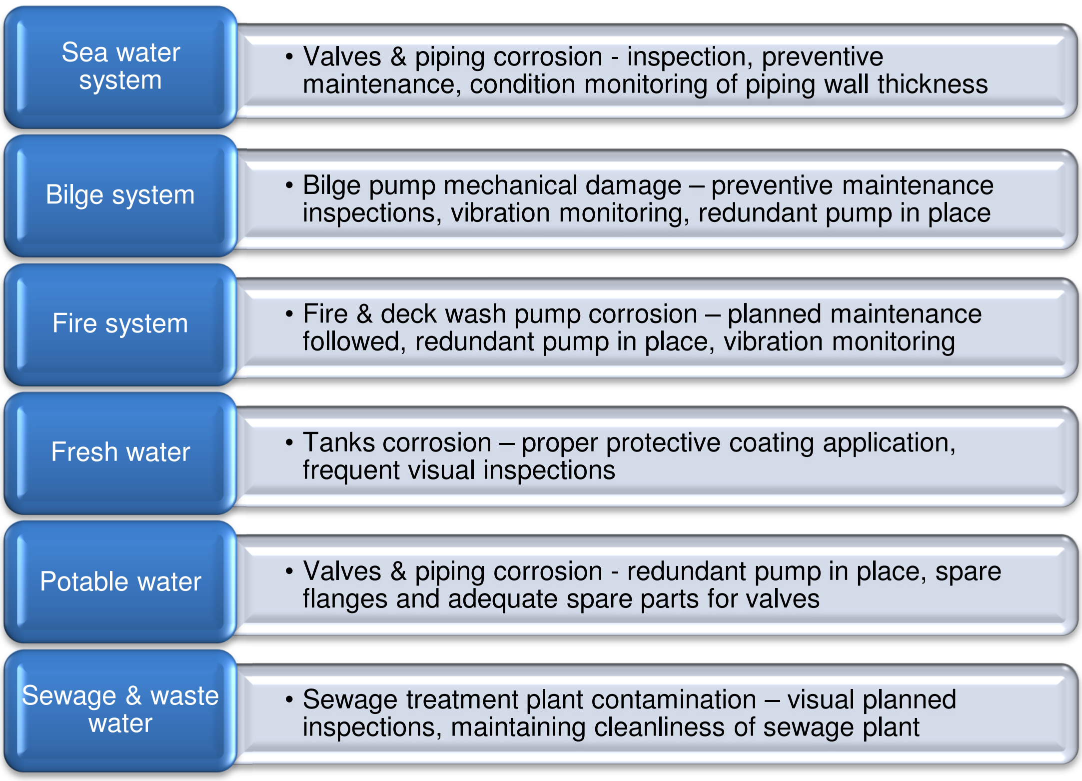

Figure 6.19 Most critical items/components, failure causes and maintenance measures suggested for the Water system

As shown above, the most significant item and accordingly failure cause identified for the seawater sub-system is the corrosion of the seawater valves and adjacent piping. For this failure, more thorough inspections are required so as to detect potential flaws such as holed pipes, leaking valves and flanges which are some of the most exposed components of the ship to failure and deterioration especially when in contact with the highly corrosive seawater. It has to be mentioned that the inspections suggested need to be followed as part of the preventive maintenance procedure onboard the vessel, which in some cases is not carried out in a proper manner. The latter leads to the identification of a set of secondary reasons of not detecting the failures mentioned above including among others inappropriate implementation of the planned maintenance sequence, inattention on behalf of the personnel onboard to follow the maintenance programme as well as not sufficient supervision and validation of the maintenance plan in place.

In this regard, additional measures in order to rectify the above include the cross-reference of any maintenance activity onboard the ship and supervisory tasks on behalf of the higher officers as well as superintendents when onboard. Furthermore, seawater piping can be checked for the deterioration of its wall thickness by carrying out ultrasonic thickness measurements (UTM) at regular intervals assisted by either the crew of the ship or by an outsourced company. In this case the capital investment about purchasing a UTM device for regular use onboard the ship (including the various updates of the condition monitoring systems) should be considered as well as the initial training cost of the personnel that will be involved in performing the specific task.

For the bilge sub-system, the mechanical damage of the bilge pump is the predominant failure cause for this sub-system according to the reliability and criticality analysis performed. At an initial stage, this can be dealt with regular checks of the subject pump as part of the daily routine inspections and preventive maintenance tasks carried out by the ship's crew. At a further stage, a vibration monitoring examination of the pump may be performed (usually by a sub-contracted condition monitoring company) in order to examine the case of an imbalanced motor and/or bearings of the subject pump. On top of the above, an additional measure in terms of proactive maintenance involvement is a redundant pump being operated in a stand-by mode and which is coupled to the main pump so as to overcome potential malfunctions presented in the future.

In the case of the fire sub-system, corrosion of the fire & deck wash pump is the major failure event that requires particular attention. In this respect, it is not unusual to reveal rusty surfaces in the pump, especially in the case that highly corrosive seawater is used to wash deck surfaces. In addition, this pump (regarding its use for fire-fighting) is a major and most critical component of the whole operation of the ship in terms of the safety equipment needed onboard. The main failure cause identified can be fixed with further inspections carried out and, as in the case of the bilge pump described above, redundant equipment/pump in place. This may include a general service pump or a seawater pump connected through valves and piping so as to provide the water capacity required in the case of an emergency.

As for the fresh water sub-system, the corrosion of the tanks used for fresh water is the main failure cause present in this sub-system. Although corrosion problems are not frequently encountered in fresh water tanks-especially when compared to seawater ballast tanks-, they can be also initiated and expanded for a number of reasons. These include the potential of incorrect coating application in the first place which means that particular attention is needed when application of protective coatings is performed in the initial construction stage at the new-building shipyard. Additionally, because of the particular protective nature of fresh water on steel surfaces, onboard inspections of these tanks tend to be omitted for prolonged periods of time until a leakage is propagated and discovered by the ships' crew alas too late.

In this respect, one way of dealing with corrosion problems in this sort of tank can be handled with the correct - and according to international standards - application of protective coatings. Furthermore, regular inspections by the crew as per the ship's schedule and planned maintenance procedures should be performed so as to foresee any coating detachment or blisters created that may lead to potential coating flaws and the initiation of localised corrosion. The latter should be followed for all tanks onboard the ship and especially for the seawater and sewage ones.

In the case of the potable water sub-system, the main failure identified is the corrosion of the water valves. In a similar way, as in the case of the fire & deck wash pump, this item can be treated with additional visual inspections as part of the planned maintenance procedure of the ship. On top of the above, if the corrosion failure is not detected in a timely manner and a subsequent failure occurs, sufficient number of high quality pump spare parts should be always included in the inventory list of the ship.

Finally, for the sewage & waste water sub-system, the contamination of the sewage treatment plant is the major challenge identified when carrying out the reliability and criticality analysis. As an initial maintenance measure, visual inspection can to be carried out by the ship's crew at regular intervals. At a second level, this can be followed by proper cleaning of the subject tanks performed so as to avoid further propagation of the deterioration of the sewage treatment plant.

As presented before, the ways to improve the reliability results of the Water system by proposing additional maintenance measures are shown in terms of introducing 'SPARE' gates in the FT structure. The new set of results is shown in Figure 6.20.

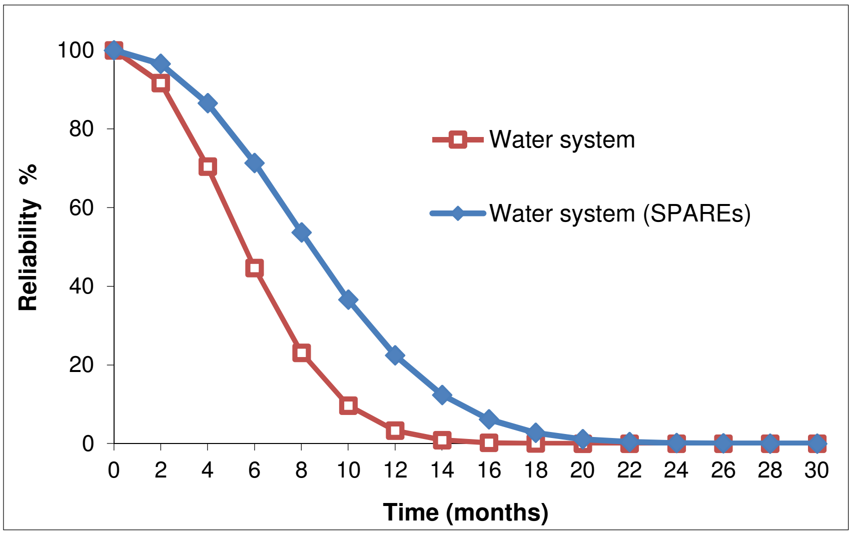

Figure 6.20 Comparison of reliability results of Water system before and after the introduction of 'SPARE' gates

As is shown, the reliability of the Water system increases compared to the previous results. In this case, the additional maintenance measures refer to the various failure events of the different sub-systems examined and presented above. As can be seen, the improvement of the overall reliability of the Water system is not great (from 2 months of good operational level it has been increased to 3 months). Nonetheless, the criticality analysis of this system has indicated areas of improvement which can enhance the overall operation of the subject system. These are mentioned in terms of maintenance tasks allocated to the Water system which form part of the overall maintenance procedure, which needs to be further enhanced.

6.7 Reliability calculation results for the Diving system

In this section, the reliability calculation results for the Diving system of *"DSV A"* are presented next. As mentioned in section §5.3.4, the Diving system includes all the relevant sub-systems which can preserve the living conditions for all diving personnel involved in the diving operations of the vessel. This includes the following sub-systems: the chambers, bell & sphl, handling, gas systems and electrical communications & cut-outs.

6.7.1 Reliability results for the Diving system

In this section, the reliability results for the diving system and sub-systems of the subject vessel are presented in Figures 6.21-6.23.

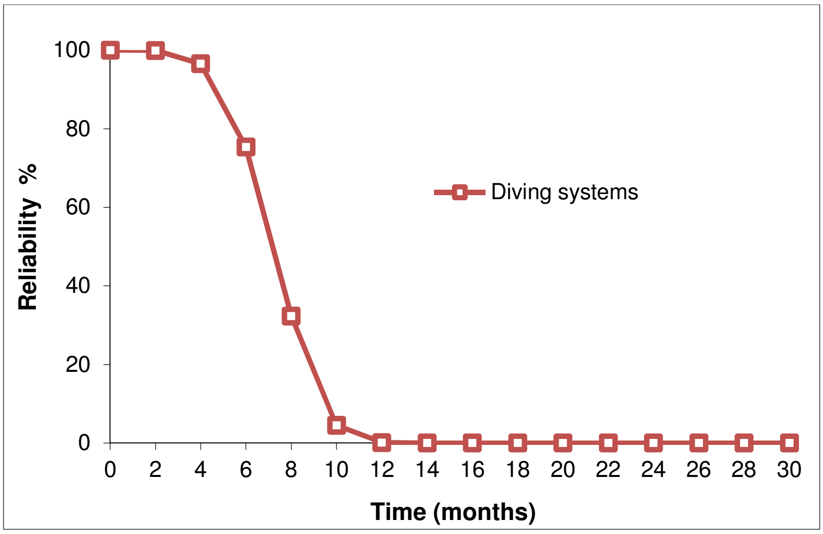

Figure 6.21 Reliability results for the Diving system

As observed, the reliability of the diving system drops below 90% just after 6 months of operational time and reaches its minimum value after 12 months. The Diving system is a very critical system for the entire operation of *"DSV A"*. At this point it should be mentioned once again that the low reliability results do not indicate that the actual operational reliability of this system is low and is actually minimised after a period of 12 months. This is because the present study aims at identifying the systems that need further improvement through the identification and improvement of specific events of each system. This is clearly demonstrated in the next section of this Chapter where the Birnbaum, Criticality and Fussell-Vesely IMs are presented.

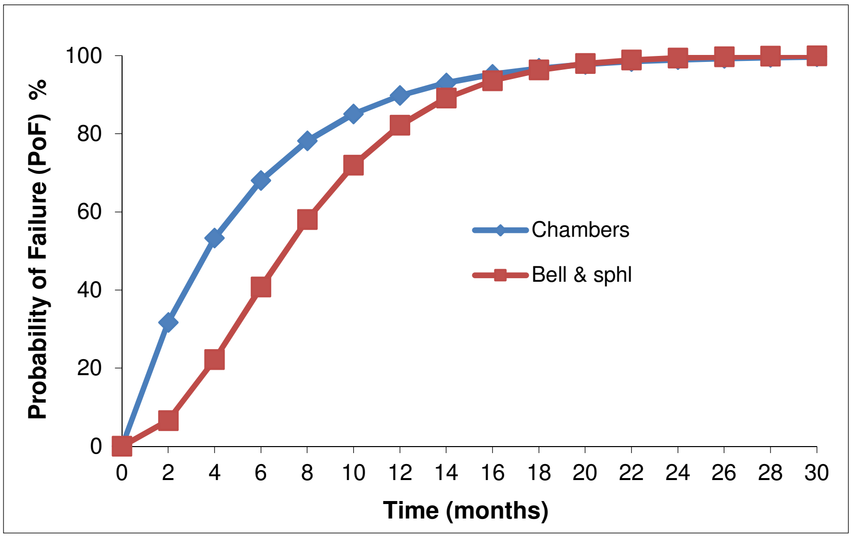

Figure 6.22 Probability of failure results for the sub-systems of chambers and bell & sphl

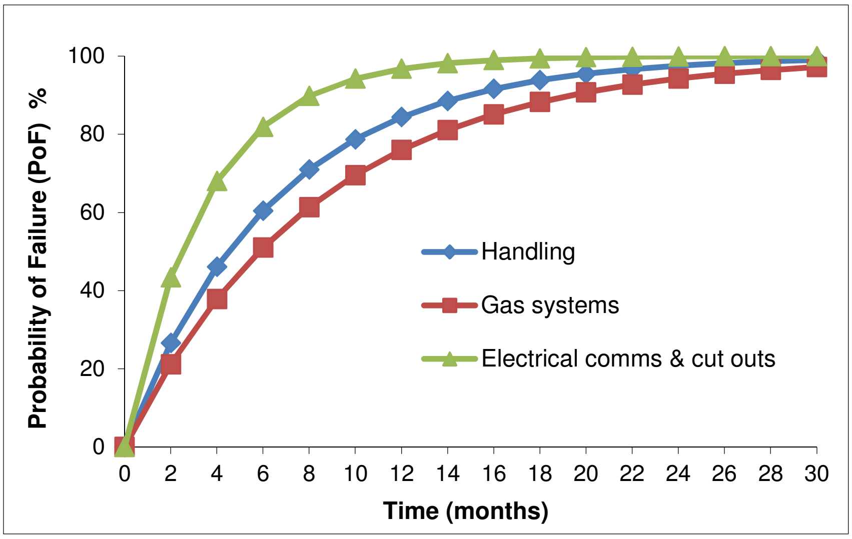

Figure 6.23 Probability of failure results for the sub-systems of handling, gas systems and electrical comms & cut outs

In the case of the sub-systems of chambers and bell & sphl (Figure 6.18), they show similar PoF patterns followed for the entire period of 30 months although the initial curves are slightly different (PoF 10% for bell & sphl sub-system at 3 months and just one month for chambers sub-system). The PoF curves for the handling, gas systems and electrical comms & cut outs sub-systems are also quite similar, following an exponential growth after the first few months of simulation time.

6.7.2 Reliability IMs results for the Diving system

The Diving system is one of the most important systems of *"DSV A"*, maintaining the diving equipment as well as the diving facilities for the saturation divers in excellent condition. Having this in mind, the IMs of the Diving system are shown in Tables 6.40-6.42.

Table 6.40 Birnbaum IM for the Diving system

##	Event	Birnbaum	##	Event	Birnbaum
1	fwt compr	0.356%	10	fwt launch	0.278%
2	crac compr	0.356%	11	mecd launch	0.278%
3	comp compr	0.356%	12	comp launch	0.278%
4	comp sdc	0.326%	13	cont cham	0.230%
5	cont sdc	0.326%	14	fwt cham	0.230%
6	corr sdc	0.326%	15	wrcm cham	0.230%
7	comp sphl	0.300%	16	comp elec	0.162%
8	fwt sphl	0.300%	17	cabl elec	0.162%
9	mecd sphl	0.300%	18	fwt elec	0.162%

Table 6.41 Criticality IM for the Diving system

##	Event	Criticality	##	Event	C-riticality
1	comp elec	59.574%	10	crac compr	30.087%
2	fwt cham	48.848%	11	comp compr	30.087%
3	fwt launch	45.416%	12	cont sdc	27.518%
4	comp sdc	44.790%	13	corr sdc	27.518%
5	fwt sphl	41.192%	14	mecd sphl	25.308%
6	fwt compr	39.636%	15	mecd launch	23.490%
7	comp sphl	33.339%	16	fwt elec	22.295%
8	cont cham	31.608%	17	wrcm cham	19.420%
9	comp launch	30.944%	18	cabl elec	18.045%

Table 6.42 Fussell-Vesely IM for the Diving system

##	Event	Fussell-Vesely	##	Event	Fussell-Vesely
1	comp elec	59.642%	10	crac compr	30.158%
2	fwt cham	48.925%	11	comp compr	30.158%
3	fwt launch	45.499%	12	cont sdc	27.579%
4	comp sdc	44.883%	13	corr sdc	27.579%
5	fwt sphl	41.273%	14	mecd sphl	25.361%
6	fwt compr	39.726%	15	mecd launch	23.537%
7	comp sphl	33.407%	16	fwt elec	22.327%
8	cont cham	31.661%	17	wrcm cham	19.455%
9	comp launch	31.005%	18	cabl elec	18.072%

As can be seen, the most important component according to the Bir IM is the compressor (fwt, crac, comp) followed by the submersible decompression chamber (sdc) with major causes the component failure (comp), the contamination (cont), and the corrosion (corr). For the Cri and F-V IMs there are similarities in the identification of the top ranked events. In this case, the component failure (comp) of the electrics is the leading failure event followed by the fair, wear and tear (fwt) of the chambers and the launch system. Then, it is component failure of the sdc that follows in the IMs list and fair, wear and tear of the sphl. As mentioned in the case of other systems in previous sections of this Chapter (§6.6.2), the difference in the values of the Bir and Cri and F-V IMs is related to the very definition of calculation of these reliability IMs. In addition to the above, the reliability IMs for the mentioned sub-systems of the Diving system are presented and examined next (Tables 6.43-6.47)

Table 6.43 Birnbaum, Criticality and Fussell-Vesely IMs for the bell & sphl sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	comp sdc	23.951%	40.666%	46.224%
2	corr sdc	23.668%	24.692%	28.403%
3	cont sdc	23.668%	24.692%	28.403%
4	fwt sphl	22.153%	37.614%	42.506%
5	comp sphl	22.034%	30.281%	34.405%
6	mecd sphl	21.913%	22.861%	26.119%

Table 6.44 Birnbaum, Criticality and Fussell-Vesely IMs for the chambers sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	fwt cham	82.642%	45.245%	54.748%
2	cont cham	76.941%	27.260%	35.430%
3	wrcm cham	73.362%	15.971%	21.771%

Table 6.45 Birnbaum, Criticality and Fussell-Vesely IMs for the handling sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	fwt launch	84.635%	42.359%	50.049%
2	comp launch	80.678%	27.515%	34.105%
3	mecd launch	78.781%	20.397%	25.891%

Table 6.46 Birnbaum, Criticality and Fussell-Vesely IMs for the gas sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	fwt compr	86.673%	37.157%	42.870%
2	crac compr	84.635%	27.544%	32.545%
3	comp compr	84.635%	27.544%	32.545%

Table 6.47 Birnbaum, Criticality and Fussell-Vesely IMs for the electrical comms & cutouts sub-system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	comp elec	80.698%	55.643%	68.951%
2	fwt elec	63.633%	16.425%	25.812%
3	cabl elec	62.135%	12.981%	20.892%

Regarding the bell & sphl sub-system, the submersible decompression chamber is the first ranked in all three IMs, with 'comp', 'corr' and 'cont' as the failure causes. This is in accordance to what is mentioned above for the influence of the sdc in the IMs of the main Diving system as well. For the chambers, handling, gas and electrical communications & cutouts sub-systems are presented. As can be observed, these make up a small part of the main Diving system since they contain three failure events each. For the chambers sub-system, the fair, wear and tear of the chambers is the most important failure event, which means that the improvement efforts need to be concentrated in this direction. 'Fwt' of the launch system is also the most important event for all IMs for the handling sub-system, which means that a more careful inspection programme and maintenance needs to be placed on board regarding the diving chambers.

For the gas sub-system the 'fwt' of the compressors is the most important event while the component failure of the electrical sub-system needs more careful consideration to improve its operating condition. It is worth mentioning that fair, wear and tear are amongst the top failure causes of the Diving system as this is a most common defect observed in the ordinary operation of the vessel. As it is also observed, in all five sub-systems the Bir as well as the Cri and F-V IMs present high values (values higher than 20% and up to 80%) in contrast to what was observed in the results of previously examined systems. This highly denotes that the specific sub-systems of the Diving system need immediate attention and maintenance tasks allocated as their criticality index in all three importance measures is very high. This is further addressed in the section which also examines the application of additional maintenance procedures in the form of 'SPARE' gates for the DFT.

6.7.3 Cut set results for the Diving system

As already discussed before, the cut set results with regards to the Diving system are shown in Table 6.48.

Table 6.48 Cut set results for the Diving system (10 out of 729 events)

##	Cut set events	Order	PoOcc
1	fwt cham, comp sdc, fwt sphl, fwt launch, fwt compr, comp elec	6	0.0008%
2	comp sphl, fwt cham, comp sdc, fwt launch, fwt compr, comp elec	6	0.0006%
3	crac compr, fwt cham, comp sdc, fwt sphl, fwt launch, comp elec	6	0.0006%
4	comp compr, fwt cham, comp sdc, fwt sphl, fwt launch, comp elec	6	0.0006%
5	comp launch, fwt cham, comp sdc, fwt sphl, fwt compr, comp elec	6	0.0005%
6	cont cham, comp sdc, fwt sphl, fwt launch, fwt compr, comp elec	6	0.0005%
7	cont sdc, fwt cham, fwt sphl, fwt launch, fwt compr, comp elec	6	0.0005%
8	mecd sphl, fwt cham, comp sdc, fwt launch, fwt compr, comp elec	6	0.0005%
9	comp sphl, crac compr, fwt cham, comp sdc, fwt launch, comp elec	6	0.0005%
10	comp sphl, comp compr, fwt cham, comp sdc, fwt launch, comp elec	6	0.0005%

As is observed, the first cut set includes the fair, wear and tear of the chambers, sphl, compressors as well as the component failure of the sdc and the component failure of the electrics of the Diving system. This system has cut sets of the sixth order, comprising a combination of six events per cut set. It should be mentioned that the low figures in the probability of occurrence of the mentioned cut sets do not mean that the cut sets will not occur (even if their probability is very low). On the other hand, the above ranking suggests the quickest path of events that will lead to the loss of the reliability of the main system and also provide a measure of which combination of events is the most critical for the specific system. Once again, in practice this means that the specific sequence of events has a very limited probability to occur; consequently, the focus regarding the criticality of the mentioned components and failures should be looked at through the reliability IMs, as is already performed in section §6.7.2. Next, the cut set results for the bell & sphl sub-system are shown in Table 6.49.

Table 6.49 Cut set results for the bell & sphl sub-system

##	Cut set events	Order	PoOcc
1	comp sdc, fwt sphl	2	1.262%
2	comp sphl, comp sdc	2	1.021%
3	cont sdc, fwt sphl	2	0.775%
4	corr sdc, fwt sphl	2	0.775%
5	mecd sphl, comp sdc	2	0.775%
6	cont sdc, comp sphl	2	0.627%
7	corr sdc, comp sphl	2	0.627%
8	cont sdc, mecd sphl	2	0.476%
9	corr sdc, mecd sphl	2	0.476%

As is shown, the second order cut sets include the component failure of the sdc and the fair, wear and tear of the sphl as the primary events affecting this sub-system. Next in this list are the component failure of the sphl and that of the sdc, which suggest that these two components need to be looked at with more attention regarding the specific sub-system. These results also agree with the cut set results of the overall Diving system, which are also examined and presented in Tables 6.50-6.51, in the case of the next sub-systems (chambers, handling, hauling & anchoring, gas and electrical communications & cutouts).

Table 6.50 Cut set results for the chambers and handling, hauling & anchoring sub-systems

Order	**Chambers**		**Handling, hauling & anchoring**	
	Cut set events	**PoOcc**	**Cut set events**	**PoOcc**
1	fwt cham	17.356%	fwt launch	13.341%
1	cont cham	11.232%	comp launch	9.091%
1	wrcm cham	6.902%	mecd launch	6.902%

Table 6.51 Cut set results for the gas and electrical comms & cutouts sub-systems

Order	**Gas systems**		**Electrical comms & cutouts**	
	Cut set events	**PoOcc**	**Cut set events**	**PoOcc**
1	fwt compr	9.091%	comp elec	30.004%
1	comp compr	6.902%	fwt elec	11.232%
1	crac compr	6.902%	cabl elec	9.091%

In these four sub-systems, it appears that a single order of cut sets is present with a single event leading to the occurrence of the top event of each sub-system. The events mentioned are the fair, wear and tear for the chambers, the fair, wear and tear of the launching for the handling, hauling & anchoring, once again the fair, wear and tear of the compressors for the gas and finally the component failure for the electrical communications & cutouts.

6.7.4 ‘SPARE’ gates - Discussion and suggestions for the Diving system

In the case of the Diving system, the main sub-systems identified for the purposes of the reliability and criticality assessment are the chambers, bell & sphl, handling, gas systems and the electrical communications & cut-outs. Bearing the above analysis in mind, the critical equipment and their failures for all subject sub-systems as well as the maintenance measures suggested are summarised in Figure 6.24 and described in detail in the following paragraphs.

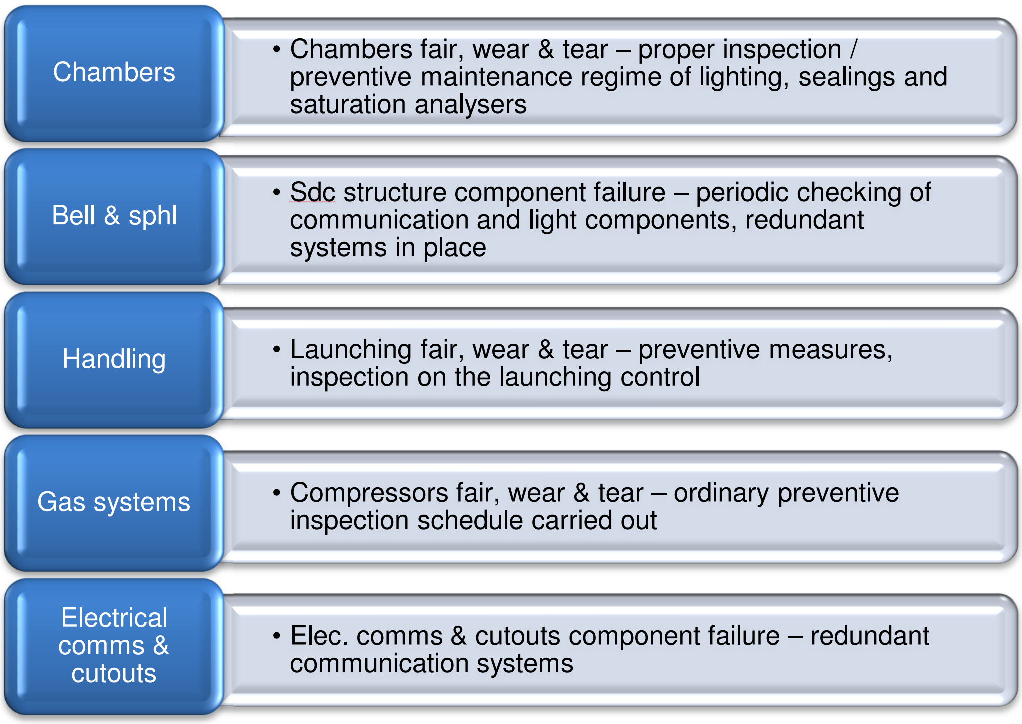

Figure 6.24 Most critical items/components, failure causes and maintenance measures suggested for the Diving system

As shown in Figure 6.24, the fair, wear and tear of the saturation chambers is the most critical failure cause and item respectively regarding the Chambers sub-system. The saturation chambers, as is the case for all equipment related to the divers' living and safety conditions are closely monitored at all times from a highly qualified engineer/operator. They are also continuously supervised by a competent superintendent responsible for providing the best conditions as described in international standards and regulations for diving facilities and living quarters onboard ships (HSE 1997). The ordinary fair, wear and tear issues are dealt with and rectified by careful and proper inspection by the ship's crew so as to discover the initiating event of this failure cause. The exact failures identified refer to lighting quality deterioration and the analysers for the saturation control within the chambers. Also, the sealing items of the chambers are also subject to usual 'fwt' and can be dealt with continuous monitoring of the sealing that provide for the pressure sealing within the decompression chambers, diving bells and other pressure sealing compartments.

For the Bell & sphl sub-system, component failure is the most significant failure identified from the results of the analysis in the present thesis. This is another vital part for this ship-type as the bell sustains the divers' good working conditions on a daily basis as well as providing a means of escape in an emergency in the case of the sphl. In this case, the component failures refer to the communications umbilical failure as well as faults presented in the external lights used on the bell. In order to overcome these failure events, adequate inspection and maintenance periodic checks of all the equipment are required. Additionally, better components need to be used in the subject sub-system in order to enhance its functionality. In terms of the Handling sub-system, the fair, wear and tear of the equipment of the launching sub-system is the most common failure originating from the analysis performed. 'Fwt' is a common failure observed in mechanical equipment onboard ships and this is the case for the launching components too. Ordinary preventive maintenance tasks are suggested in this case such as carrying out the usual inspections and planned maintenance jobs for all equipment necessary according to manufacturers' recommendations as well as offshore industry's best practice guidelines.

The fair, wear and tear is the predominant failure cause for the Gas systems as well. More specifically, the equipment that is influenced more is the compressors, which maintain the vital supply of mixture of gases to the bell and the saturation chambers, thus assuring the safe and healthy living conditions of the divers onboard the ship. In this case, the high standards regarding maintenance tasks as followed in the offshore oil and gas industry, are implemented onboard the ship while precautionary inspections and checks may be also carried out as part of a planned maintenance sequence in order to eliminate the irregularities observed. As for the electrical communications & cut-outs, their condition can be improved by additional redundant communication systems in place especially in the case of communication breakdowns between the saturation chambers and the dive control room. At a higher level, periodic visual inspections and maintenance according to the PMS of the vessel are required to adhere to a good quality maintenance procedure. Overall, as observed from the results of the reliability and criticality analysis of the Diving system, the majority of the failures identified are due to fair, wear and tear in which case the suggested maintenance measures are related to the commitment of the operating company of the vessel to the implementation of the preventive maintenance schedule.

As already performed in the previous sections of this Chapter, the comparison of the reliability results of the Diving system before and after the introduction of 'SPARE' gates is presented in Figure 6.25.

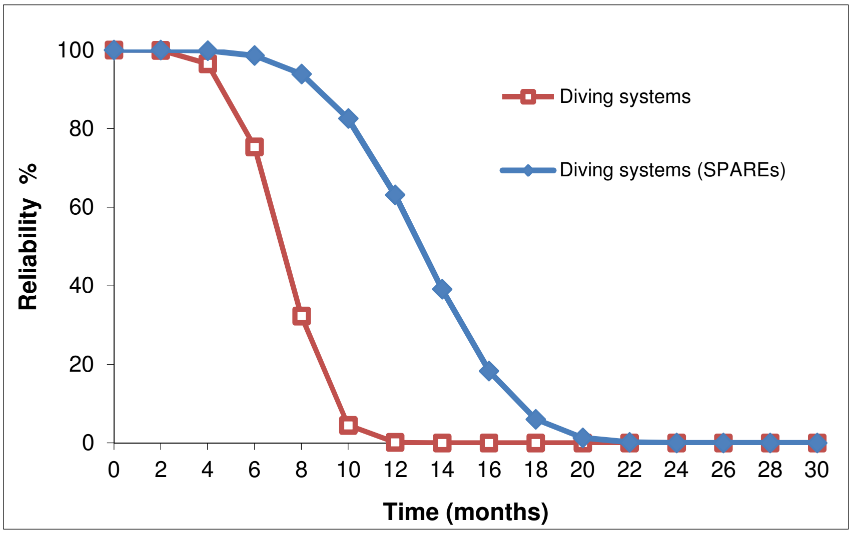

Figure 6.25 Comparison of reliability results of Diving system before and after the introduction of 'SPARE' gates

By comparing the results, it is clearly seen that the introduction of predictive maintenance assists in the improvement of the reliability of the system. Good operational conditions are sustained up to 9 months of operation of this system. As in the case of the Water system, the 'SPARE' gates introduced in the FT structure refer to the most critical components of each sub-system examined. For the chambers, handling and gas sub-systems, the fair, wear and tear is the most important failure identified ('fwt' of the chambers, launching system and compressor respectively). Likewise, for the bell and sphl sub-system, the component failure ('comp') of the sdc is the primary failure cause. This is the same with the electrical communications and cutouts sub-system which maintain the vital operational conditions for all the saturation divers both in the saturation chambers and the diving bells.

6.8 Reliability calculation results for Safety system

In this section, the reliability calculation results for the Safety system of *"DSV A"* are presented next. These refer to the sub-systems identified from the data elaboration performed before including the fire fighting equipment and hatches & doors sub-systems.

6.8.1 Reliability results for the Safety system

The reliability curves for the safety system and its sub-systems of fire fighting equipment and hatches & doors are presented in Figures 6.26-6.27.

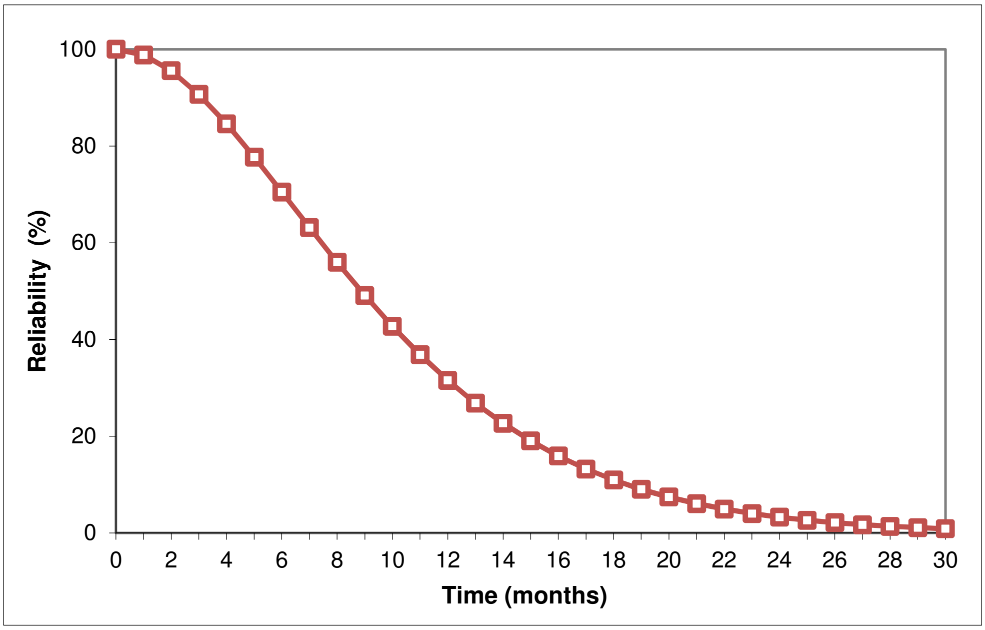

Figure 6.26 Reliability results for the Safety system

As is shown in Figure 6.26, the reliability of the safety system decreases with time and falls below 90% after just 3 months of operation, while it reaches its minimum value after 30 months of simulation time. This result is also justified by the PoF outcome of the sub-systems presented; the fire fighting equipment and hatches & doors sub-systems.

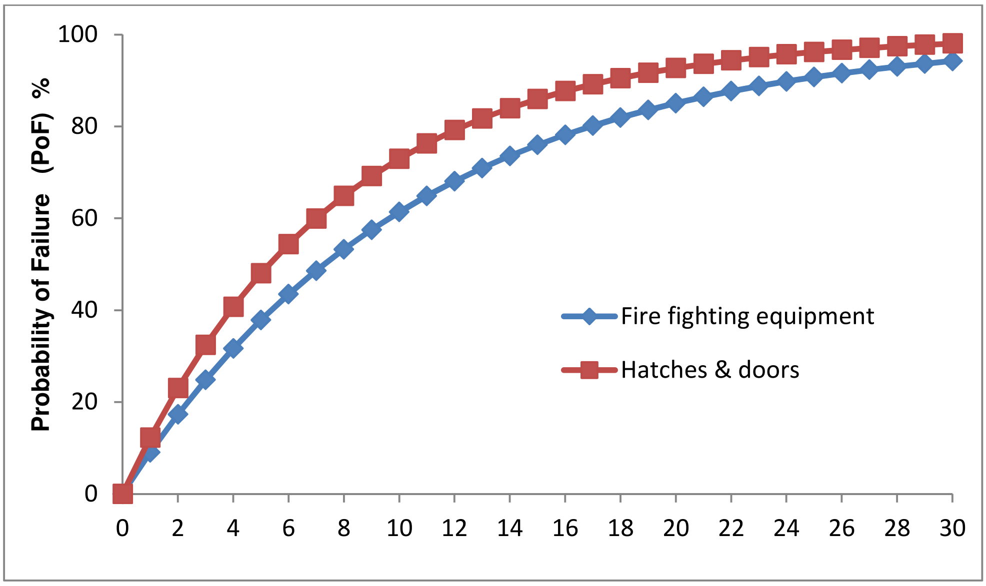

Figure 6.27 Probability of failure results for the sub-systems of fire fighting equipment and hatches & doors

As shown in Figure 6.27, the fire fighting equipment as well as the hatches & doors sub-systems follows similar patterns regarding their PoF results (PoF 10% for the fire fighting equipment after 2 months, similar to the PoF for the hatches & doors). This pattern can be further investigated by looking into the specific end-events/components of this sub-system, which contribute more in the criticality and deterioration of the fire fighting equipment. This is explicitly shown in the next paragraph, in which the reliability IMs are examined in more detail.

6.8.2 Reliability IMs results for the Safety system

In this respect, Table 6.52 demonstrates the IMs for the Safety system. As mentioned in the previous main systems of the subject vessel, the Bir, Cri and F-V IMs are examined.

Table 6.52 Birnbaum, Criticality and Fussell-Vesely IMs for the Safety system

##	Event	Birnbaum	Criticality	Fussell-Vesely
1	corr firefight eq	50.110%	37.318%	90.665%
2	comp firefight eq	39.457%	20.633%	61.915%
3	fwt wt doors	32.494%	20.633%	54.475%
4	fwt wt hatches	32.494%	20.067%	54.475%
5	fwt hydraulics	29.697%	15.103%	43.630%

As is observed, for both the Bir, Cri and F-V IMs the key events which affect the reliability of the safety system are the corrosion and the component failure of the fire fighting equipment such as the fire hydrants, water piping, water mist systems etc. The fair, wear and tear of the watertight doors is the next most important event followed by the fair, wear and tear of the watertight hatches and hydraulic systems.

6.8.3 Cut set results for the Safety system

In this section, the cut set results for the Safety system are presented in Table 6.53.

Table 6.53 Cut set results for the Safety system

##	Cut set events	Order	PoOcc
1	corr fire fighting eq, fwt wt doors	2	22.157%
2	corr fire fighting eq, fwt wt hatches	2	22.157%
3	corr fire fighting eq, fwt hydr	2	17.747%
4	comp fire fighting eq, fwt wt doors	2	15.131%
5	comp fire fighting eq, fwt wt hatches	2	15.131%
6	comp fire fighting eq, fwt hydr	2	12.119%

As shown, the minimal cut sets for this system are the corrosion of the fire fighting equipment and fair, wear and tear of the watertight doors (corr fire fighting eq, fwt wt doors) followed by the corrosion of the fire fighting equipment and fair, wear and tear of the watertight hatches (corr fire fighting eq, fwt wt hatches), which means that the maintenance efforts need to be concentrated in these specific events to improve the overall reliability of the Safety system. This is better shown in the following section, in which 'SPARE' gates and events are introduced for all the main systems. This represents the enhanced maintenance measures needed for each system based on the analysis carried out so far.

6.8.4 'SPARE' gates - Discussion and suggestions for the Safety system

In the case of the Safety system, the most critical items/components, failure causes and maintenance measures suggested for the Water system are presented in Figure 6.28.

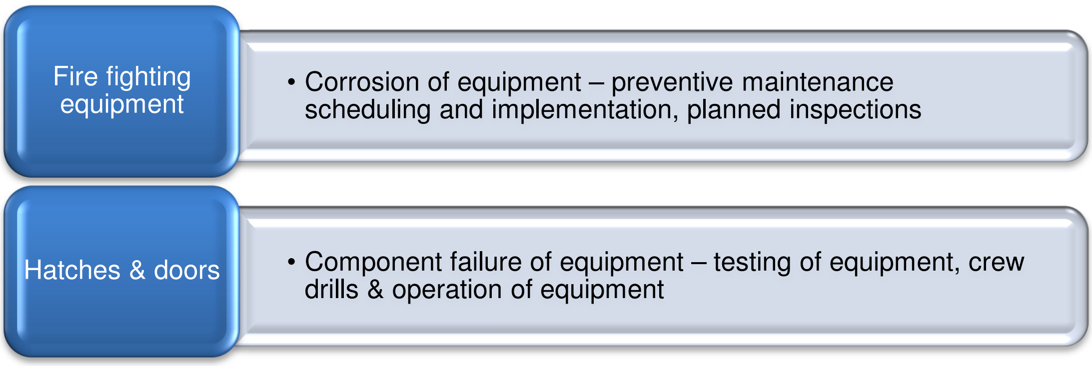

Figure 6.28 Most critical items/components, failure causes and maintenance measures suggested for the Safety system

In the case of the Safety system, regular inspections for the equipment in place like water piping, hydrants and watertight doors can minimise the need for repairs and increase the reliability of the overall system. This can be achieved by following the PMS plan as per the ISM code requirements and the Safety Management System (SMS) implemented by the shipping company operating the subject vessel. More specifically, the additional measures implemented deal with the corrosion and the component failure of the fire-fighting equipment. This equipment is a most critical part for the operation of the entire vessel and specific attention is needed. In this respect, both the corrosion and the component failure are dealt with by regular inspections and operation to ensure the good functioning condition of the equipment. Additionally, by testing the equipment at regular intervals as well as carrying out all the necessary equipment and ship's crew fire drills including the actual operation of the emergency fire pump, operation of fire hoses, checking the fire extinguishers, wearing and testing the emergency escape breathing apparatus, use a fireman's outfit with its full equipment, etc. As suggested for all the systems examined so far, 'SPARE' gates are introduced to simulate the maintenance measures needed to enhance the reliability results of this system. Figure 6.28 shows the comparison of the reliability results of the Safety system before and after the introduction of 'SPARE' gates.

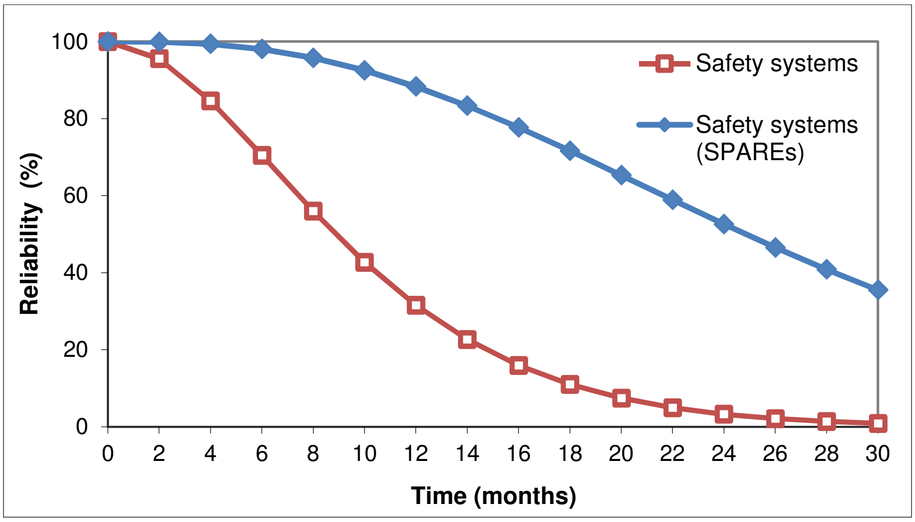

Figure 6.29 Comparison of reliability results of Safety system before and after the introduction of 'SPARE' gates

As can be seen, the reliability of the Safety system increases significantly retaining its good operational capacity to 10 months (from 3 months of initial results). In this case, the additional measures implemented deal with the corrosion and the component failure of the fire-fighting equipment. This equipment is a most critical part for the operation of the entire vessel and specific attention is needed. In this respect, both the corrosion and the component failure are dealt with by regular inspections and deployment to ensure the good functioning condition of the equipment.

6.9 Calculation of overall availability of *"DSV A"*

So far in Chapter 6, the reliability results of the separate systems and sub-systems of *"DSV A"* have been investigated as well as additional maintenance measures have been suggested in order to enhance the reliability and operability of the subject vessel. Bearing the above in mind, the overall availability of the vessel is also assessed next. In this case, *"DSV A"* is considered in its entity thus combining the above mentioned systems into one single system. The availability of *"DSV A"* is calculated as discussed in section §4.5.2.3. Furthermore, it is studied by modelling the main systems examined in the previous sections of this thesis with the use of the DFTA tool as shown in Figure 6.30. The entire DFT structure modelling regarding the vessel availability is presented in Appendix D.

As can be seen, in the case of the calculation of the entire system availability, an 'OR' gate has been used, meaning that the availability of *"DSV A"* is influenced from the availability of all the other individual systems shown below it in the DFT structure. For the Power plant, a dynamic 'PAND' gate is used to show the interrelation of the two separate engine rooms onboard the vessel (failure of one E/R does not render the ship unavailable as there is a back-up system kicking-in to substitute the failed one). The rest of the main systems are modelled with static gates ('AND' gate for the LA&H system and 'OR' gates for all the rest of the main systems). In the case of the LA&H system, both crane sub-systems (heavy and light ones) need to be out of operation in order for them to be unavailable while for the rest of the main systems, any failure of the main sub-systems reduces their availability. Having discussed the availability modelling of *"DSV A"*, the aforementioned results are explicitly shown in Table 6.54 and Figure 6.31 presented next.

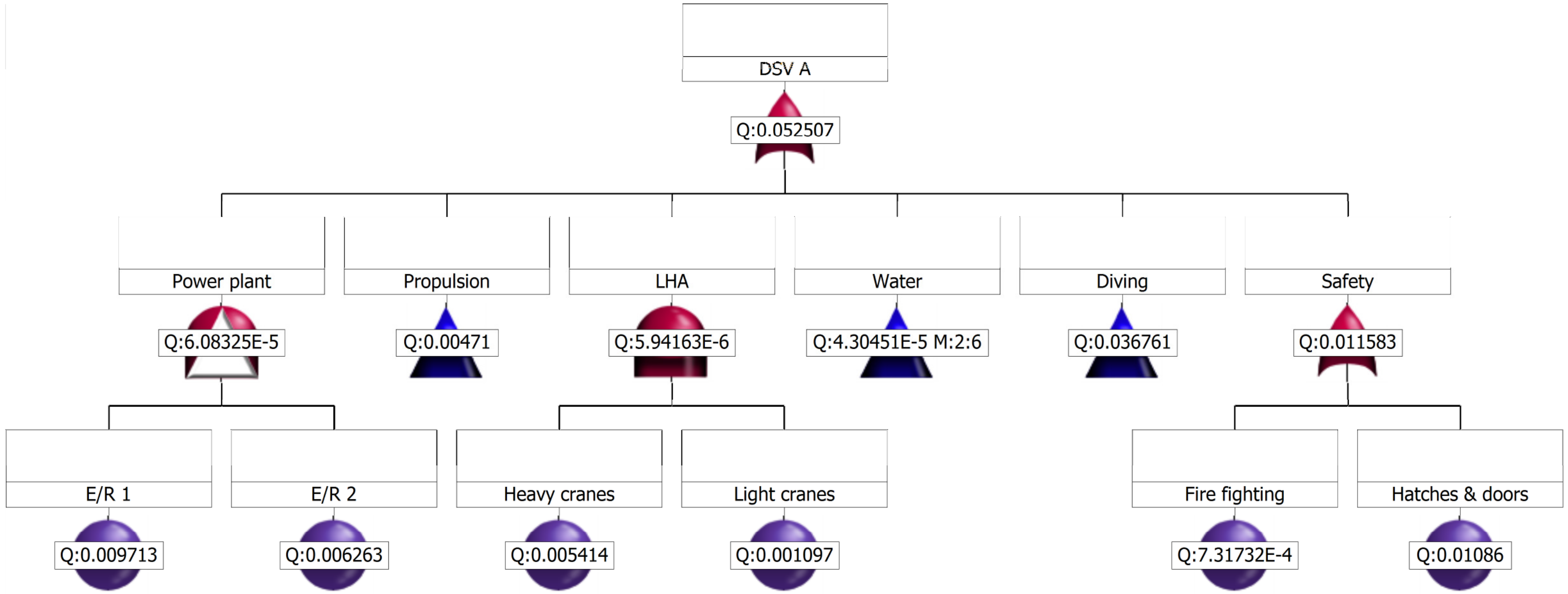

Figure 6.30 DFTA structure for the availability of *"DSV A"*

Table 6.54 Availability results of *"DSV A"* before and after the introduction of maintenance measures

	Availability results		
Time (months)	**Initial (%)**	**Final (%)**	**Increase (%)**
0	100.00	100.00	0.00
2	88.60	94.76	6.16
4	78.38	89.78	11.40
6	69.23	85.04	15.82
8	61.06	80.54	19.48
10	53.78	76.26	22.48
12	47.30	72.19	24.88
14	41.55	68.32	26.77
16	36.46	64.65	28.19
18	31.95	61.16	29.21
20	27.97	57.86	29.88
22	24.46	54.72	30.26
24	21.36	51.74	30.37
26	18.64	48.91	30.27
28	16.25	46.23	29.98
30	14.15	43.69	29.53

As can be observed, the comparison of the results regarding the availability of *"DSV A"* before and after the introduction of the suggested maintenance measures shows that the availability of the vessel increases over time when considered as a single system (entire ship). The improvement in the overall availability of the vessel initiates from 6.16% in the first few months of its operation whereas it reaches its maximum value after 26 months (more than 30%). Following this increasing trend, the enhancement of the availability slowly starts declining till the end of the computed time of 30 months, reaching a level of 29.53%.

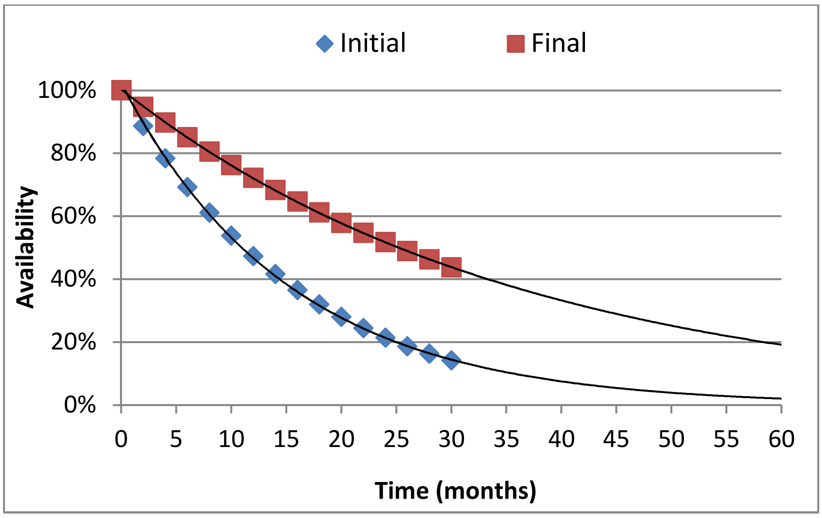

Figure 6.31 Availability results for *"DSV A"* over time before and after the introduction of maintenance measures

Furthermore, in Figure 6.31, the availability curve is projected to cover a period of 60 months (equivalent to the time till the next Special Survey of the vessel) in order to examine the time-point at which the vessel may prolong its extended maintenance survey. As can be seen, the initial availability results decrease exponentially and reach their minimum level after 60 months. This indicates that the vessel can still perform satisfactorily according to the national and international regulations as well as the company's internal maintenance and operational policy. However, the new results regarding the availability of the vessel are still high enough to extend the dry-docking interval beyond that time-point (60 months) and thus carry out the needed surveys and extensive maintenance programme according to the guidelines of the Classification Society and the Flag State that the vessel is registered with. In addition to the last remark, the owners of the vessel may opt for a preliminary inspection of the ship's systems when the results of the availability index of the vessel reach the lower level of 50%; that is after 25 months of operation based on the new enhanced availability results (almost 40% increase compared to the initial results of 10 months), thus increasing the originally planned maintenance and repair interval as well.

6.10 Chapter summary

In this Chapter, the results of the first case study in which the RCBM strategy is applied, are demonstrated. This includes the case study of the reliability and criticality analysis of Diving Support Vessel *"DSV A"* with its systems and sub-systems. In this respect, the main systems identified are the Power plant, Propulsion, Lifting, Anchoring & Hauling, Water, Diving and finally the Safety system. Initially, the reliability results of the main systems examined are presented followed by the Probability of Failure (PoF) results of each one of the sub-systems. Then, the Birnbaum, Criticality and Fussell-Vesely importance measures are examined, validating the initial results of the DFTA and identifying the most critical items and components of the subject vessel. Moreover, remedial measures have been suggested for each one of the critical items. The above maintenance measures are suggested in terms of the introduction of 'SPARE' gates in the DFT structure for each main system examined. Furthermore, the availability of the vessel considered as an overall system is also scrutinised and shows the clear benefits of the reliability and criticality based maintenance strategy. What follows next is the second part of the application of the RCBM strategy; that is, the presentation of the results for the case of the DG system of a motor sailing cruise vessel.

7 CHAPTER 7 – RELIABILITY RESULTS OF THE DG SYSTEM IN A MOTOR SAILING CRUISE VESSEL

7.1 Chapter outline

In this Chapter, the results of the second application of the RCBM framework are presented. That is, the reliability and criticality analysis of the Diesel Generator (DG) system of a motor sailing cruise ship. The DG system is divided into five sub-systems which are the five individual DGs (DG 1, DG 2, DG 3, DG 4, DG 5-emergency generator) providing the entire power generation of the subject vessel. The FMECA approach for the overall DG system is initially used in order to examine the generic criticality index of the mentioned system. The Dynamic FTA (DFTA) tool is employed next presenting the reliability results of the main system and sub-systems. Then the Birnbaum (Bir), Criticality (Cri) and Fussell-Vesely (F-V) Importance Measures (IMs) are applied and the cut sets assist in identifying the most critical components of the subject system. Following the above, maintenance measures are suggested for each one of the identified critical items of the individual DGs. Additionally, an evaluation of the entire DG system of the subject vessel is performed, comparing the critical items of each separate DG with each other concerning the specific sub-systems (main body/frame, fuel oil, lube oil, air, electrical components and miscellaneous sub-systems). Moreover, a cost assessment of the different maintenance options regarding the overall DG system is also performed. Based on the results obtained with this approach, the discussion for each one of the system and sub-systems examined takes place in the following sections.

7.2 FMECA results

The results of the generic FMECA approach for the overall DG system are initially shown in this section in order to introduce the experts' judgement (technical manager, superintendent engineer, 2nd engineering officer) into the present analysis following the RCBM strategy framework as is mentioned in section §4.3. The results of the FMECA include the presentation of the most critical components of the DG sub-system examined based on the frequency of the failures of the components as well as the severity of these failures occurring. The full description as well as all the details of the criticality ranking of the equipment examined is shown in Appendix H. In addition to the above, generic mitigation and/or prevention measures are also suggested and provided by the experts' team in order to avoid the high criticality failures.

As already mentioned in the methodology Chapter (section §4.5), the DG system is examined in the light of the various FMECA types: Personnel Safety (S), Environmental protection (E), Asset integrity (A) and Operation (O). Moreover, these are categorised according to their severity of impact that may occur and their frequency of occurrence. In terms of the severity categories the following five ones are identified; that is A (minor), B (marginal), C (major), D (critical) and E (catastrophic). Regarding the frequency ranking, another five categories are demonstrated as well: category 1 (extremely unlikely), 2 (remote), 3 (occasional), 4 (probable) and 5 (very frequent). Their combination signifies the criticality index for each specific component examined. Thus, the overall criticality matrix is divided into:

- Level 1: Low (negligible criticality-categories A1, A2 and A3)
- Level 2: Moderate (tolerable criticality- categories A4, A5, B3, C2, D1, E1))
- Level 3: Significant (tolerable criticality with specific measures in place to prevent/mitigate the end-results-categories B4, B5, C3, C4, D2, D3, E2)
- Level 4: High (intolerable criticality-categories C5, D4, D5, E3, E4, E5)

Bearing the above in mind, the results of the generic FMECA are displayed in Table 7.1.

Table 7.1 Results of the FMECA approach for the DG system

Sub-system	Failed item	Failure event	Criticality			
			S	E	A	O
Main body/frame	Oil mist detectors	blocked	D2	D2	D2	D2
	Valves & fuel injectors	blocked valve and/or injectors	B3	B3	C3	C3
	Governor	erratic function	A3	A3	C3	C3
	Cylinder heads 1-6	leakage, overheating	B3	B3	C3	C3
	Turbocharger	bearing failure, seizure	A3	B3	C3	C3
Fuel oil	Fuel system, valves, piping	Rupture of pipe, leakage, sludge/water in the line	D2	D3	D3	D3
	Fuel filter autoclean	blocked	B3	B3	B3	B3
	Fuel filter duplex	blocked	A3	B3	B3	B3
	Thermostatic valve circuit	blocked	B2	B2	B2	B2
Lube oil	L/O system valves & piping	blocked valve, burst flange connecting piping, leakage, overheating	C2	C2	C2	C2
	Filter, glacier oil	blocked	B3	A3	A3	B3
	Filter, lube oil (duplex)	blocked	B3	A3	A3	B3
Air	Start limiter	fail to start	A3	A3	B3	B3
	Start air system	fail to start	A3	A3	B3	B3
	Air cooler & manifold	blocked	A3	A3	B3	B3
Electrical components	Alternator	cannot put on load	B3	A3	D3	C3
	DG control panel	malfunctioning	A2	A2	C2	C2
Miscellaneous	Engine preheating unit	cannot start, structural cracks due to thermal stress	A2	B2	C2	C2
	Alarms	not operational	B3	A3	A3	B3
	Instruments	unable to start	A3	A3	B3	B3
	Special tools	broken or lost	A2	A2	A2	B2

Having performed the FMECA, the most critical items for each individual sub-system (main body/frame, fuel oil, lube oil, air, electrical components and miscellaneous sub-system) identified through the FMECA approach are as follows:

- Main body/frame

For this sub-system, the oil mist detectors are the most critical item as identified from the experts' judgement throughout the various categories mentioned (criticality ranking D2 for personnel safety, environmental impact, asset integrity and operation). This is then followed by the valves & fuel injectors together with the cylinder heads (criticality ranking B3, B3, C3 and C3 respectively). The turbocharger follows next (A3, B3, C3, C3) as well as the governor (A3, A3, C3, C3).

- Fuel oil

For this sub-system, the most critical item is the valves & piping (criticality ranking of D2, D3, D3, D3). The next most critical item is the fuel filter autoclean (criticality ranking of B3, B3, B3, B3 respectively) followed by the fuel filter duplex (criticality of A3, B3, B3, B3) and the thermostatic valve circuit (criticality of B2, B2, B2, B2).

- Lube oil

For the lube oil sub-system, the valves & piping item is the most critical one. Its criticality properties are the same for all mentioned categories (C2). This is then followed by the LO filter duplex and the filter glacier oil (criticality of B3, A3, A3, B3) regarding the criticality categories mentioned above.

- Air

In the case of the air sub-system of the DG, all three items present similar criticality results (criticality of A3, A3, B3, B3). This includes the start limiter, the start air system and the air cooler & manifold. It is interesting to notice that for the experts that participated in the formulation of the FMECA Table, the criticality of all the items for the specific sub-system have the same importance in all four categories these are examined (personnel safety, environmental impact, asset integrity and operation).

- Electrical components

For the electrical components sub-system, the alternator has resulted in being the most critical item (criticality of B3, A3, D3, C3) followed by the DG control panel (criticality of A2, A2, C2, C2). Although the criticality indices for both items are quite similar, the alternator is attributed higher severity index (D3) in one of the categories examined (asset integrity) than that of the DG control panel.

- Miscellaneous

Finally, for the miscellaneous sub-system the most critical item identified from FMECA is the engine preheating unit (criticality index of A2, B2, C2, C2) followed by the instruments (criticality index of A3, A3, B3, B3) and the alarms (criticality index of B3, A3, A3, B3).

7.3 Reliability results for the overall DG system

Following the results of the FMECA, the Dynamic FTA (DFTA) approach is used next to perform the reliability and criticality analysis of the DG system. At this point it is important to note that a decisive step in this case study was to set the threshold of good reliability results for the examining system and sub-systems. This threshold must be neither very low nor very high so as to provide a good measure for the comparison of the results stemming from the analysis performed. After discussing with professionals in the maritime field (i.e. technical managers, superintendent engineers, chief engineers) as well as bearing in mind the best practice standards in the industry, it was decided to set a threshold of 95% of good operational capability for each one of the DGs and the entire DG system as well. In the following paragraphs, the analysis and the results of the entire DG system as well as of each one of the individual DGs are presented.

At first the calculation results for the entire DG system are shown together with the reliability IMs and the cut set results of the same system. The IMs consist of the Birnbaum (Bir), Criticality (Cri) and Fussell-Vesely (F-V) IMs. It is important to notice that each one of the IMs describes different characteristics of the events identified, hence the combination of these IMs provide a good evaluation of which end-events are the most critical for the operation of the DG system. Apart from the IMs, the identification of the cut set results for the main system also takes place. Subsequently, based on the identification of the most critical event/component of the subject system, ‘SPARE’ gates and events are introduced so as to investigate the effectiveness of the maintenance measures to be introduced in order to improve the current condition of the DG. The new results regarding the reliability of the subject system are also presented in a graph comparing the condition of the system before and after the introduction of ‘SPARE’ gates and events. Overall the study shows the benefits of the novel reliability and criticality based assessment. Having this in mind, the entire DG system calculation results are presented next.

7.3.1 Calculation results for the DG system

The reliability calculation results of the overall DG system of the entire cruise ship are shown in Figure 7.1.

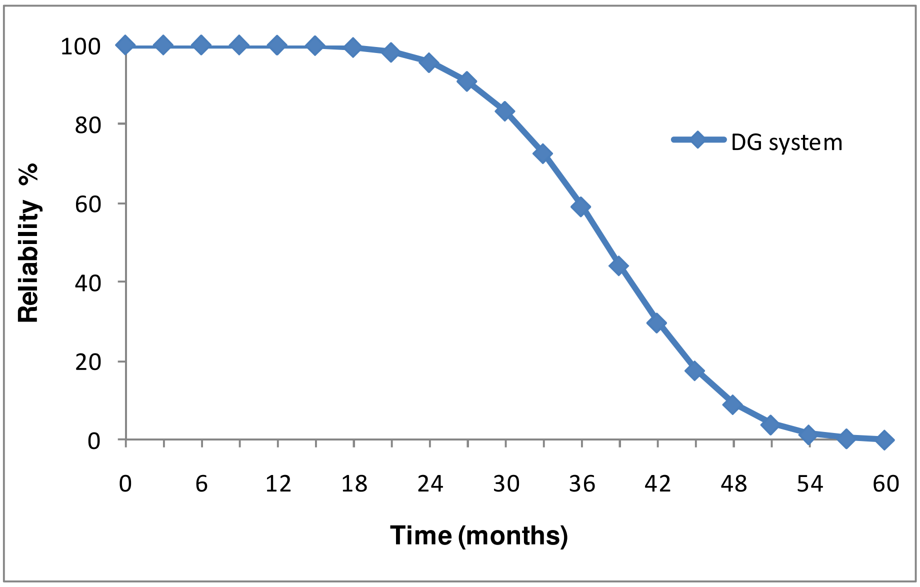

Figure 7.1 Reliability results of the overall DG system of the cruise ship

As can be observed from the above Figure, the entire DG system presents steadily good results for a period of 24 months. It then starts deteriorating following an exponential decrease in reliability reaching a figure of about 50% at 37 months. It then diminishes completely at 54 months of operation without any maintenance intervention or corrective measures applied to it. In general it can be said that the initial results are satisfactory in terms of the current maintenance and operational regime of the DG system of the subject vessel. These mostly refer to preventive maintenance tasks carried out following the Planned Maintenance System (PMS) of the vessel while the restricted use of condition monitoring applications is also applied especially in the case of vibration monitoring of rotating equipment. On the other hand, the condition of the DG system and the individual DG sub-systems can be further improved by examining which events/components are more critical through the investigation of the reliability IMs and cut set results of the individual DGs as is shown in the next section.

7.3.2 Reliability IMs results for the main DG system

In Tables 7.2-7.4 the reliability IMs for the entire DG system of the cruise vessel are shown. At first, the Birnbaum IM is presented followed by the Criticality and Fussell-Vesely IMs. By examining the results of the IMs for the overall DG system, it will be possible to identify the most critical DG sub-system, in which specific attention will be required in order to suggest relevant maintenance measures.

Table 7.2Birnbaum IM for the entire DG system (21 out of 105)

	Event	Birnbaum		Event	Birnbaum
1	Start air system 1	0.1284%	12	Valves & piping 1	0.0272%
2	Start limiter 1	0.0991%	13	Filter autoclean 1	0.0267%
3	LO Filter duplex 1	0.0986%	14	Control panel 1	0.0242%
4	LO valves & piping 1	0.0986%	15	Alternator 1	0.0242%
5	Engine preheating unit 1	0.0857%	16	Special tools 1	0.0226%
6	Instruments 1	0.0857%	17	thermo valve circuit 3	0.0138%
7	Thermo valve circuit 1	0.0849%	18	Valves/fuel injectors 1	0.0128%
8	Filter duplex 1	0.0649%	19	Turbocharger 1	0.0128%
9	Filter glacier oil 1	0.0442%	20	Governor 1	0.0128%
10	Air cooler & manifold 1	0.0338%	21	Cylinder heads 1	0.0128%
11	Alarms 1	0.0327%			

Table 7.3 Criticality IM for the entire DG system (21 out of 105)

	Event	Criticality		Event	Criticality
1	Filter autoclean 1	84.294%	12	Special tools 1	49.024%
2	Valves & piping 1	84.294%	13	Alarms 1	49.022%
3	Filter duplex 1	84.279%	14	Engine preheating unit 1	49.010%
4	Thermo valve circuit 1	84.271%	15	Instruments 1	49.010%
5	Air cooler & manifold 1	73.449%	16	Oil mist detectors 1	26.336%
6	Start limiter 1	73.426%	17	Cylinder heads 1	25.446%
7	Start air system 1	73.417%	18	Governor 1	20.928%
8	Alternator 1	73.326%	19	Control panel 1	13.859%
9	Filter glacier oil 1	56.426%	20	Filter autoclean 3	7.901%
10	LO Filter duplex 1	56.412%	21	Valves & piping 3	7.901%
11	LO valves & piping 1	56.412%			

Table 7.4 Fussell-Vesely IM for the entire DG system (21 out of 105)

	Event	**Fussell-Vesely**		**Event**	**Fussell-Vesely**
1	Filter autoclean 1	84.309%	12	Special tools 1	49.037%
2	Valves & piping 1	84.309%	13	Alarms 1	49.037%
3	Filter duplex 1	84.309%	14	Engine preheating unit 1	49.037%
4	Thermo valve circuit 1	84.309%	15	Instruments 1	49.037%
5	Air cooler & manifold 1	73.466%	16	Oil mist detectors 1	26.343%
6	Start limiter 1	73.466%	17	Cylinder heads 1	25.454%
7	Start air system 1	73.466%	18	Governor 1	20.935%
8	Alternator 1	73.340%	19	Control panel 1	13.864%
9	Filter glacier oil 1	56.445%	20	Filter autoclean 3	7.903%
10	LO Filter duplex 1	56.445%	21	Valves & piping 3	7.903%
11	LO valves & piping 1	56.445%			

As is observed, DG 1 is the most important sub-system in terms of both the criticality and prone to happening in the overall system (Cri and F-V IMs) but also in terms of further improvement needed for its specific components (Bir IM). DG 3 follows in this list with the most critical sub-systems of the DG system of the vessel, focusing on the maintenance remedies required for the vessel on these two sub-systems. It is reminded that the numeric figures for each event of the DFT presented in these Tables (especially the comparison between the Bir and the rest of the IMs) are for reference only so as to distinguish the most important event in the same IM. Consequently, they do not denote that one event in one category of IM is less or more important than another event in another IM as every IM category describes different characteristics of the DFT system and sub-systems. On the other hand, although it should be assumed that the same maintenance approach is applied on both DG 1 and DG 3, by carrying out the reliability and criticality analysis it is observed that there is a difference in the maintenance results for each separate DG.

In this respect, this is a significant finding and benefit of performing the suggested maintenance analysis and RCBM strategy as substantial conclusions can be derived regarding the actual operation of the overall DG system of the vessel and consequently the maintenance policy applied on each one of the separate DGs. As shown in section §5.4.1, the main DGs are located in pairs in both sides of the vessel (port for DG 1 and DG 2 and starboard for DG 3 and DG 4 accordingly). In this respect, any differences in the operation and overall function of the DGs will also reflect on the presentation of the results for the subject DGs as these are shown in the results of the reliability IMs. Additionally, remedial measures can be suggested to improve working condition of the DGs as is shown in the next sections of this Chapter in which their individual performance is examined.

7.3.3 Cut set results for the main DG system

In this section, the presentation of the cut set results of the main DG system takes place (Table 7.5).

Table 7.5 Cut set results for the entire DG system (10 of 235)

	Events	Cut set Order
1	Oil mist detectors 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
2	Cylinder heads 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
3	Governor 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
4	Turbocharger 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
5	Valves/fuel injectors 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
6	Oil mist detectors 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Control panel 1	12
7	Cylinder heads 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Control panel 1	12
8	Governor 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Control panel 1	12
9	Oil mist detectors 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1, Engine preheating unit 1, Alarms 1, Instruments 1, Special tools 1	12
10	Cylinder heads 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1, Engine preheating unit 1, Alarms 1, Instruments 1, Special tools 1	12

As is shown from this small extract, the cut set results of the entire DG system verify the results obtained from the IMs for the subject system. DG 1 is the most critical sub-system followed by DG 3. By analysing the total number of cut set results, DG 2 is next with the most critical DGs followed next by DG 4 and DG 5. The results show that DG 1 and DG 3 are the most exposed DGs to failure and maintenance measures should be primarily focused on them by introducing maintenance remedial tasks as will be shown in the next Chapter. The results also show that potential operational issues that may be attributed to these results such as overloading of the specific DGs in comparison to the other two in each pair of DGs. Another interesting outcome of the analysis of the cut set results for the entire DG system is that the Emergency DG (DG 5) is the most effective from all DGs. This is something expected as this DG is only used in emergency situations and for practicing emergency drills so as to keep it in good operational condition (not used on a daily basis as with the other DGs). Moreover, the cut set order in this case 12, which means that is 12 different DG components take part in the failure of the subject system. Consequently, it can be derived that since a big number of end-events/components need to occur for the failure of the DG to occur, it is highly probable that this will not take place. On the contrary, in the case of a small number of cut sets appearing, it would indicate the very high probability of occurrence of the subject failures for the examined DG. Following the above, the reliability calculation results for the individual DGs are shown followed by the presentation and analysis of the IM and cut set results for each one of the DG sub-systems.

7.4 Reliability results for the individual DGs

In this section, the reliability results for each individual DGs are presented next. In this respect, the reliability calculation results are shown first, followed by the IMs and the cut sets results for each DG (DG 1-DG 5)

7.4.1 Calculation results for the individual DGs

As mentioned before, the reliability results for the individual DGs are shown (Figure 7.2).

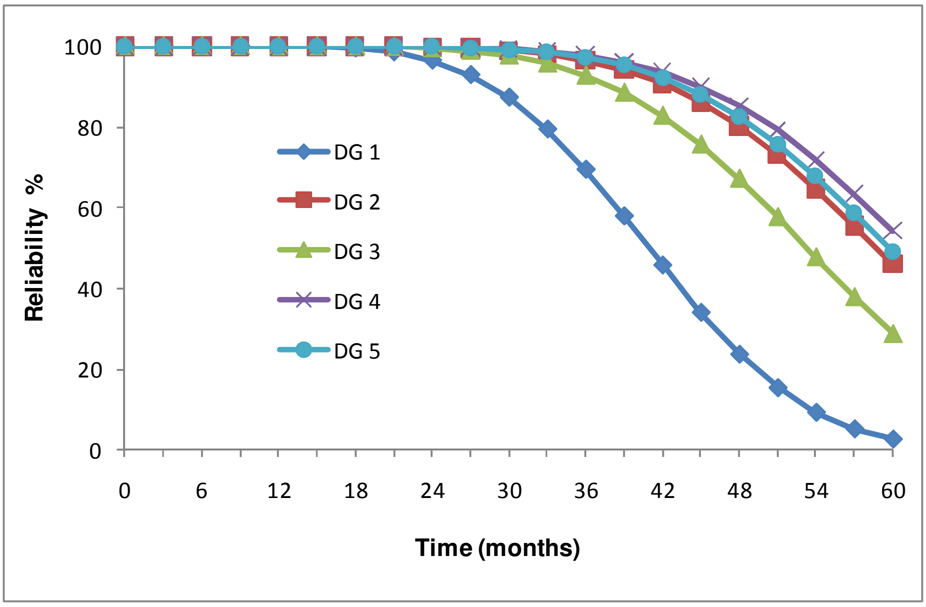

Figure 7.2 Reliability results of DG 1, DG 2, DG 3, DG 4 and DG 5 sub-systems

In this case, DG 1, DG 2, DG 3, DG 4 and DG 5 show good results for a long period of time (more than 30 months of simulation time), similar to the one for the main DG system. The reliability of the majority of the DGs remains in high standards for up to 36 months while the reliability of DG 1 operates at high level for a period of up to 24 months. This is expected in practical terms for the reliability of the DGs since on a cruise ship all the systems need to perform at their highest level in order to deal with the high demand of reliable as well as safe operation due to passengers onboard, environmental performance, asset integrity and company reputation in this type of demanding shipping market. Following the results of DG 1, DG 3 preserves its reliability excellence for 35 months while DG 2 and DG 4 show better reliability results with 38 months of good operational period each. Additionally, the emergency DG (DG 5) also presents very good reliability results, which is anticipated as this DG is practically used in emergency situations and it always needs to be in excellent condition.

After the presentation of the reliability results of all the individual DGs, a separate analysis of the measures to be taken so as to improve the condition of each one of the DGs is mentioned. In this analysis, the reliability IMs results as well as the cut set results of each DG are examined. The combination of these results identifies the DG components that are most critical for the operation of the DGs, therefore ‘SPARE’ gates and events can be introduced so as to examine the improvement of the reliability results for the subject DG. Bearing this in mind, the reliability results for DG 1 are described in the next section.

7.5 Reliability results for DG 1

As stated before, the reliability results of DG 1 are presented next.

7.5.1 Reliability IMs results for DG 1

At first, the reliability IM results for DG 1 are shown in Tables 7.6-7.8.

Table 7.6 Birnbaum IM for DG 1

	Event	Birnbaum		Event	Birnbaum
1	Start air system 1	0.128%	12	Filter autoclean 1	0.027%
2	Start limiter 1	0.099%	13	Valves & piping 1	0.027%
3	LO Filter duplex 1	0.099%	14	Alternator 1	0.024%
4	LO valves & piping 1	0.099%	15	Control panel 1	0.024%
5	Engine preheating unit 1	0.086%	16	Special tools 1	0.023%
6	Instruments 1	0.086%	17	Oil mist detectors 1	0.013%
7	Valve circuit 1	0.085%	18	Turbocharger 1	0.013%
8	Filter duplex 1	0.065%	19	Governor 1	0.013%
9	Filter glacier oil 1	0.044%	20	Cylinder heads 1	0.013%
10	Air cooler & manifold 1	0.034%	21	Valves/fuel injectors 1	0.013%
11	Alarms 1	0.033%			

Table 7.7 Criticality IM for DG 1

	Event	Criticality		Event	Criticality
1	Filter autoclean 1	96.278%	12	Engine preheating unit 1	55.994%
2	Valves & piping 1	96.278%	13	Alarms 1	55.991%
3	Filter duplex 1	96.261%	14	Special tools 1	55.978%
4	Thermostatic valve circuit 1	96.252%	15	Instruments 1	55.978%
5	Air cooler & manifold 1	83.891%	16	Oil mist detectors 1	30.080%
6	Start air system 1	83.865%	17	Cylinder heads 1	29.064%
7	Start limiter 1	83.854%	18	Governor 1	23.904%
8	Alternator 1	83.751%	19	Control panel 1	15.830%
9	LO Filter duplex 1	64.448%	20	Valves/fuel injectors 1	8.361%
10	Filter glacier oil 1	64.432%	21	Turbocharger 1	8.361%
11	LO valves & piping 1	64.432%			

Table 7.8 Fussell-Vesely IM for DG 1

	Event	Fussell-Vesely		Event	Fussell-Vesely
1	Filter autoclean 1	96.291%	12	Engine preheating unit 1	56.006%
2	Filter duplex 1	96.291%	13	Special tools 1	56.006%
3	Thermostatic valve circuit 1	96.291%	14	Instruments 1	56.006%
4	Valves & piping 1	96.291%	15	Alarms 1	56.006%
5	Start air system 1	83.907%	16	Oil mist detectors 1	30.087%
6	Start limiter 1	83.907%	17	Cylinder heads 1	29.071%
7	Air cooler & manifold 1	83.907%	18	Governor 1	23.910%
8	Alternator 1	83.764%	19	Control panel 1	15.835%
9	LO Filter duplex 1	64.467%	20	Turbocharger 1	8.363%
10	Filter glacier oil 1	64.467%	21	Valves/fuel injectors 1	8.363%
11	LO valves & piping 1	64.467%			

As can be seen, the top list of the most critical events according to the Cri and F-V IMs comprises of components from the fuel sub-system (filter autoclean, fuel valves and piping, filter duplex and thermostatic valve circuit), which means that these events are the most likely to occur as well as contribute the most to the failure of DG 1. The next most critical sub-system for the operation of DG 1 is the air sub-system (start air system, start limiter and air cooler and manifold). The air sub-system is at the top of the list of the Bir IM, describing the components that can be further improved compared to the rest the components of DG 1.

In addition to the above, the most critical events/components for each sub-system of DG 1 need to be identified so as to suggest specific maintenance measures for each one of them. In order to carry out this task, a combination of the reliability IMs is needed in terms of specifying the event/component most likely to occur, the one that is more critical to the operation of DG 1 as well as the one that can be improved the most by applying additional maintenance effort. At this point it should be reminded that the low values of the Bir IM signify that the ranking of the specific components are not as important as the other two IMs (Cri and F-V). Nevertheless, this initial ranking list shows which of the mentioned components are more significant compared to the other events in the same system and can be considered in combination with the Cri and F-V IM at a later stage. The verification of the above results is also evident from the observation of the cut set results of DG 1 shown in the following sections.

7.5.2 Cut set results for DG 1

In this section the cut set results of DG 1 are presented (Table 7.9). Each cut set is a set of DG components which shows the potential way of the DG failure. This means that the failure of any one of the components of a cut set may lead to the failure of DG 1. In this way, the worst combination of component failures can be described and compared with the IMs identified previously. The first 10 of 47 cut sets are shown. It is interesting to note that the cut set results are of the 12th order, which means that each cut set consists of a combination of 12 basic events.

Table 7.9 Cut set results for DG 1(10 of 47)

	Events	Cut set Order
1	Oil mist detectors 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
2	Cylinder heads 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
3	Governor 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
4	Turbocharger 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
5	Valves/fuel injectors 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1	12
6	Oil mist detectors 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Control panel 1	12
7	Cylinder heads 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Control panel 1	12
8	Governor 1, Valves & piping 1, Filter autoclean 1, Filter duplex 1, Thermo valve circuit 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Control panel 1	12
9	Oil mist detectors 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1, Engine preheating unit 1, Alarms 1, Instruments 1, Special tools 1	12
10	Cylinder heads 1, LO valves & piping 1, Filter glacier oil 1, LO Filter duplex 1, Start limiter 1, Start air system 1, Air cooler & manifold 1, Alternator 1, Engine preheating unit 1, Alarms 1, Instruments 1, Special tools 1	12

As can be observed, the unique combination of events that is at the top of the list includes the events identified as the most critical for each one of the parts of DG 1. For example, the oil mist detectors (body/frame), the fuel filter autoclean (fuel oil), the LO filter duplex (lube oil), the start air (air) and the alternator (electrical) are part of the top of the cut set list. Additionally, the cut set results are of the 12^{th} order; that is a combination of 12 end-events/failures needs to take place first for the overall system to fail, which on the other hand shows that the probability of this occurring is very low. Based on the above as well as on the IMs identified before, 'SPARE' gates and events are introduced for each one of the specific parts of DG 1. In this respect the events/components that are selected for further improvement for each one of the sub-systems of DG 1 are the following:

- Body/frame: oil mist detectors
- Fuel oil: fuel filter autoclean
- Lube oil: LO filter duplex
- Air: start air
- Electrical: alternator
- Miscellaneous: engine preheating unit

Based on the above, the discussion and suggestions as well as the comparison of the reliability results of DG 1 before and after the introduction of 'SPARE' gates are presented in the next section.

7.5.3 'SPARE' gates – Discussion and suggestions for DG 1

As presented in sections §7.5.1-7.5.2 of Chapter 7, the most critical items identified from the reliability and criticality analysis in the case of DG 1 are summarised in Figure 7.3.

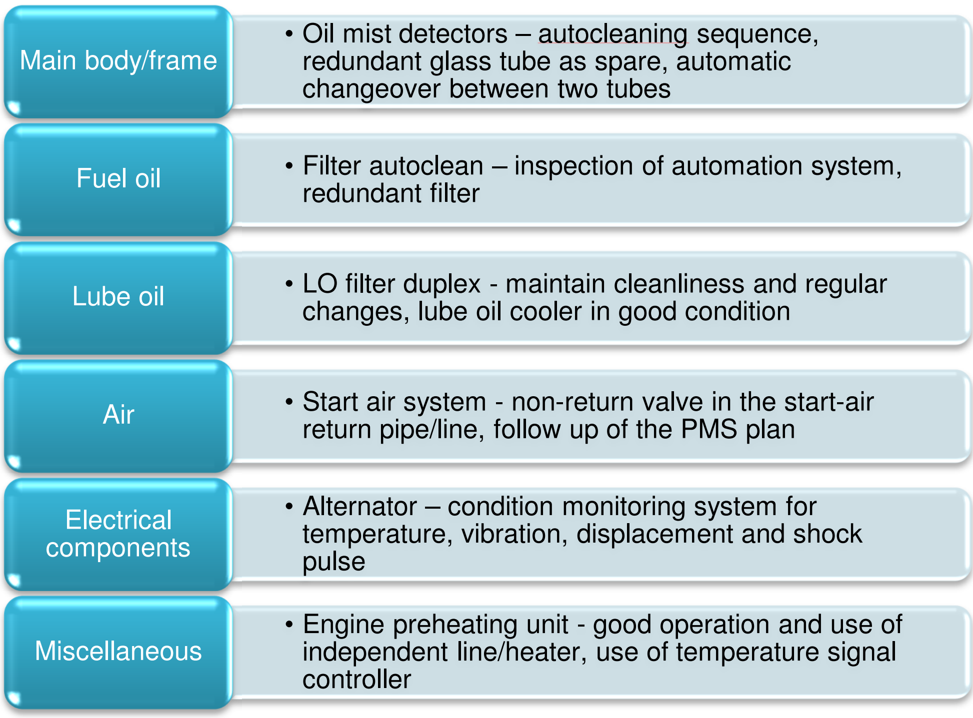

Figure 7.3 Most critical items/components and maintenance measures suggested for DG 1

As can be observed for the main body/frame sub-system, the oil mist detectors are shown as the most important component for DG 1. The operation of the oil mist detectors is based on taking samples of the oil mist in the crankcase every 30 minutes when in operation. In this way, oil mist detectors check the condition of the mist and compare it with standard value hydrocarbon percentage. However, the test sampling tube, which is located on the frame of the DG gets dirty, it requires further cleaning through the autoclean cycle in order to improve its operation. Another proactive maintenance measure is to auto-calibrate or clean it manually with fresh air and reset it to achieve the required oil mist checking. Apart from the above, a redundant glass tube should be considered to be kept as spare onboard to be ready for use when required after an initial visual inspection has been carried out by the engineer on duty as well as after following the instructions of the Chief Engineer. Furthermore, in case of two tubes being fitted, an automatic changeover could occur to prolong the cleaning interval of the oil mist detectors.

For the fuel oil sub-system, the filter autoclean includes a spindle, which is connected with the cleaning disc and which regulates the cleaning process of the fuel oil. In this respect, inspection and regular checks of the automation system (pneumatic tube connected to the spindle of the filter) should be carried out in order to achieve a smooth operation of the device. Additionally, a redundant filter arrangement next to the autoclean filter could be introduced to allow the main filter sufficient time interval to be cleaned. In this way, the cleaning disc will not underperform and further problems will be avoided.

For the lube oil sub-system, the lube oil filter duplex is the most critical item in this category. Its operation is related to keeping the lube oil passing through the pipes and valves in an as good condition as possible. The main maintenance task that needs to be considered for this item is to maintain cleanliness and regular changes so to be able to continue its function. A relevant maintenance task to the above is also to preserve the lube oil cooler at good condition through regular inspection.

For the air sub-system, the start air system presents the highest criticality results. For this piece of equipment, a potential failure root cause can be the incorrect timing as well as the incorrect pressure, which may lead to a fault in the air distributor. This in turn will lead to moisture present in the air used to accumulate in the air pipes/lines and consequently the valves being blocked. In the case that this becomes inefficient or inoperable, the pressure may rise from 30 bar initially in the line to 250 bar from the engine return-start air, which can lead to severe problems/explosion (initially the line can tolerate build-up pressure $1^{1/2}$ the initial pressure indicated). Another reason for the above can be a fault in the air dryer after the air passing from the air bottle. In this case, a maintenance measure can be allowing for a non-return valve in the start-air return pipe/line for not letting exhaust air coming back to the start air pipe/line. Furthermore, an additional measure can be the introduction of a flame trap, which can stop any flames build-up and allow only heat to pass through. If these turn out to be faulty, explosion might occur in the start air pipe/line as well. The above can be rectified by performing regular inspections in the machinery area and following the maintenance plan according to the manufacturer’s guidelines and specifications.

The alternator is identified as the most important component of the electrical sub-system of the DGs that requires further attention regarding its maintenance programme. Overall, the alternator is a major part of the power generation process onboard the ship and consequently there are a number of issues to consider more specifically in terms of maintenance rectification and optimisation. One of them is the failure of the main bearing (alternator end and thrust bearing), which may be caused by the misalignment of the alternator and the engine or not a strong enough foundation of the alternator, leading to sagging and consequently to misalignment problems. Moreover, the main bearing lubrication may be insufficient in addition to high axial loads imposed on starting, stopping as well as load changing when operating the specific DG.

In this case, remedial measures include the introduction of an online monitoring system, which will enable the measurement of temperature, vibration, displacement and shock pulse with transducers permanently installed on the DG and proximity probe to measure the vibrations on the main bearing. The permanently installed condition monitoring equipment can then send the relevant signal/data directly to the engine room control-unit to enable the continuous monitoring of the equipment in question. Alternatively, this can be achieved with the sub-contracting of competent personnel on periodical intervals (6 months) in order to carry out the condition monitoring inspection and identify potential faults in the operation of the alternator.

Regarding the miscellaneous equipment sub-system, the engine-preheating unit is the most significant item identified in terms of criticality. The engine preheating unit is an effective automatic temperature controller, which is capable of maintaining the temperature in the jacket liners within a safe operational limit (of usually 70^{o} C) in order to avoid any thermal stresses originating in it. For this piece of equipment to be efficient, maintenance tasks include the good operation and use of independent line/heater for the preheating unit for each DG as well as the deployment of an electric heater, which will boost the temperature for the other operating DGs. Furthermore, the use of a proportional integral derivative (PID) controller, which is a control loop feedback mechanism measuring the difference/error between the current temperature value and the one that is preset and adjusts it accordingly may be deployed.

Having the above in mind, the introduction of ‘SPARE’ gates and events in the DFT structure is presented, bearing in mind the results of the reliability IMs and cut sets described in the previous paragraphs (Figure 7.3).

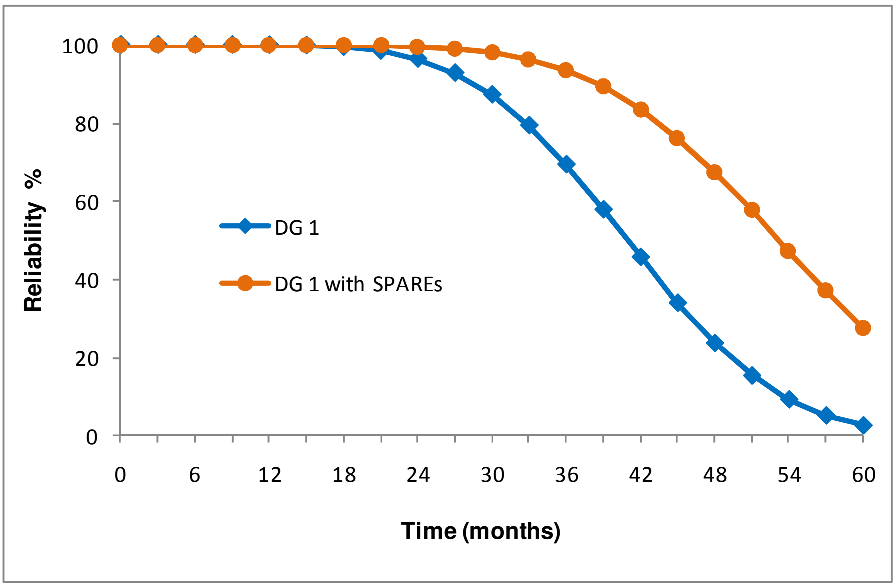

Figure 7.4 Reliability results of DG 1sub-system before and after the introduction of maintenance measures ('SPARE' gates)

As shown in Figure 7.4, the reliability results of DG 1 are improved after the introduction of the 'SPARE' gates (41% increase compared to the previous condition). The good reliability level of 95% is maintained for 34 months compared to the previous level of 24 months, which, in terms, contributes to the overall increase of the reliability of the main DG system.

7.6 Reliability results for DG 2

In this section, the reliability IMs for DG 2 are shown together with the cut set results and the introduction of 'SPARE' gates so as to observe the effect of additional maintenance measures on the condition of this system. At first, the IMs of DG 2 are presented.

7.6.1 Reliability IMs results for DG 2

In this section the results of the DG 2 IMs are shown in Tables 7.10-7.12.

Table 7.10 Birnbaum IM for DG 2

	Event	Birnbaum		Event	Birnbaum
1	Start limiter 2	0.0037%	12	Alarms 2	0.0008%
2	Air cooler & manifold 2	0.0037%	13	Instruments 2	0.0008%
3	LO Filter duplex 2	0.0036%	14	Alternator 2	0.0006%
4	LO valves & piping 2	0.0036%	15	Control panel 2	0.0006%
5	Thermostatic valve circuit 2	0.0034%	16	Filter autoclean 2	0.0006%
6	Filter duplex 2	0.0034%	17	Oil mist detectors 2	0.0004%
7	Valves & piping 2	0.0024%	18	Turbocharger 2	0.0004%
8	Filter glacier oil 2	0.0016%	19	Governor 2	0.0004%
9	Start air system 2	0.0010%	20	Cylinder heads 2	0.0004%
10	Engine preheating unit 2	0.0008%	21	Valves/fuel injectors 2	0.0004%
11	Special tools 2	0.0008%			

Table 7.11 Criticality IM for DG 2

	Event	Criticality		Event	Criticality
1	Start limiter 2	96.067%	12	Oil mist detectors 2	40.131%
2	Start air system 2	96.066%	13	Cylinder heads 2	23.433%
3	Air cooler & manifold 2	96.066%	14	Engine preheating unit 2	20.618%
4	LO Filter duplex 2	93.566%	15	Special tools 2	20.618%
5	Filter glacier oil 2	93.566%	16	Alarms 2	20.618%
6	LO valves & piping 2	93.566%	17	Instruments 2	20.618%
7	Valves & piping 2	89.866%	18	Control panel 2	15.808%
8	Filter autoclean 2	89.866%	19	Governor 2	14.805%
9	Thermostatic valve circuit 2	89.865%	20	Turbocharger 2	12.295%
10	Filter duplex 2	89.865%	21	Valves/fuel injectors 2	9.292%
11	Alternator 2	84.118%			

Table 7.12 Fussell-Vesely IM for DG 2

	Event	Fussell-Vesely		Event	Fussell-Vesely
1	Start limiter 2	96.068%	12	Oil mist detectors 2	40.131%
2	Start air system 2	96.068%	13	Cylinder heads 2	23.433%
3	Air cooler & manifold 2	96.068%	14	Special tools 2	20.618%
4	LO Filter duplex 2	93.567%	15	Engine preheating unit 2	20.618%
5	Filter glacier oil 2	93.567%	16	Alarms 2	20.618%
6	LO valves & piping 2	93.567%	17	Instruments 2	20.618%
7	Valves & piping 2	89.867%	18	Control panel 2	15.808%
8	Filter autoclean 2	89.867%	19	Governor 2	14.805%
9	Thermostatic valve circuit 2	89.867%	20	Turbocharger 2	12.295%
10	Filter duplex 2	89.867%	21	Valves/fuel injectors 2	9.292%
11	Alternator 2	84.118%			

From the Tables above (7.10-7.12), it can be seen that the most sensitive system of DG 2 is the air sub-system (start limiter, start air system and air cooler & manifold) followed by the lube oil sub-system (filter duplex, filter glacier oil and LO valves and piping). Then the fuel oil sub-system is next in the list with the most important events of DG 2 in all three categories of reliability IMs. Overall, as in the case of DG 1, the combination of the three IMs can provide the most critical components of this sub-system so as to be able to concentrate the maintenance effort on the specific components for each main element of DG 2. The verification of the above results is also evident from the observation of the cut set results shown in the next section. It is reminded that as mentioned in the case of DG 1, the Bir IM results should not be considered as of principal importance compared to the Cri and F-V IMs due to their extremely low values (in the range of 0.005%).

7.6.2 Cut set results for DG 2

In this section, the cut set results of DG 2 are shown (Table 7.13). As in the presentation of the cut set results of DG 1, the top ten of 21 cut sets are shown.

The cut set results presented herein are also of the 12th order as in the case of DG 1. This means that each cut set consists of 12 different events that lead to the failure of the main system, which in this case is DG 2. The cut set results verify the results obtained from the analysis of the IMs, which show the component failures most probable to occur as well as the ones that are most critical for the operation of the specific DG and also have the highest margin for improvement compared to the other components of the DG. In this respect the events/components that are selected for further improvement and which will be represented by ‘‘SPARE’’ gates and events are the following:

- Body/frame: oil mist detectors
- Fuel oil: valves & piping
- Lube oil: LO filter duplex
- Air: start limiter
- Electrical: alternator
- Miscellaneous: engine preheating unit

Table 7.13 Cut set results for DG 2(10 of 47)

	Events	Cut set Order
1	Oil mist detectors 2, Valves & piping 2, Filter autoclean 2, Filter duplex 2, thermo valve circuit 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Alternator 2	12
2	Cylinder heads 2, Valves & piping 2, Filter autoclean 2, Filter duplex 2, thermo valve circuit 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Alternator 2	12
3	Governor 2, Valves & piping 2, Filter autoclean 2, Filter duplex 2, thermo valve circuit 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Alternator 2	12
4	Turbocharger 2, Valves & piping 2, Filter autoclean 2, Filter duplex 2, thermo valve circuit 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Alternator 2	12
5	Valves/fuel injectors 2, Valves & piping 2, Filter autoclean 2, Filter duplex 2, thermo valve circuit 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Alternator 2	12
6	Oil mist detectors 2, Valves & piping 2, Filter autoclean 2, Filter duplex 2, thermo valve circuit 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Control panel 2	12
7	Oil mist detectors 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Alternator 2, Engine preheating unit 2, Alarms 2, Instruments 2, Special tools 2	12
8	Cylinder heads 2, Valves & piping 2, Filter autoclean 2, Filter duplex 2, thermo valve circuit 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Control panel 2	12
9	Cylinder heads 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Alternator 2, Engine preheating unit 2, Alarms 2, Instruments 2, Special tools 2	12
10	Governor 2, Valves & piping 2, Filter autoclean 2, Filter duplex 2, thermo valve circuit 2, LO valves & piping 2, Filter glacier oil 2, LO Filter duplex 2, Start limiter 2, Start air system 2, Air cooler & manifold 2, Control panel 2	12

7.6.3 ‘SPARE’ gates – Discussion and suggestions for DG 2

Based on the above regarding DG 2, the discussion and suggestions as well as the comparison of the reliability results of DG 2 before and after the introduction of ‘SPARE’ gates are presented in Figure 7.5. As can be seen, there are similarities in some of the sub-systems examined compared to DG 1. These ones are briefly mentioned while the rest of the critical items identified are described in detail in the following paragraphs.

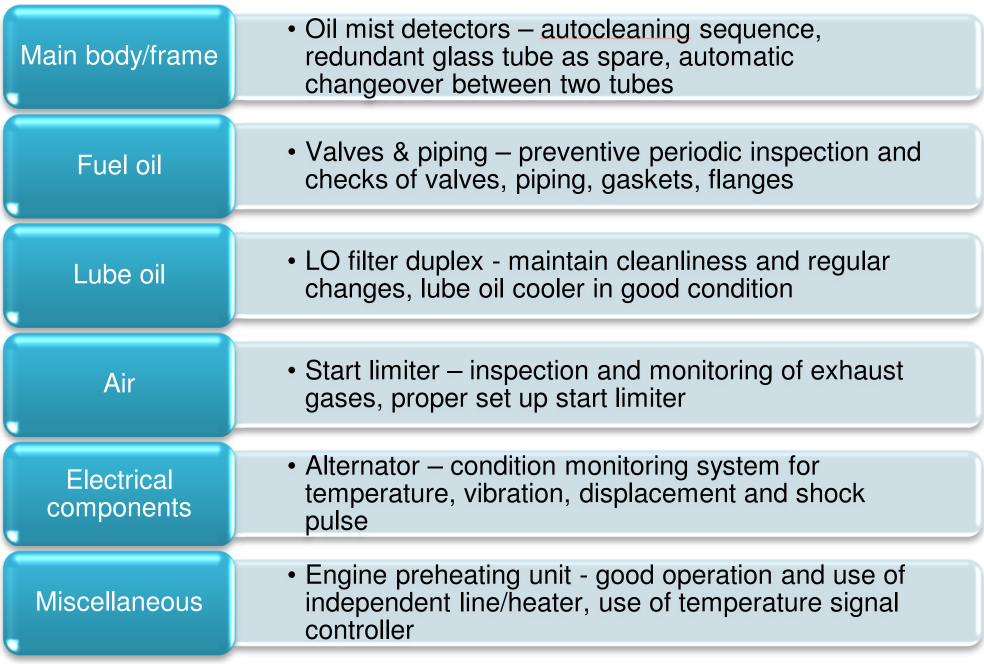

Figure 7.5 Most critical items/components and maintenance measures suggested for DG 2

In this respect, the oil mist detectors are the most critical item of the main body/frame of DG 2. The same failure causes as identified for the same sub-system of DG 1 apply in this case too. Regarding the fuel oil sub-system, the valves and piping present the highest criticality. In this case, the valves need to be checked periodically as per the scheduled maintenance plan as well as the piping for potential hot surfaces and not properly insulated areas in addition to leakages from gaskets and flanges.

For the lube oil sub-system of DG 2, the duplex filter is also identified as highly critical as in the case of DG 1. In this regard, similar maintenance procedures and tasks are suggested as well such as keeping the cleanliness and regular changes in order for this filter to be able to continue its function. Regarding the air sub-system, the start air limiter is the most critical item. In order to suggest adequate maintenance tasks for this item, one first needs to comprehend its function in the overall DG system. The start air limiter is used in turbocharged DGs and is connected to the governor of the DG. This operates as follows: a small ducting from the scavenge air manifold is connected to the governor, thus in this way controlling and limiting the amount of engine fuel supplied for the combustion during acceleration. The latter is proportional to the manifold air pressure. In case of a failure, a lot of smoke is generated since during the start of acceleration the scavenge pressure is very less but it improves as the engine picks up speed. The start air limiter ensures that the engine gets the right amount of fuel during start up and is proportional to the manifold air pressure. As the manifold air pressure increases, the governor acts to release more fuel to the engine.

In this way, the efficiency of the DG is improved during the acceleration of the engine while it substantially reduces the noxious exhaust emissions associated with the starting of the engine. It also reduces the black smoke that is very critical in connection with MARPOL Annex VI (air pollution) especially in European countries and U.S., in which waters the vessel is being employed. In this case, proper visual inspections as well as monitoring of the exhaust gas emissions temperature is part of the condition monitoring measures in order to observe anomalies in the combustion cycle, in which case malfunction of the start air limiter is a potential initiating event.

In the case of the electrical components sub-system, the alternator presents the highest criticality results. The alternator is a major part of the power generation process and is treated in the same manner as it has been already described in the case of DG 1 in the previous paragraphs. In brief, the main bearing is a critical component for the overall function of the alternator and its lubrication is of the foremost importance. Maintenance measures involve in most cases the application of condition monitoring techniques such as temperature, vibration and displacement monitoring. As for the miscellaneous sub-system, the engine preheating unit is once again regarded as of major importance for this DG as well.

Based on the above, the introduction of 'SPARE' gates and events in the DFT structure is carried out, bearing in mind the results of the reliability analysis described in the previous paragraphs. Figure 7.6 shows the comparison of the reliability results of DG 2 before and after the use of 'SPARE' gates, that is, before and after the introduction of additional maintenance measures.

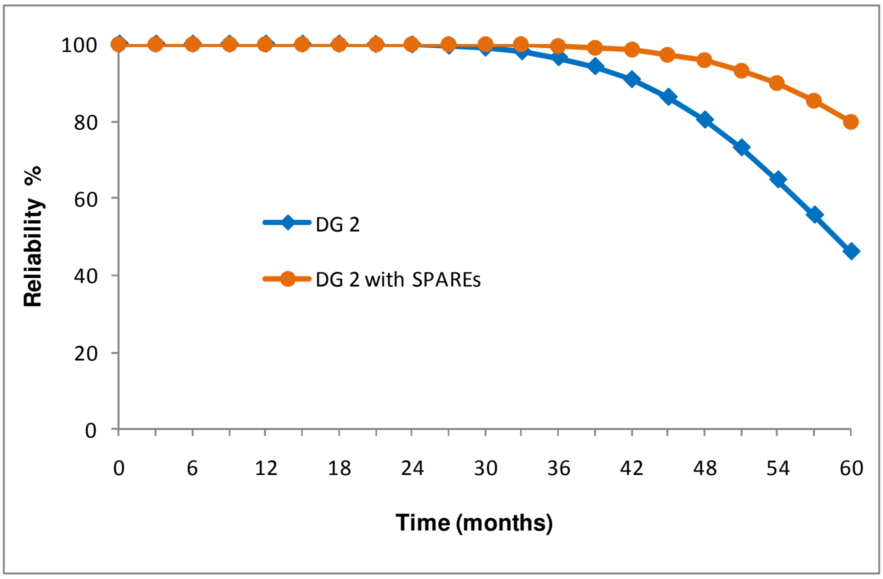

Figure 7.6 Reliability results of DG 2 sub-system before and after the introduction of maintenance measures ('SPARE' gates)

As shown in Figure 7.6, the reliability of DG 2 is significantly improved after introducing the 'SPARE' gates and events. The operational reliability of DG 2 is maintained to high level (above 95%) after 49 months, improvement which is in the order of 28% more than the original reliability level. This is a considerable percentile which adds to the reliability of the overall DG system of the vessel. Following DG 2, the results of the analysis for DG 3 are described in the next section.

7.7 Reliability results for DG 3

In this section, the analytical steps regarding the reliability results of DG 3 are followed in a similar way as already presented in the previous paragraphs. At first, the IMs are described and then the cut set results are presented so as to identify the most critical components of DG 3. Finally the introduction of 'SPARE' gates and events is proposed for the specific components identified as above.

7.7.1 Reliability IMs results for DG 3

In Tables 7.14-7.16 the reliability IMs for DG 3 are shown.

Table 7.14 Birnbaum IM for DG 3

	Event	Birnbaum		Event	Birnbaum
1	Thermostatic valve circuit 3	0.014%	12	Engine preheating unit 3	0.003%
2	Special tools 3	0.012%	13	Filter autoclean 3	0.003%
3	Alarms 3	0.012%	14	Valves & piping 3	0.003%
4	LO Filter duplex 3	0.009%	15	Alternator 3	0.002%
5	LO valves & piping 3	0.009%	16	Control panel 3	0.002%
6	Start air system 3	0.009%	17	Valves/fuel injectors 3	0.001%
7	Air cooler & manifold 3	0.009%	18	Governor 3	0.001%
8	Start limiter 3	0.009%	19	Cylinder heads 3	0.001%
9	Filter glacier oil 3	0.008%	20	Turbocharger 3	0.001%
10	Filter duplex 3	0.008%	21	Oil mist detectors 3	0.001%
11	Instruments 3	0.004%			

Table 7.15 Criticality IM for DG 3

	Event	Criticality		Event	Criticality
1	Filter autoclean 3	95.863%	12	Filter glacier oil 3	63.304%
2	Valves & piping 3	95.863%	13	Start air system 3	59.856%
3	Thermostatic valve circuit 3	95.860%	14	Air cooler & manifold 3	59.856%
4	Filter duplex 3	95.860%	15	Start limiter 3	59.856%
5	Alternator 3	84.425%	16	Valves/fuel injectors 3	42.696%
6	Alarms 3	81.304%	17	Turbocharger 3	19.518%
7	Instruments 3	81.304%	18	Cylinder heads 3	16.438%
8	Special tools 3	81.301%	19	Control panel 3	15.372%
9	Engine preheating unit 3	81.301%	20	Governor 3	11.436%
10	LO Filter duplex 3	63.305%	21	Oil mist detectors 3	9.782%
11	LO valves & piping 3	63.304%			

Table 7.16 Fussell-Vesely IM for DG 3

	Event	Fussell-Vesely		Event	Fussell-Vesely
1	Thermostatic valve circuit 3	95.864%	12	LO Filter duplex 3	63.308%
2	Valves & piping 3	95.864%	13	Start air system 3	59.859%
3	Filter duplex 3	95.864%	14	Air cooler & manifold 3	59.859%
4	Filter autoclean 3	95.864%	15	Start limiter 3	59.859%
5	Alternator 3	84.426%	16	Valves/fuel injectors 3	42.697%
6	Alarms 3	81.306%	17	Turbocharger 3	19.519%
7	Instruments 3	81.306%	18	Cylinder heads 3	16.438%
8	Special tools 3	81.306%	19	Control panel 3	15.372%
9	Engine preheating unit 3	81.306%	20	Governor 3	11.437%
10	Filter glacier oil 3	63.308%	21	Oil mist detectors 3	9.782%
11	LO valves & piping 3	63.308%			

In the case of DG 3, the most important sub-system identified is the fuel sub-system (filter autoclean, valves and piping, Thermostatic valve circuit, filter duplex) followed by the alternator and then the miscellaneous equipment (alarms, instruments, special tools, engine preheating unit). It is important to note that the above mentioned sub-systems are first in the list for all three IMs examined, which means that these sub-systems are not only critical for the operation of DG 3 but also have the highest potential for improvement compared to the rest of the sub-systems of the subject DG. In the next section, this will be clearly shown as the cut set results of DG 3 are presented. As observed, the results of the Bir IM which show the range that each specific component can affect the operation of DG 3 are very low compared to the Criticality and Fussell-Vesely measures.

7.7.2 Cut set results for DG 3

As mentioned before, the cut set results of DG 3 are presented in Table 7.17. Regarding the number of cut sets shown, the same condition as with DG 1 and DG 2 applies in this case too, that is the first 10 of 47 cut sets are presented in the following Table.

As observed, all cut sets shown are of the 12th order, consisting of 12 different DFT events. The sequence of the events of a cut set demonstrates the path leading to the failure of the top gate of the DFT, which in this case is DG 3. In this case, the same justification for the number of cut sets being shown is applied as in the case of the previous DGs examined before. The components identified in the IMs analysis are also part of the top ranked cut sets presented in the Table above. Therefore, in order to proceed to the next step which is the use of 'SPARE' gates and events, the following components are selected for implementing improved maintenance tasks:

- Body/frame: valves & fuel injectors
- Fuel oil: thermostatic valve circuit
- Lube oil: LO filter duplex
- Air: start air system
- Electrical: alternator
- Miscellaneous: alarms

Table 7.17 Cut set results for DG 3 (10 of 47)

	Events	Cut set Order
1	Valves/fuel injectors 3, Valves & piping 3, Filter autoclean 3, Filter duplex 3, thermo valve circuit 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Alternator 3	12
2	Turbocharger 3, Valves & piping 3, Filter autoclean 3, Filter duplex 3, thermo valve circuit 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Alternator 3	12
3	Cylinder heads 3, Valves & piping 3, Filter autoclean 3, Filter duplex 3, thermo valve circuit 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Alternator 3	12
4	Governor 3, Valves & piping 3, Filter autoclean 3, Filter duplex 3, thermo valve circuit 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Alternator 3	12
5	Oil mist detectors 3, Valves & piping 3, Filter autoclean 3, Filter duplex 3, thermo valve circuit 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Alternator 3	12
6	Valves/fuel injectors 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Alternator 3, Engine preheating unit 3, Alarms 3, Instruments 3, Special tools 3	12
7	Valves/fuel injectors 3, Valves & piping 3, Filter autoclean 3, Filter duplex 3, thermo valve circuit 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Control panel 3	12
8	Turbocharger 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Alternator 3, Engine preheating unit 3, Alarms 3, Instruments 3, Special tools 3	12
9	Cylinder heads 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Alternator 3, Engine preheating unit 3, Alarms 3, Instruments 3, Special tools 3	12
10	Turbocharger 3, Valves & piping 3, Filter autoclean 3, Filter duplex 3, thermo valve circuit 3, LO valves & piping 3, Filter glacier oil 3, LO Filter duplex 3, Start limiter 3, Start air system 3, Air cooler & manifold 3, Control panel 3	12

7.7.3 ‘SPARE’ gates – Discussion and suggestions for DG 3

In the case of DG 3, the discussion and suggestions as well as the comparison of the reliability results of DG 3 before and after the introduction of ‘SPARE’ gates are presented in Figure 7.7.

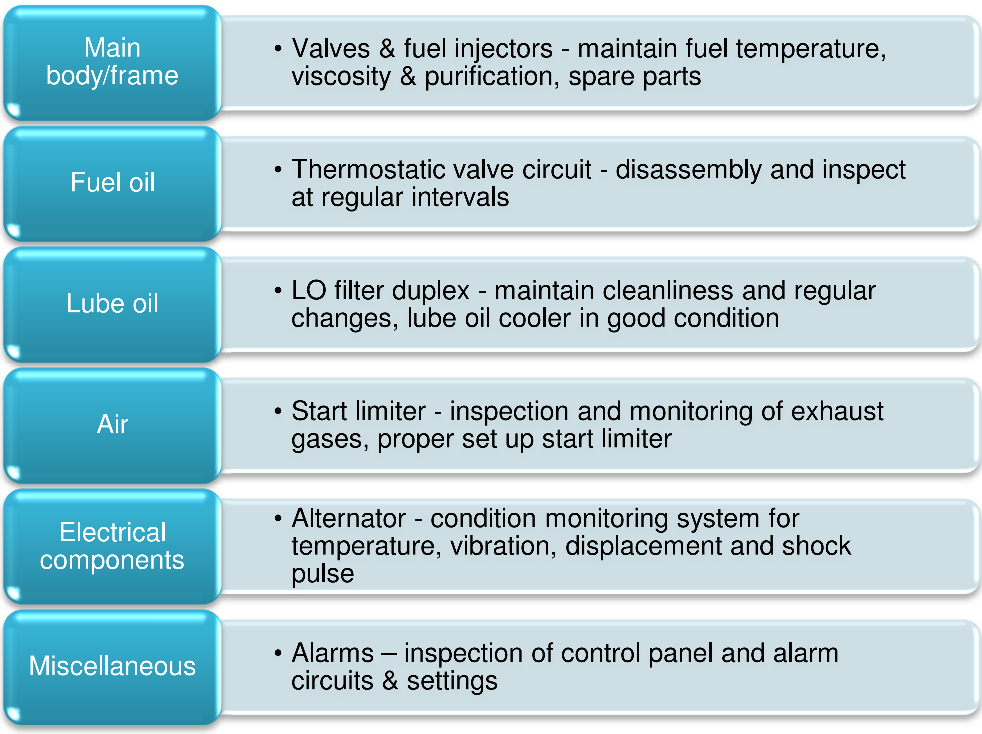

Figure 7.7 Most critical items/components and maintenance measures suggested for DG 3

As shown above, the valves & fuel injectors are identified as the most critical item for the fuel oil sub-system. In this case, it is very important to continuously maintain the correct fuel temperature, viscosity and purification of the fuel oil before it reaches the fuel injectors in order to achieve the optimum fuel oil burning and combustion sequence in the cylinder. Together with the above, the continuous checking of the fuel quality for any sign of excessive particles and water content is a prerequisite as well as whether the fuel oil temperature is retained to the standard level. It is also vital to check the DG periodically for its performance in addition for any sign of dripping nozzles and damaged spindles.

Furthermore, a full set of valves and injectors ready to be used in a case of immediate or even routine repair, should be kept onboard the ship. In the above case, the fuel injectors are included in the set of spare cylinder covers to be used when necessary. In such a case, the old valves are inspected and if deemed necessary, they are reconditioned and stored for use in the next set of repaired cylinder covers. Usual practice in such circumstances is to change a full set of cylinder covers in a DG when the operating condition of the vessel is the appropriate one (i.e. engine crew available to carry out the maintenance tasks and the vessel has enough time available for works). Additionally, if the reconditioning cannot be applied, an extra set of manufacturer's original valves and fuel injectors should be carried onboard the ship, depending on logistical restrictions as well as on the sailing route of the vessel.

With respect to the fuel oil sub-system, the thermostatic valve circuit is identified as the most critical item for DG 3. Overall, the thermostatic valves are used to control the cooling of the DGs by means of checking the low and high temperature of water passing through them. They are robust in structure and the maintenance tasks required to be carried out include the disassembly of the circuit/valve and inspecting of its condition periodically on an annual basis. For the lube oil sub-system, the duplex filter used is also identified as a critical item as in the case of DG 1 and DG 2. In this respect, the same maintenance tasks related to the previous mentioned DGs also apply in this case as well.

This is the case for the start air limiter as well, which is also identified as the most critical item for DG 2. In this respect, the inspection and monitoring of the temperature of the exhaust gas emissions could trace malfunction of the start air limiter. For the electrical equipment, the alternator is the critical item that poses risk in the operation of DG 3. The remedial measures regarding this piece of equipment are similar to the ones discussed in the previous section (i.e. DG 2). As for the miscellaneous components sub-system, the alarms are the most critical item as resulted from the criticality analysis of DG 3. Despite their oblique function, they should be also kept in the optimum condition in order to provide indications soon enough for any anomalies in the operation of the DGs so that the crew of the vessel may intervene and address the maintenance/repair tasks required. In this case, the criticality of the alarms refer to potential fault signals originating from various areas of the engine room or otherwise faults in the control panel where the various alarms settings are introduced. In order to improve this situation, an initial attempt to identify the origins of the faulty alarms in the control panel should be made by inspecting the control panel as well as including the alarm settings and the associated wiring. At a second level, inspection of the related machinery equipment should be performed to identify any discrepancies present in the existing equipment.

Following the above, the introduction of 'SPARE' gates and events in the DFT structure is performed. In this section, the reliability results of DG 3 after employing 'SPARE' gates and events is shown. In addition to the above, the comparison of the condition of DG 3 before and after the introduction of the maintenance measures is shown in Figure 7.8.

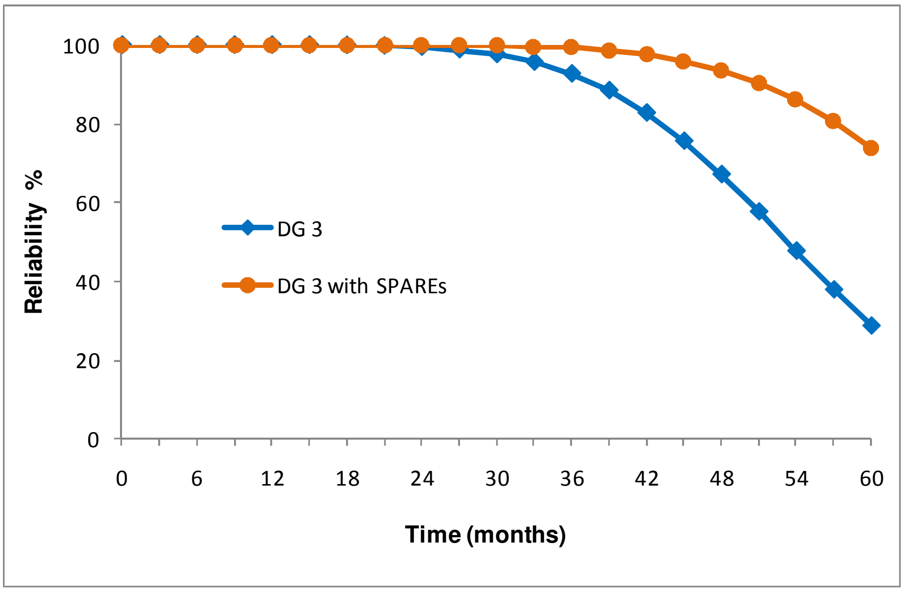

Figure 7.8 Reliability results of DG 3 sub-system before and after the introduction of maintenance measures ('SPARE' gates)

From Figure 7.8, the reliability results of DG 3 are about 31% higher than the previous results without the introduction of additional maintenance measures (from 38 months of high reliability performance to about 47 months). The maintenance measures taken in this case refer to the single components identified in the previous section when the IMs and the cut set results were identified. In continuation to the analysis of the DG system, the reliability results of DG 4 are presented next.

7.8 Reliability results for DG 4

In this section, the reliability results of DG 4 are shown starting from the IMs, carrying on with the cut set and finalising with examining the effect of 'SPARE' gates and events in the overall reliability of DG 4.

7.8.1 Reliability IMs results for DG 4

By examining the results of the IMs of DG 4, the failure of the components most probable to occur are shown together with the components that can achieve the higher improvement compared to the rest of the components in the same system (DG 4). These are presented in Tables 7.18-7.20.

Table 7.18 Birnbaum IM for DG 4

	Event	Birnbaum		Event	Birnbaum
1	LO valves & piping 4	0.002%	12	Engine preheating unit 4	0.0005%
2	Thermostatic valve circuit 4	0.002%	13	Special tools 4	0.0005%
3	Filter duplex 4	0.002%	14	Alternator 4	0.0003%
4	Start limiter 4	0.002%	15	Control panel 4	0.0003%
5	Start air system 4	0.002%	16	Filter autoclean 4	0.0003%
6	Air cooler & manifold 4	0.002%	17	Governor 4	0.0001%
7	Filter glacier oil 4	0.001%	18	Valves/fuel injectors 4	0.0001%
8	Valves & piping 4	0.001%	19	Oil mist detectors 4	0.0001%
9	LO Filter duplex 4	0.001%	20	Cylinder heads 4	0.0001%
10	Instruments 4	0.001%	21	Turbocharger 4	0.0001%
11	Alarms 4	0.001%			

Table 7.19 Criticality IM for DG 4

	Event	Criticality		Event	Criticality
1	Filter glacier oil 4	95.435%	12	Governor 4	43.333%
2	LO Filter duplex 4	95.435%	13	Instruments 4	27.229%
3	LO valves & piping 4	95.435%	14	Alarms 4	27.229%
4	Filter autoclean 4	90.629%	15	Engine preheating unit 4	27.229%
5	Valves & piping 4	90.629%	16	Special tools 4	27.229%
6	Filter duplex 4	90.628%	17	Cylinder heads 4	20.676%
7	Thermostatic valve circuit 4	90.628%	18	Oil mist detectors 4	20.091%
8	Start limiter 4	86.808%	19	Control panel 4	15.576%
9	Start air system 4	86.808%	20	Turbocharger 4	7.933%
10	Air cooler & manifold 4	86.808%	21	Valves/fuel injectors 4	7.933%
11	Alternator 4	84.357%			

Table 7.20 Fussell-Vesely IM for DG 4

	Event	Fussell-Vesely		Event	Fussell-Vesely
1	Filter glacier oil 4	95.436%	12	Governor 4	43.333%
2	LO Filter duplex 4	95.436%	13	Instruments 4	27.229%
3	LO valves & piping 4	95.436%	14	Alarms 4	27.229%
4	Thermostatic valve circuit 4	90.629%	15	Engine preheating unit 4	27.229%
5	Valves & piping 4	90.629%	16	Special tools 4	27.229%
6	Filter duplex 4	90.629%	17	Cylinder heads 4	20.676%
7	Filter autoclean 4	90.629%	18	Oil mist detectors 4	20.091%
8	Start limiter 4	86.809%	19	Control panel 4	15.576%
9	Start air system 4	86.809%	20	Turbocharger 4	7.933%
10	Air cooler & manifold 4	86.809%	21	Valves/fuel injectors 4	7.933%
11	Alternator 4	84.357%			

In the case of DG 4, the most important sub-system identified is the lube oil sub-system (filter glacier oil, LO Filter duplex, LO valves & piping) followed by the fuel oil sub-system (thermostatic valve circuit, valves & piping, filter duplex, filter autoclean) and the air sub-system (start limiter, start air system, air cooler & manifold). This is shown in both the Criticality and Fussell-Vesely IMs describing the importance of a single component for the reliability of DG 4 as well as in the Birnbaum IM showing the improvement boundary for each specific component present in the analysis of DG 4. These results are also examined in conjunction with the calculation of the cut set results as shown below.

7.8.2 Cut set results for DG 4

As already discussed, the results of DG 4 cut sets are shown in Table 7.21.

As shown above, the cut set results include the set of components/events of the FT that lead to the failure of DG 4. The top of the list shows the shortest path/way that the specific set of components which contribute to the failure of DG 4 may occur. By examining the list of cut sets as well as having in mind the components identified through the investigation of the IMs of DG 4, the following list of components for each sub-system are suggested for further improvement:

- Body/frame: governor
- Fuel oil: thermostatic valve circuit
- Lube oil: filter glacier oil
- Air: start limiter
- Electrical: alternator
- Miscellaneous: instruments

Table 7.21 Cut set results for DG 4 (10 of 47)

	Events	Cut set Order
1	Governor 4, Valves & piping 4, Filter autoclean 4, Filter duplex 4, thermo valve circuit 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Alternator 4	12
2	Cylinder heads 4, Valves & piping 4, Filter autoclean 4, Filter duplex 4, thermo valve circuit 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Alternator 4	12
3	Oil mist detectors 4, Valves & piping 4, Filter autoclean 4, Filter duplex 4, thermo valve circuit 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Alternator 4	12
4	Governor 4, Valves & piping 4, Filter autoclean 4, Filter duplex 4, thermo valve circuit 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Control panel 4	12
5	Turbocharger 4, Valves & piping 4, Filter autoclean 4, Filter duplex 4, thermo valve circuit 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Alternator 4	12
6	Valves/fuel injectors 4, Valves & piping 4, Filter autoclean 4, Filter duplex 4, thermo valve circuit 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Alternator 4	12
7	Governor 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Alternator 4, Engine preheating unit 4, Alarms 4, Instruments 4, Special tools 4	12
8	Cylinder heads 4, Valves & piping 4, Filter autoclean 4, Filter duplex 4, thermo valve circuit 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Control panel 4	12
9	Oil mist detectors 4, Valves & piping 4, Filter autoclean 4, Filter duplex 4, thermo valve circuit 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Control panel 4	12
10	Cylinder heads 4, LO valves & piping 4, Filter glacier oil 4, LO Filter duplex 4, Start limiter 4, Start air system 4, Air cooler & manifold 4, Alternator 4, Engine preheating unit 4, Alarms 4, Instruments 4, Special tools 4	12

7.8.3 ‘SPARE’ gates – Discussion and suggestions for DG 4

Based on the above, the discussion and suggestions as well as the comparison of the reliability results of DG 4 before and after the introduction of ‘SPARE’ gates are presented in the next section (Figure 7.9).

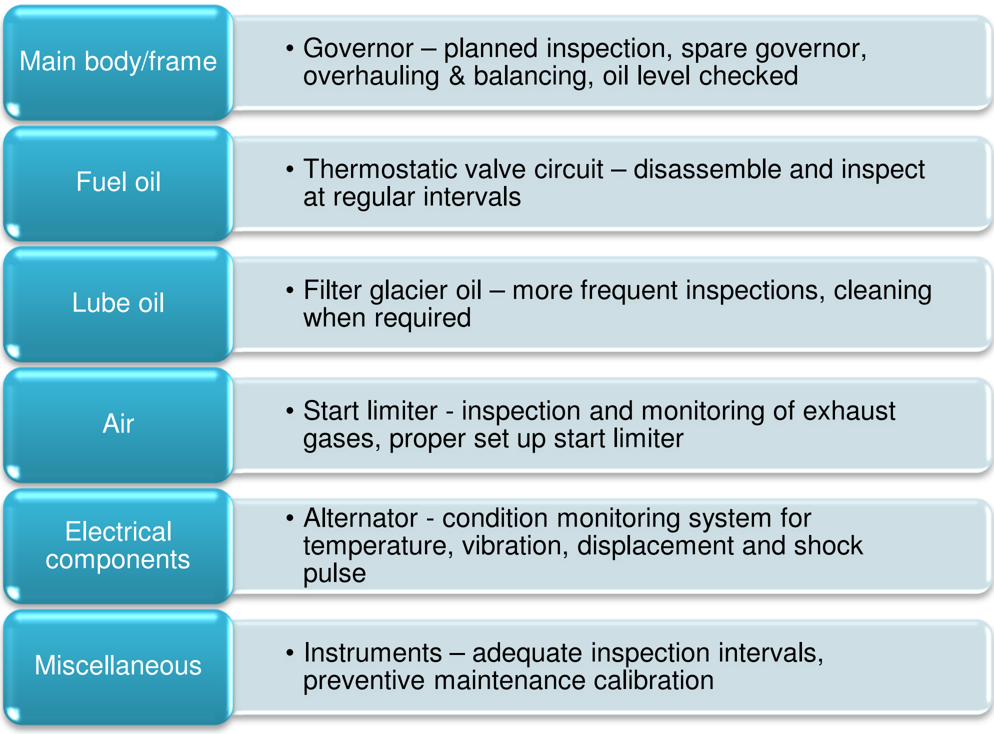

Figure 7.9 Most critical items/components and maintenance measures suggested for DG 4

As can be observed, the governor is the most critical component for the fuel oil sub-system, differentiating from the critical findings for the previous DGs examined. The governor is in general a major part of the DG and is responsible for controlling the rate of fuel delivery to the engine, thus maximising power and efficiency. In this respect, a spare governor should be kept onboard at all times and when one is found to be underperforming or is defective, it should be replaced. Moreover, the governor should be sent to the workshop for overhauling and put back at least once every major dry-docking period. The new one that will be put back in place should be perfectly balanced and the droop setting should be working as originally indicated (controlling the fuel supply for variable load conditions). As a more ordinary maintenance routine, the oil levels should be checked twice in an engine watch to ascertain sufficient oil level.

For the thermostatic valve circuit of the fuel oil sub-system, the same maintenance measures apply in this case as for DG 3. With regards to the lube oil sub-system, the glacier filter oil is identified as the most important one based on the results of the criticality analysis of DG 4. For this type of filter, more frequent inspections and cleaning are required as it is usual to accumulate sludge deposits if not cleaned properly. Another measure refers to the overall operation of the lube oil cleaning process and the sludge accumulated over time, which depends on the oil quality as well as the running hours of the engine.

For the air and electrical components sub-systems of DG 4, the most critical items identified are similar to the ones identified in the case of DG 3; that is the start limiter and the alternator respectively. For the miscellaneous sub-system, the various instruments are categorised as most important items in this group although, they indirectly interfere in maintaining a good operational condition of the DG system. These include pressure transducers, indicators, tachometers and pressure gauges. For this type of items, the indication of malfunction must be recognised and dealt with as promptly as possible, thus proper inspection intervals are needed as well as maintenance tasks implemented. These include calibrating the instruments to their standard tolerances according to the manufacturer and operating conditions they are allowed to work in. Moreover, although the above remarks and suggestions are of general interest, they indicate that there are potential flaws in the application of the maintenance process regarding the specific system, as these components tend to be overlooked over time through the daily maintenance routine.

In this respect, they should be kept in excellent condition and assist in providing the correct indications in ample time for any notifications needed so as for any maintenance or repair action to take place. The latter includes receiving the correct information onboard the ship, evaluating the situation, either as an urgent one (carry out corrective maintenance) or as a maintenance and repair work that can be dealt with at a later stage (preventive maintenance). In the first case, the chief engineer should decide the maintenance sequence, spare parts and crew involved to carry out such a task. In the second case, the company headquarters should be notified for the extended operation period and the subsequent planned repair works so as to indicate the potential need for extra spare parts, tools or even specific technicians (riding squad) boarding the vessel at a convenient port/anchorage point to carry out the repair if required.

As described above, the introduction of 'SPARE' gates and events in the DFT structure is shown with regards to the reliability calculation results regarding DG 4 before and after the introduction of enhanced maintenance measures (Figure 7.10).

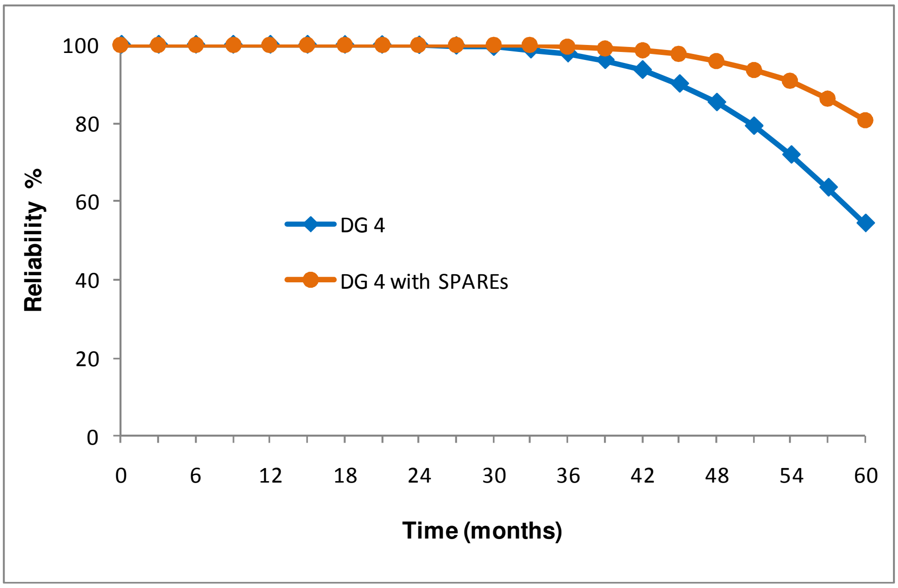

Figure 7.10 Reliability results of DG 4 sub-system before and after the introduction of maintenance measures ('SPARE' gates)

As is shown in Figure 7.10, the reliability of DG 4 increases from 38 months to 48 months of high operational condition (increase of 26% compared to the previous results of DG 4). The enhancement of DG 4 includes measures which deal specifically with the components identified before for each one of the sub-systems of DG 4 such as enhancing the operation of the governor for the body/frame sub-system, improving the thermostatic valve circuit for the fuel sub-system etc. Furthermore, in the next section the reliability results of the last of the DGs examined (DG 5-Emeergency DG) are presented.

7.9 Reliability results for DG 5 (Emergency DG)

In this section, the reliability results of the Emergency Generator (DG 5) are shown by presenting the IMs, the cut set and finally the effect of 'SPARE' gates and events in the overall reliability of this particular DG.

7.9.1 Reliability IMs results for DG 5

As mentioned previously for the other DGs, the three different IMs are examined for DG 5 as well (Tables 7.22-7.24).

Table 7.22 Birnbaum IM for DG 5

	Event	Birnbaum		Event	Birnbaum
1	LO valves & piping 5	0.002%	12	Engine preheating unit 5	0.0005%
2	Start limiter 5	0.002%	13	Special tools 5	0.0005%
3	Start air system 5	0.002%	14	Alternator 5	0.0003%
4	Air cooler & manifold 5	0.002%	15	Control panel 5	0.0003%
5	Filter duplex 5	0.002%	16	Filter autoclean 5	0.0003%
6	Thermostatic valve circuit 5	0.002%	17	Governor 5	0.0001%
7	LO Filter duplex 5	0.001%	18	Valves/fuel injectors 5	0.0001%
8	Valves & piping 5	0.001%	19	Oil mist detectors 5	0.0001%
9	Filter glacier oil 5	0.001%	20	Cylinder heads 5	0.0001%
10	Instruments 5	0.001%	21	Turbocharger 5	0.0001%
11	Alarms 5	0.001%			

Table 7.23 Criticality IM for DG 5

	Event	Criticality		Event	Criticality
1	LO valves & piping 5	95.435%	12	Governor 5	43.333%
2	LO Filter duplex 5	95.435%	13	Control panel 5	31.110%
3	Filter glacier oil 5	95.435%	14	Instruments 5	27.227%
4	Thermostatic valve circuit 5	90.629%	15	Alarms 5	27.227%
5	Valves & piping 5	90.628%	16	Engine preheating unit 5	27.227%
6	Filter duplex 5	90.628%	17	Special tools 5	27.227%
7	Filter autoclean 5	90.628%	18	Cylinder heads 5	20.676%
8	Start limiter 5	86.808%	19	Oil mist detectors 5	20.091%
9	Start air system 5	86.808%	20	Turbocharger 5	7.933%
10	Air cooler & manifold 5	86.808%	21	Valves/fuel injectors 5	7.933%
11	Alternator 5	68.825%			

Table 7.24 Fussell-Vesely IM for DG 5

	Event	Fussell-Vesely		Event	Fussell-Vesely
1	LO valves & piping 5	95.436%	12	Governor 5	43.333%
2	LO Filter duplex 5	95.436%	13	Control panel 5	31.110%
3	Filter glacier oil 5	95.436%	14	Instruments 5	27.227%
4	Thermostatic valve circuit 5	90.629%	15	Alarms 5	27.227%
5	Valves & piping 5	90.629%	16	Engine preheating unit 5	27.227%
6	Filter duplex 5	90.629%	17	Special tools 5	27.227%
7	Filter autoclean 5	90.629%	18	Cylinder heads 5	20.676%
8	Start limiter 5	86.809%	19	Oil mist detectors 5	20.091%
9	Start air system 5	86.809%	20	Turbocharger 5	7.933%
10	Air cooler & manifold 5	86.809%	21	Valves/fuel injectors 5	7.933%
11	Alternator 5	68.825%			

In the case of DG 5, the most important sub-system identified is the lube oil sub-system (LO valves & piping, LO Filter duplex, filter glacier oil). This is followed by the fuel oil sub-system (thermostatic valve circuit, valves & piping, filter duplex, filter autoclean) and the air sub-system (start limiter, start air system, air cooler & manifold). In addition to the analysis carried out herein, the investigation of the cut set results can also verify the identification of the criticality of the above mentioned sub-systems as it is shown in the next paragraph.

7.9.2 Cut set results for DG 5

The cut set results for DG 5 are shown in Table 7.25.

Table 7.25 Cut set results for DG 5 (10 of 47)

	Events	Cut set Order
1	Governor 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Alternator 5	12
2	Cylinder heads 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Alternator 5	12
3	Oil mist detectors 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Alternator 5	12
4	Governor 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Control panel 5	12
5	Cylinder heads 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Control panel 5	12
6	Oil mist detectors 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Control panel 5	12
7	Turbocharger 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Alternator 5	12
8	Valves/fuel injectors 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Alternator 5	12
9	Governor 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Alternator 5, Engine preheating unit 5, Alarms 5, Instruments 5, Special tools 5	12
10	Turbocharger 5, Valves & piping 5, Filter autoclean 5, Filter duplex 5, thermostatic valve circuit 5, LO valves & piping 5, Filter glacier oil 5, LO Filter duplex 5, Start limiter 5, Start air system 5, Air cooler & manifold 5, Control panel 5	12

As observed above, the cut set results are of the 12th order, showing the number of basic events which comprise each chain of cut sets. The top cut sets in the Table shown above include the body/frame sub-system as well as the fuel sub-system as the primary sub-systems which influence the underperformance of DG 5. Items such as the governor, the thermostatic valve circuit, the LO valves & piping are among the top ones in the cut set results shown above and verify the most critical components identified by the reliability IMs in the previous section. Summarising, the components which are chosen to be enhanced furthermore regarding the operation of DG 5 are listed below:

- Body/frame: governor
- Fuel oil: Thermostatic valve circuit
- Lube oil: LO valves & piping
- Air: start limiter
- Electrical: alternator
- Miscellaneous: instruments

The application of specific maintenance measures regarding the above mentioned components is clearly shown in the next section in which 'SPARE' gates and events are used and a comparison is made between the results of DG 5 before and after the introduction of maintenance measures.

7.9.3 'SPARE' gates – Discussion and suggestions for DG 5

Based on the above, the discussion and suggestions as well as the comparison of the reliability results of DG 1 before and after the introduction of 'SPARE' gates are presented in the next section (Figure 7.11).

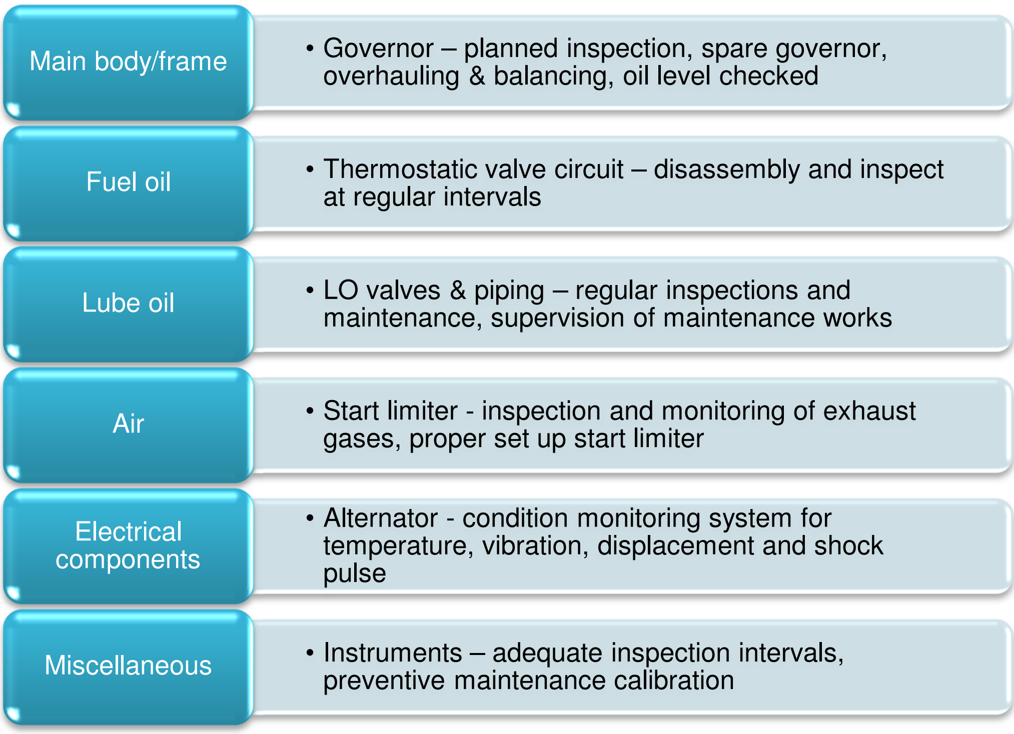

Figure 7.11 Most critical items/components and maintenance measures suggested for DG 5

In terms of the items for each one of the different sub-systems of DG 5 which present the highest criticality, the majority of the items are similar to the specific items identified for other DGs. These are explicitly examined and described in the previous paragraphs. In summary, the governor is the most critical item for the main body/frame sub-system. The thermostatic valve circuit is the most significant one for the fuel oil sub-system while the start limiter, the alternator and the various instruments are considered as critical for the air, electrical components and miscellaneous sub-systems respectively.

The single most critical item for DG 5 which has not been identified yet in the operation of the rest of the DGs is the lube oil valves & piping item as part of the lube oil sub-system. This item is described with more details next. In this case, the valves & piping of the lube oil needs to be preserved in good operational condition by regular inspections and maintenance if required. Usually, lube oil valves & piping do not constitute an area of concern in a DG system, even more particularly in the case of an emergency diesel generator which is always maintained in an excellent operating condition. In this case, the identified criticality is the result of potential lube oil leakages from gaskets and flanges of the subject sub-system, which then refer to possible flaws in terms of previous maintenance tasks performed by the crew of the vessel or external maintenance technicians. This in turn means that the maintenance works carried out have not been not properly supervised and checked.

As discussed before, the results of DG 5 before and after the introduction of 'SPARE' gates and events is shown in Figure 7.12.

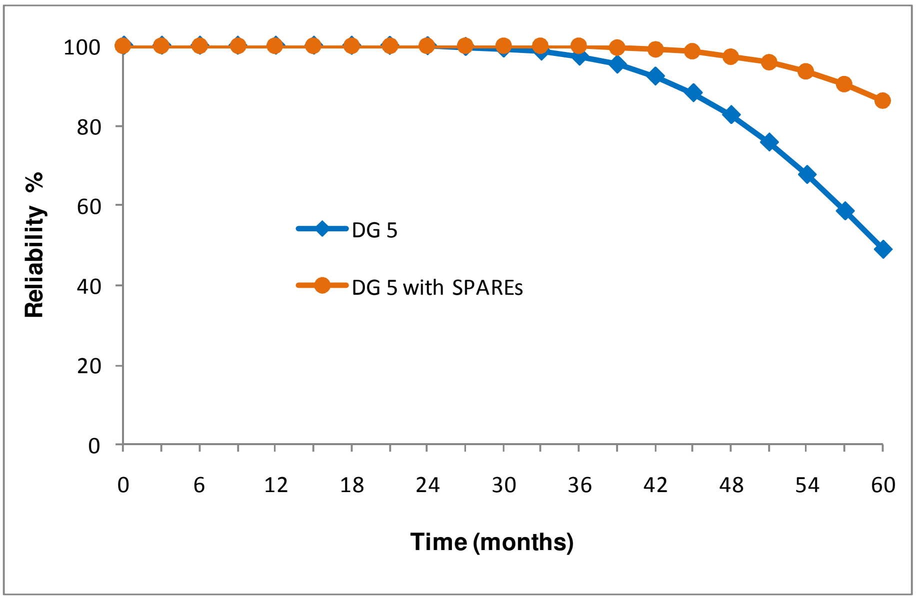

Figure 7.12 Reliability results of DG 5sub-system before and after the introduction of maintenance measures ('SPARE' gates)

As is shown, DG 5 presents very good reliability results in the first place (as expected) since this is a diesel generator which is used in emergency situations and must be preserved in excellent operational condition. However, with the use of additional maintenance measures concerning the specific components identified before, the reliability of DG 5 can be further enhanced (from 38 months to 54 months of good operational level) increasing the operational capacity of this DG. One must also bear in mind that according to the ISM code this is one of the most critical items that have to be examined during an ISM audit or Class/port state control survey.

7.10 Discussion of the result of the overall DG system

7.10.1 'SPARE' gates for the overall DG system

After examining the reliability and criticality results for each individual DG as well as identifying the most critical components for their operation, the reliability of the overall DG system is examined once again. The latter is performed in the light of the introduction of maintenance measures suggested for each separate DG as presented in the previous sections of Chapter 7 in the form of 'SPARE' gates used in the DFTA tool. In this respect, the reliability results of the overall DG system before and after the introduction of maintenance measures ('SPARE' gates) is presented in Figure 7.13.

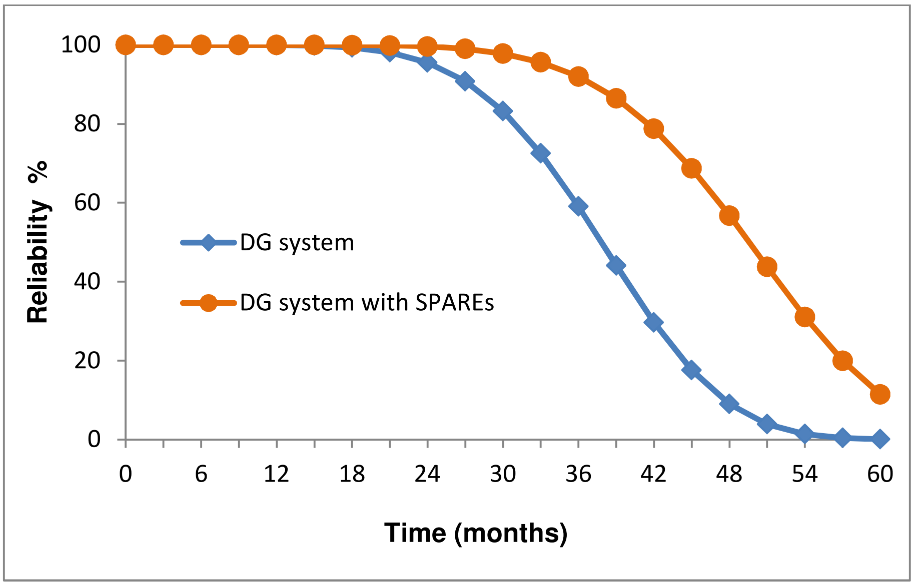

Figure 7.13 Reliability results of the overall DG system before and after the introduction of maintenance measures ('SPARE' gates)

As can be observed, the good reliability level of 95% for the operation of the entire DG system is preserved for a period of 34 months compared to the initial 24 months period as initially examined in §7.3.1. That signifies an increase of more than 40% for the DG system and includes the maintenance measures that have been suggested for each individual DG in the previous sections of Chapter 7. Subsequently, these results clearly demonstrate the benefits of applying the reliability and criticality based assessment and maintenance framework.

7.10.2 Comparison of results for the DG system

After examining the reliability results of all the DGs participating in the DG system of this ship, it is also important to investigate and compare the reliability results of each one of the DGs before and after the introduction of 'SPARE' gates and events so as to find out which DGs is the least reliable compared to the others and also has the most potential for improvement. In this way, more of the maintenance efforts will focus on this/these specific

DGs so as to preserve the most important function of the overall DG system of the ship. Thus, the summary of the reliability results for all the individual DGs is shown in Table 7.26.

Table 7.26 Summary of the reliability results for all the individual DGs

DG	DG1	DG2	DG3	DG4	DG5
Initial results (months)	24	38	35	38	38
Updated results (months)	34	49	46	48	54
Change	41.67%	28.95%	31.43%	26.32%	42.11%

As shown in the Table above, DG 1 presents the lowest reliability results with 24 months of high operational performance (set up to 95% as mentioned at the beginning of this Chapter). After the use of a course of maintenance measures, its reliability increases to 34 months, almost 42% more than originally presented. DG 3 also shows low initial reliability results compared to the rest of the DGs (35 months increased to 46 months after employing an appropriate maintenance sequence, increase of more than 30%). DG2, DG 4 and DG 5 follow in the list of the initial reliability results (38 months each) while after the maintenance measures the results are increased to 49, 48 and 54 months respectively.

It is important to notice that the DGs with the highest margin for improvement are DG 1 and DG 5 (more than 40% increase) compared to the rest of the diesel generators (26% to 31% improvement on average). In the first place, this can be due to more frequent use of DG 1 and consequently more breakdowns. In this case, the use of more frequent inspections are needed as well as upgrading the application of the standard preventive maintenance regime with condition monitoring examination and prioritisation of the maintenance load. In the case of DG 5, the improvement margin signifies that even if the specific DG is maintained in very good operational condition, there is still space for upgrading. This is even more important since in some cases, equipment which is redundant or is used in emergency situations only, may be sometimes left without proper preservation and without being tested that it actually delivers its full operational capacity (with potential catastrophic consequences in the long term).

Another significant conclusion stemming from the comparison of the initial and final results of the DGs before and after the implementation of the proposed maintenance measures is that DG 1 still has the lowest actual updated result (34 months) compared to the rest of the DGs.

This signifies that further potential improvements can be suggested such as the application of full condition monitoring of DG 1 and scrutinised inspections. On the other hand, since the updated result is more than the two and a half years interval that the engine is overhauled, it can be concluded that the improvement is sufficient enough in order to sustain the function of the specific DG and accordingly the operation of the ship overall.

7.10.3 Comparison of DGs critical items

So far, the most critical items of the sub-systems for each one of the individual DGs have been examined and described along with the maintenance measures suggested for rectification of the anomalies identified. In this section, the various DGs are examined as an entire system and compared based on the critical items identified above. The latter is shown in Table 7.27.

Table 7.27 Summarised critical items of the main sub-systems of Diesel Generators 1-5

Main sub-systems	DG 1	DG 2	DG 3	DG 4	DG 5
Main body/frame	Oil mist detectors	Oil mist detectors	Valves & fuel injectors	Governor	Governor
Fuel oil	Filter autoclean	Valves & piping	Thermo valve circuit	Thermo valve circuit	Thermo valve circuit
Lube oil	LO filter duplex	LO filter duplex	LO filter duplex	Filter glacier oil	LO valves & piping
Air	Start air system	Start limiter	Start limiter	Start limiter	Start limiter
Electrical components	Alternator	Alternator	Alternator	Alternator	Alternator
Miscellaneous	Engine preheating unit	Engine preheating unit	Alarms	Instruments	Instruments

As observed in Table 7.27, it is interesting to notice that there are certain similarities regarding the most critical items for the various sub-systems of the DGs. More specifically, the similar critical items per sub-system are identified mostly when comparing the two pairs of DGs; that is DG 1 with DG 2 and DG 3 with DG 4. These two pairs of DGs are further examined in the following paragraphs. On the other hand, when observing the Table above, it is obvious that there exist quite a few common critical items among DG 5 and the rest of the

DGs, especially when comparing DG 5 with DG 4 in terms of the main body/frame, fuel oil, air, electrical and miscellaneous sub-systems. In this case, one needs to consider that DG 5 is the emergency DG of the vessel, meaning that this is a stand-alone part of the machinery of the subject ship. In this manner, it does not participate in the daily operational profile of the vessel, thus it is not subject to the same deterioration and maintenance regime as the rest of the DGs of the ship. Therefore, it must be treated separately and on its own respect regarding its overall operation, inspection and monitoring and maintenance condition.

In this respect, considering the main body/frame sub-system, DG 1 and DG 2 have the same most critical item, which refers to the oil mist detectors. Similarities are also present in the lube oil sub-system with the lube oil filter duplex. Moreover, the electrical components and miscellaneous sub-systems have commonalities in terms of the alternator and the engine preheating unit respectively. The number of common critical items can be attributed to the operational profile of the subject vessel regarding the overall DG system. As mentioned before, the subject vessel is a cruise motor sailing ship with four main DGs providing for its overall propulsion and power needs. In addition to that, the maintenance sequence for the subject system is carried out based on a predefined planned/preventive plan which needs to be upgraded furthermore to include condition monitoring applications.

Bearing the above in mind, the pairs of DGs mentioned above are functioning together in order to achieve the power loading requirements and thus are operated in tandem. At an initial stage, the critical items of the DGs identified from the reliability and criticality analysis as well as their failures can be treated individually through the maintenance approach of the company, combining preventive and predictive maintenance programmes. The latter can also employ condition monitoring tools to enhance the predictability of the failure of the specific items and eventually lead to an enhanced maintenance strategy. Another useful conclusion is that the management company of the vessel and subsequently the crew onboard the ship (captain, chief engineer) can introduce the operation of different DGs as working DG pairs. In this way, the working power load of the DGs can be distributed evenly and consequently the failures can be minimised and dealt with accordingly.

7.10.4 Comparison of FMECA and DFTA results

After presenting the results of the FMECA and DFTA approaches, it would be worth examining whether there exist any similarities and/or differences among the critical items of the DG system identified before. This is presented in Table 7.28.

Table 7.28 Comparison of FMECA and DFTA results for the overall DG system

System	FMECA	DFTA
Main body/frame	oil mist detectors, valves & fuel injectors, turbocharger, governor	oil mist detectors, valves & fuel injectors, governor
Fuel oil	valves & piping, fuel filter autoclean, fuel filter duplex, thermostatic valve circuit	valves & piping, fuel filter autoclean, thermostatic valve circuit
Lube oil	valves & piping, LO filter duplex, filter glacier oil	valves & piping, LO filter duplex, filter glacier oil
Air	start limiter, start air system, air cooler & manifold	start limiter, start air system, air cooler & manifold
Electrical components	alternator, DG control panel	alternator
Miscellaneous	engine preheating unit, instruments, alarms	engine preheating unit, instruments, alarms

As was mentioned before, an overall distinction for the reliability and criticality analysis performed herein is that the FMECA approach is a more generic tool which is used to investigate the criticality of the components of the DG system of the subject vessel at a higher level. In order to drill down into the details of each individual DG and its most critical components, the DFTA tool is also employed. In this respect, the majority of the critical items of each sub-system identified by the FMECA coincide with the criticality analysis results of the DFTA. Bearing the above in mind it can be concluded that the criticality results originating from the DFTA are validated by the experts', who have worked towards the completion of the FMECA.

More specifically, for the main body/frame sub-system the oil mist detectors are the most critical item identified for DG 1 and DG 2 while the valves & fuel injectors are the most important one for DG 3 followed by the governor for DG 4 and DG 5. For the fuel oil sub-system, the valves & piping present the highest criticality for DG 2, whereas the fuel filter autoclean is the most critical component for DG 1. The thermostatic valve circuit presents the highest criticality results for DG 3, DG 4 and DG 5 as shown from the DFTA results, which may be in contrast with the results of the FMECA as the thermostatic valve circuit is ranked with lower criticality than other items of the specific sub-system. This can be ascribed to the fact that the FMECA approach is carried out in a generic way examining the criticality of the overall DG system of the subject vessel. Moreover, the DFTA tool is also used in order to complement the reliability and criticality analysis performed.

For the rest of the sub-systems examined, the valves & piping, LO filter duplex and the filter glacier oil are the main components identified by the FMECA for the lube oil sub-system. These are also confirmed by the critical items resulting from the DFTA of the individual DGs. That is the case for DG 5 (LO valves & piping), DG 1, DG 2 and DG 3 (LO filter duplex) and DG 4 (filter glacier oil). As for the air sub-system, there is an overlap between the two approaches. In this respect, the start limiter, the start air system and the air cooler & manifold are the most critical items identified from the FMECA as well as from the DFTA with DG 2, DG 3, DG 4 and DG 5 (start limiter) as well as DG 1 (start air system).

For the electrical components sub-system, the alternator is the common most critical item for all five DGs as confirmed by the FMECA too. This is also true as from a practical point of view, the alternator is a major part of a DG and any failure of this item can render the DG unavailable for a significant period of time. Finally, regarding the miscellaneous components sub-system, the engine preheating unit has resulted in the most critical item from the FMECA as well as from the DFTA with respect to DG 1 and DG 2. This the case for the most crucial components of DG 4 and DG 5 (instruments) and DG 3 (alarms) identified from both the FMECA and the DFTA reliability and criticality applications.

7.11 Maintenance cost for the overall DG system

In this section of Chapter 7, the cost assessment of the case study of the overall DG system is performed in order to assess the impact of the application of different maintenance approaches on the ship's operational profile. In this regard, the three major maintenance categories (corrective, preventive and predictive) are examined in terms of their financial cost effect on the maintenance of the DG system considering their specific characteristics as these are mentioned next. Starting with the case of corrective maintenance, the overall maintenance cost (C_{COR}) consists of the following:

$$C_{COR} = N_{DGs} * (C_{LAB} + C_{SP} + C_{OIL}) + C_{OP} + C_{DR} + C_{CAN} \quad (7.1)$$

where:

C_{COR} Corrective maintenance cost (£)

N_{DGs} Number of DGs onboard the vessel

C_{LAB} Labour cost (£)

C_{SP} Spare parts cost (£)

C_{OIL} Lube oil change cost (£)

C_{OP} Operation loss cost (£)

C_{DR} Dry-docking cost (£)

C_{CAN} Cancelations cost (£)

For the corrective maintenance category, it is assumed that one of the DGs fails to operate and needs immediate major repair. Furthermore, the Labour cost (C_{LAB}) is the product of the number of engine technicians involved in the repair/corrective maintenance (N_{tec}), being paid a certain amount of money/rate per hour (R_{hr}), working for a specified number of hours per day (H_{day}) and number of days (N_d). The above are described in Equation 7.2:

$$C_{LAB} = N_{tec} * R_{hr} * H_{day} * N_d \quad (7.2)$$

where:

C_{LAB} Labour cost (£)

N_{tec} Number of engine technicians

R_{hr} Rate/hour (£)

H_{day} Hours/day

N_d Number of days

In this case, it is assumed that four engine technicians are working for 10 hours per day for a total of 7 days in order to carry out the corrective maintenance tasks and that their working rate is 50£ per hour. Moreover, the Spare parts cost (C_{SP}) consists of the product of the number of cylinders of the DG in question (N_{cyl}) as well as the allocated cost of spare parts per DG cylinder cover (C_{spa}); that is:

$$C_{SP} = N_{cyl} * C_{spa} \tag{7.3}$$

where:

C_{SP} Spare parts cost (£)

N_{cyl} Number of cylinder covers/DG

C_{spa} Cost of spare parts/DG cylinder cover (£)

In the case of the DG system in hand, each DG consists of six cylinder covers. The spare parts required for them are assumed to be similar to the ones used for the planned maintenance interval. Regarding the Lube oil change cost (C_{OIL}), it is the product of the litres of lube oil changed (L_{lube}) multiplied by the price of lube oil/litre (P_{lube}) as shown in Equation 7.4:

$$C_{OIL} = L_{lube} * P_{lube} \tag{7.4}$$

where:

C_{OIL} Lube oil change cost (£)

L_{lube} Litres of lube oil changed

P_{lube} Price of lube oil/litre

As for the Operation loss cost (C_{OP}), it consists of the number of days that the DG remains out of operation (D_{day}) and the revenue per day that is being lost due to the repairs undertaken for the DG system (R_{day}); that is:

$$C_{OP} = D_{day} * R_{day} \tag{7.5}$$

where:

D_{day} Number of days out of operation

R_{day} Revenue / day (£)

In terms of the Dry-docking cost (C_{DR}), it can be the derivative of the number of days at the dry-dock/port (D_{dry}) by the dry-docking rate per day (R_{dry}).

$C_{DR} = D_{dry} * R_{dry}$ (7.6)

where:

D_{dry} Number of days at the dry-dock/port

R_{dry} Dry-docking rate / day (£)

With regards to the Cancelations cost (C_{CAN}), it is presented as the combination of the total number of passengers (N_{pass}) onboard the vessel and the rate per passenger (R_{pass}) as well:

$C_{CAN} = N_{pass} * Per\ x * R_{pass}$ (7.7)

where:

N_{pass} Number of passengers

Per Percentage of passengers cancellations

R_{pass} Rate per passenger (£)

In the case examined, the dry-docking cost (cost due to major repairs undertaken and vessel moved to a repair shipyard) as well as the cancellations cost (cost due to cruise vessel passengers' cancellations) are not considered in the present cost assessment. Regarding the principal preventive maintenance cost for the overall DG system, it can be divided into two separate stages: the one implemented at 4,000 operating hours (approximately 6 calendar months) and the one carried out at 8,000 operating hours (approximately on an annual basis) based on common good seaman's practice. In this respect, the total preventive maintenance cost (C_{PRE}) consists of the cost related to the specific number of DGs (N_{DGs}), the Labour cost (C_{LAB}), Spare parts cost (C_{SP}) and the Lube oil change cost (C_{OIL}) as described in Equation 7.8:

$C_{PRE} = N_{DGs} * (C_{LAB} + C_{SP} + C_{OIL})$ (7.8)

where:

C_{PRE} Preventive maintenance cost (£)

N_{DGs} Number of DGs

C_{LAB} Labour cost (£)

C_{SP} Spare parts cost (£)

C_{OIL} Lube oil change cost (£)

The above mentioned cost elements (Labour cost, Spare parts cost and Lube oil change cost) are similar to the ones described in the case of the corrective maintenance approach. It is noted however that in the case of preventive maintenance cost assessment, the four main DGs are considered to be maintained (in distinction to the corrective maintenance cost assessment in which one DG is assumed to be out of operation due to unexpected failure).

In terms of the maintenance combination options for performing the maintenance sequence of the overall DG system of the subject vessel, the use of condition monitoring equipment is employed in order to carry out vibration monitoring, lube oil and thermography analysis assessment as well. It is also anticipated that the preventive maintenance intervals are reduced to one per year (at 8,000 operating hours), thus avoiding the intermediate planned maintenance at 4,000 hours. Similar to the case of the preventive maintenance approach, it is assumed that all four main DGs are monitored and maintained accordingly.

In this respect, two separate cases are examined. The first one (predictive maintenance 1) is based on the use of condition monitoring equipment from a sub-contractor while the second one (predictive maintenance 2) is performed by the crew of the vessel having been trained to the use condition monitoring equipment. At this point is should be mentioned that a well-established condition monitoring firm has been consulted in order to obtain the relevant information and figures in terms of the condition based assessment onboard the vessel investigated. Regarding predictive maintenance 1, it consists of the Vibration monitoring cost (C_{Vib}), the Lube oil analysis cost (C_{Lube}), the Thermography monitoring cost (C_{therm}) and the travel expenses (E_{travel}) as shown in Equation 7.9:

$$C_{PRED\ 1} = C_{Vib} + C_{Lube} + C_{therm} + E_{travel} \tag{7.9}$$

where:

$C_{PRED\ 1}$ Predictive maintenance cost- option 1 (£)

C_{Vib} Vibration monitoring cost (£)

C_{Lube} Lube oil analysis cost (£)

C_{therm} Thermography monitoring cost (£)

E_{travel} Travel expenses (1 person) (£)

The travel expenses reach to an amount of £2,500 per person attending the condition monitoring assessment of the overall DG system. Moreover, the Vibration monitoring cost is the product of the Number of days (N_d) needed to perform the vibration monitoring survey by the Daily rate cost (R_d) (Equation 7.10):

$$C_{Vib} = N_d * R_d \tag{7.10}$$

where:

N_d Number of days

R_d Daily rate cost (£)

At this point it should be mentioned that a number of four days are needed by an experienced technician to perform the condition monitoring assessment for this type of vessel. Moreover, the daily rate cost is considered as £800 per day. Furthermore, the Lube oil analysis cost (C_{Lube}) can be estimated by using the following Equation 7.11 as:

$$C_{Lube} = N_{sam} * S_{year} * C_{sam} \tag{7.11}$$

where:

N_{sam} Number of samples

S_{year} Frequency of sampling per year

C_{sam} Cost/sample (£)

In general, a number of six samples are needed per each individual DG while this is performed every three months (4 times per year). The cost per sample taken is considered as £100. In terms of the Thermography monitoring cost (C_{therm}), it can be calculated in the same way as the Vibration monitoring cost as the same technicians during the same time period are employed to perform this type of condition monitoring assessment too. In general, C_{therm} is described as the product of the number of days (N_d) needed to perform the thermography monitoring by the daily rate cost (R_d) as shown in Equation 7.12:

$$C_{therm} = N_d * R_d \tag{7.12}$$

Regarding predictive maintenance combination 2, the crew onboard the vessel are trained to carry out the condition monitoring assessment by using the particular equipment needed for these tasks. In order to achieve the above, an initial capital cost (C_{Cap}) for purchasing the condition monitoring equipment (vibration monitoring and thermography) needs to be invested as well as the relevant cost (C_{trai}) in order to train the crew so as to carry out the necessary inspections. Moreover, an additional calibration cost (C_{cal}) is incurred annually so as to maintain the condition monitoring equipment in good operational condition. The above are described in Equation 7.13:

$$C_{PRED\ 2} = C_{Cap} + C_{trai} + C_{cal} \qquad (7.13)$$

where:

$C_{PRED\ 2}$ Predictive maintenance cost - option 2 (£)

C_{Cap} Initial capital cost (£)

C_{trai} Initial training cost (£)

C_{cal} Annual calibration cost (£)

In this case the initial capital cost is a combination of the vibration monitoring equipment (£15,000) and the thermography equipment (£30,000). Moreover, the initial training cost is given by Equation 7.14:

$$C_{trai} = f_{trai} * C_{Cap} * N_{crew} \qquad (7.14)$$

where:

f_{trai} Training factor equal to 10%

N_{crew} Number of crew attending the training course

As for the initial training needed, this is in the range of about 10% of the initial capital cost needed while two crew members are expected to attend the initial training course. On the other hand, the calibration cost is the product of the initial capital cost and a calibration cost factor (Equation 7.15):

$C_{trai} = f_{cal} * C_{Cap}$ (7.15)

where:

f_{cal} Calibration cost factor equal to 5%

After all the above are considered, the estimated cost is calculated by escalating all the relevant cost elements in order to estimate the cost over a period of 5 years by employing Equation: 7.16. The escalation factor is assumed to be 3% annually.

$$C_{esc} = C_{in} * (1 + f_{esc})^n \quad (7.16)$$

where:

C_{esc} Escalated cost (£)

C_{in} initial maintenance cost (£)

f_{esc} escalation factor

n Number of years

Then, the escalated values are discounted in order to obtain the Present Value of the maintenance investment to the present year; that is (Equation 7.17):

$$PV = C_{esc} / (1 + f_{dis})^n \quad (7.17)$$

where:

PV Present Value (£)

f_{dis} discount factor

In this case, the f_{dis} is assumed to be 8%. Based on equations 7.1- 7.17, the PV for the different maintenance options (corrective, preventive, predictive option 1 and predictive option 2) over a period of five years for the overall DG system of the motor sailing cruise vessel is presented in Figure 7.14.

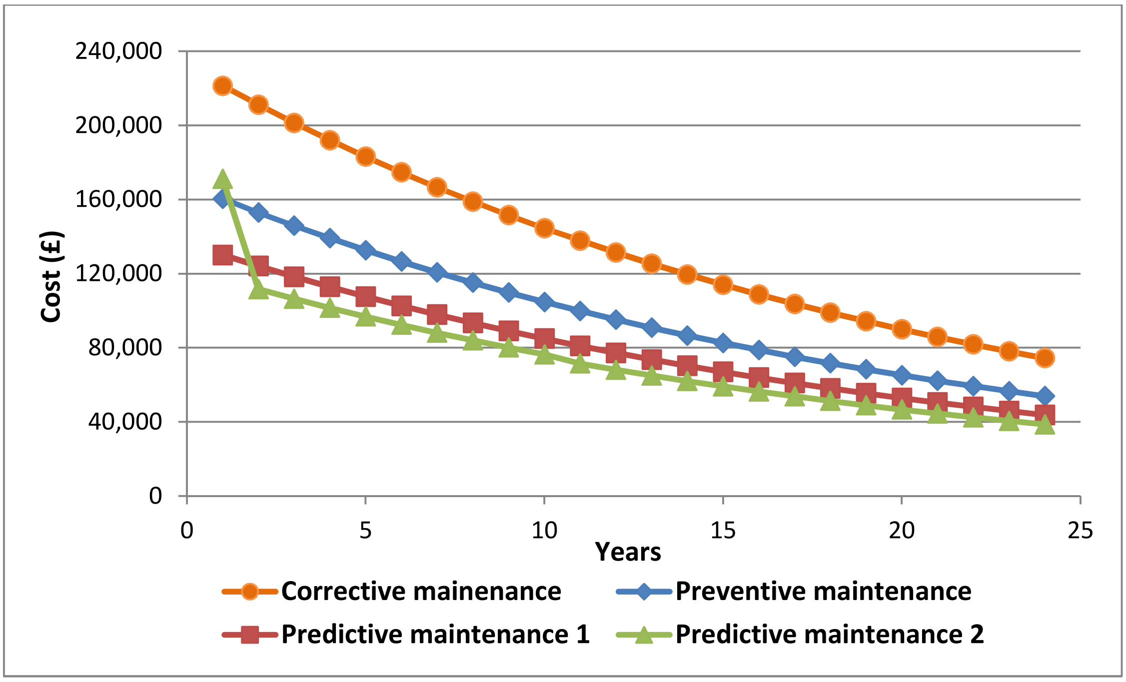

Figure 7.14 NPV for the different maintenance options for the overall DG system

As can be observed in Figure 7.14, the corrective maintenance cost constitutes the higher cost element among the other maintenance categories examined (more than £200,000 initially and reducing to £170,000 after five years). The cost for the preventive maintenance approach is the second highest for the DG system (£160,000 initially) as the maintenance type adopted is based on the specific predetermined maintenance intervals (every 4,000 and 8,000 hours). Moreover, the two different predictive maintenance approaches based on the condition monitoring assessment of the DGs present better results than the previous two approaches. More specifically, predictive maintenance 1 is more favourable than predictive maintenance 2, although very close in terms of financial expenditure. At this point it should be mentioned that the cost for the second option of the predictive maintenance is originally higher (over £160,000) compared to the first predictive maintenance option as it includes the initial capital cost for purchasing the condition monitoring equipment needed.

Moreover the comparison among the cost elements of the various maintenance approaches denotes the financial benefit of predictive maintenance over corrective and preventive maintenance types as shown in Table 7.29.

Table 7.29 Cost savings through the years of predictive vs. corrective and preventive maintenance (£)

Comparison of maintenance approaches	5 years	10 years	15 years	20 years	25 years
predictive vs. corrective					
benefit pred. maint.1 (£)	416,143	744,473	1,003,520	1,207,903	1,339,890
benefit pred. maint.2 (£)	421,625	796,885	1,099,342	1,337,976	1,492,081
predictive vs. preventive					
benefit pred. maint.1 (£)	138,107	247,071	333,041	400,870	444,673
benefit pred. maint.2 (£)	143,588	299,482	428,864	530,943	596,864

As can be seen in Table 7.29, the financial benefit stemming from the comparison of the predictive maintenance versus the corrective one is substantial over the lifetime of the vessel (25 years). The cost benefit amounts to almost one and a half million pounds sterling in both cases of predictive maintenance applied in comparison to the corrective maintenance approach. It needs to be reminded that the corrective maintenance examined in this section refers to the unexpected repairs of only one out of four generators used for the main propulsion and the overall power requirements of the vessel while the predictive maintenance acknowledges the overall DG system (all four main DGs). This is performed in order to be neither optimistic nor pessimistic about the maintenance sequence considered for the subject vessel.

Moreover, when comparing the predictive maintenance approach to the current maintenance regime of the vessel (preventive maintenance), it also proves to be beneficial over the lifetime of the vessel. In detail, the cost benefit appraisal reaches the amount of almost half a million pound sterling when preventive maintenance is compared to predictive maintenance 1 over a period of 25 years. When performing a similar assessment between preventive maintenance and predictive maintenance 2, the cost benefit rises up to almost £600,000 pounds. In practical terms, both cases refer to the outcome of purchasing a new diesel generator for free. On top of the above, these results present the benefit when solely comparing the cost elements of the different maintenance approaches, without considering the benefits originating from less unexpected repairs and the consequent cost as well as additional cancellation costs of the cruise vessel in the case of an unexpected failure occurring. The latter enhances the mentioned benefits to even higher levels.

In addition to the above cost assessment, it is obvious that the reliability and availability of the individual DGs as well as of the overall DG system has improved significantly after the introduction of the suggested maintenance measures. Thus it is proven that the proposed maintenance framework which is applied in the case of a more detailed technical system (more specific technical components and details of the DG system compared to the overall ship system examined as in the case of *"DSV A"*) can derive considerable benefits as shown before.

7.12 Chapter summary

In this Chapter, the results of the reliability and criticality analysis of the second case study, that is the Diesel Generator (DG) system of a motor sailing cruise ship, are presented. The DG system is divided into five sub-systems which are the five individual DGs (DG 1, DG 2, DG 3, DG 4, DG 5-emergency generator) providing the entire power generation capability of the subject vessel. The FMECA approach has been initially employed to examine the criticality of the DG system in a generic way. Furthermore, the Dynamic FTA (DFTA) tool is used and the reliability results of the main systems are also shown. Then the Birnbaum, Criticality and Fussell-Vesely importance measures are demonstrated followed by the presentation of the cut sets, assisting in the identification of the most critical components of the subject vessel. Dynamic 'SPARE' gates are also introduced signifying the additional maintenance measures that need to be implemented to upgrade the condition of the DGs. Additional remedial maintenance measures have been also discussed and suggested. At a second level, the critical items of all the DGs have been compared with each other in order to derive their differences and similarities. In addition to the above, more details and extended discussion on the results of the analysis are also suggested. Furthermore, the above-mentioned measures are also examined with regards to the cost assessment performed for the overall DG system. This assessment is furthermore expanded in Chapter 8 presented next, in which different attributes are included in the maintenance decision-making process employing the Fuzzy Set Theory in order to investigate the merit of the different maintenance approaches, thus fulfilling another part of the novel RCBM strategy.

8 CHAPTER 8 – MULTI ATTRIBUTE DECISION-MAKING MAINTENANCE SELECTION BASED ON FUZZY SET THEORY

8.1 Chapter outline

In this Chapter, the application of a supplementary methodology for further enhancing the novel RCBM strategy is presented. In this case, the Fuzzy Set Theory (FST) and its specific application in a Multi Attribute Decision Making (MADM) maintenance problem is demonstrated. The MADM problem employs multiple experts' judgement in order to deal with problem-solving when vague information is available by using three distinctive stages, namely the rating, aggregation and selection stage. This is the case of the maintenance approach that is best suited for a shipping company with regards to the Diesel Generator (DG) system of a motor sailing cruise vessel (presented in the previous Chapter). Concerning the final selection step of the suggested methodology, the TOPSIS ranking tool is also used, thus concluding the proposed fuzzy set methodology.

8.2 Application of the FST in a MADM maintenance problem

As described in Chapter 3 (literature review chapter), in any kind of MADM problems, such as the selection of the most appropriate maintenance approach for the DG system of a cruise vessel, there are always certain issues to be dealt with. These refer to the ways in order to make a decision on a given question when there are a number of alternatives/solutions to select from. This issue may become even more complex when each alternative is influenced by a specified set of attributes, which describes the given alternatives. Moreover, certain attributes cannot be described only with numerical/crisp answers, but also may include answers which may be expressed in linguistic terms. In this way, another approach to decision making is required. This is the case of the Fuzzy Set Theory, in which answers including linguistic (non-crisp) values can be transformed into numerical figures and assist in responding to the initial questions asked in a multi attribute decision-making problem.

As seen through the literature review presented before as well as to the best of the author's knowledge, there is no such application regarding the maintenance field in the maritime industry; that is where the novelty of this approach originates. Moreover, the FST in the MADM environment considers other parameters such as the efficiency of the maintenance, the crew training, the top management commitment and other attributes which are inherently vague and thus not easily quantified. In this section, the presentation of the MADM approach in order to achieve the identification of the most appropriate maintenance type for the DG system of the cruise vessel is described in details. The different steps in order to achieve the above follow the methodology demonstrated in Chapter 4 (methodology chapter) and are briefly presented next (Figure 8.1).

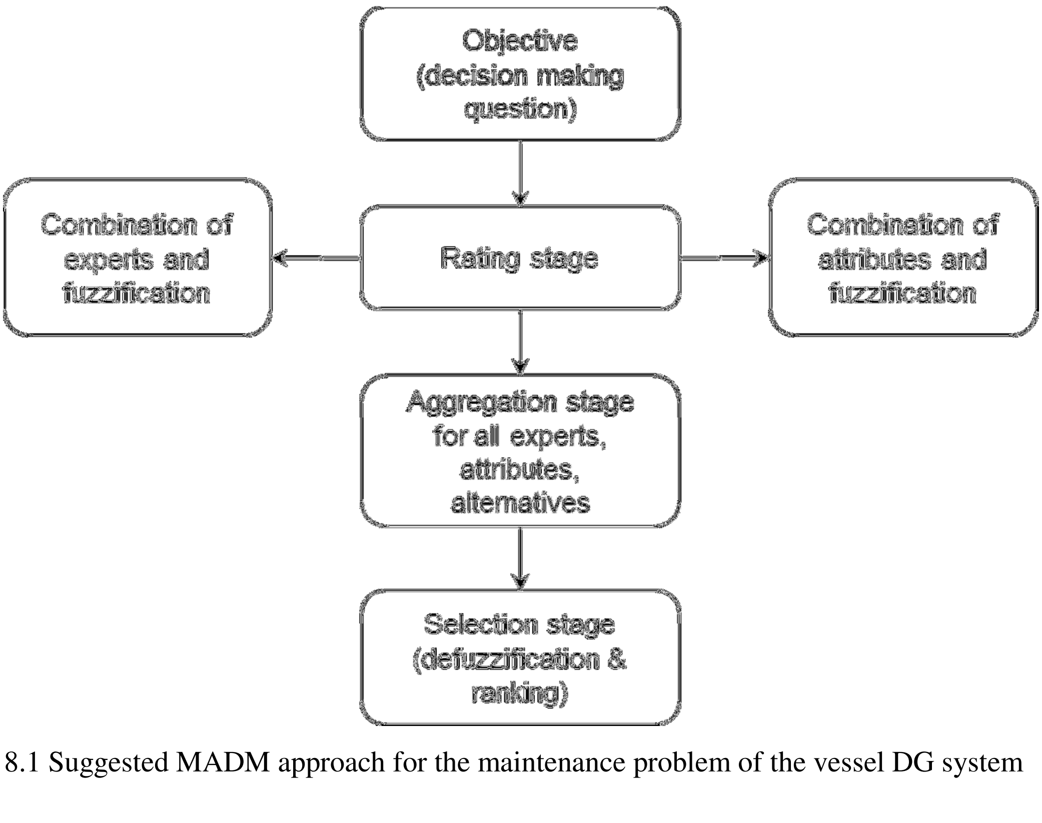

Figure 8.1 Suggested MADM approach for the maintenance problem of the vessel DG system

As can be seen in Figure 8.1, the initiation of the application of the FST in the MADM selection of the maintenance type starts with the description of the maintenance objective (or otherwise decision making question) which is satisfied in the following three stages: the rating, aggregation and selection stage. In this respect, a brief summarised description of the formulated maintenance question along with the attributes involved and the various maintenance alternatives available is shown in Figure 8.2.

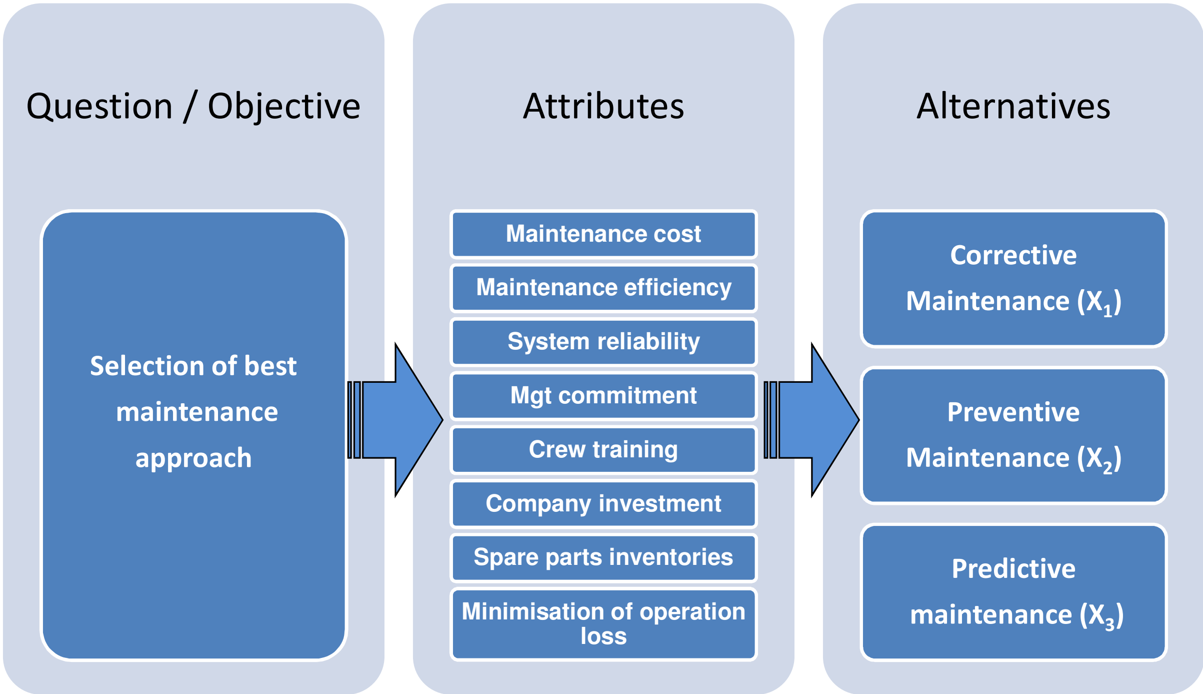

Figure 8.2 Multi attribute decision-making study layout

As is shown, the objective (question) of the MADM problem is the selection of the most appropriate maintenance approach for the DG system of a vessel. There are three alternatives (solutions) suggested for the subject objective. These refer to the three different maintenance approaches, namely corrective (X_1), preventive (X_2) and predictive (X_3) maintenance. In the following, these are examined concerning eight different attributes (A_1 - A_8) and their influence on them. The different attributes considered here are listed as:

1. Maintenance cost in case of implementation of the specific maintenance approach (A_1). In this case, maintenance cost refers to the overall cost when comparing the various maintenance alternatives over a period of 5 years
2. Maintenance type efficiency (A_2). This attribute considers how efficient is each maintenance alternative suggested
3. Increase in the system reliability after implementation of the maintenance approach (A_3). The growth in the system reliability is taken into account with this attribute (this is related to the effectiveness of the attribute)

4. Top management commitment towards implementation of each of the maintenance types (A_4). With this attribute the engagement of the high-level managerial team in order to support the maintenance effort
5. Crew training cost involved in each maintenance type (A_5). This attribute highlights the potential crew training needed in order to get specialised knowledge in the use of equipment for carrying out the maintenance tasks (e.g. condition monitoring)
6. Company investment cost regarding each maintenance approach (A_6). Discusses the initial company capital cost that needs to be tied-up in additional equipment in order to perform the selected maintenance approach
7. Spare parts inventories (A_7). Refers to the spare parts that need to be available beforehand in order to carry out the maintenance alternative
8. Minimisation of the operation loss that may occur (A_8). The last attribute considers the extent of the potential operation loss that may occur in the case that a specific maintenance alternative/approach is selected

The properties of the attributes are described in details in Table 8.1.

Table 8.1 Properties of attributes used in the case study of the ship DG system

Attributes	*Description*	*Type of assessment*	*Type of attribute*	
A_1	Maintenance cost	linguistic	cost	subjective
A_2	Maintenance type efficiency	linguistic	benefit	subjective
A_3	System reliability	linguistic	benefit	subjective
A_4	Management commitment	linguistic	benefit	subjective
A_5	Crew training	linguistic	cost	subjective
A_6	Company investment	linguistic	cost	subjective
A_7	Spare parts inventories	linguistic	cost	subjective
A_8	Minimisation operation loss	linguistic	benefit	subjective

As is shown above, all the attributes are described in linguistic terms. Furthermore, the attributes are categorised according to their contribution in the problem objective, that is whether they have a benefit/higher or cost/less impact on it. The last column of Table 8.1 signifies the subjective or objective nature of the attribute. In this case, all the attributes are of subjective type, meaning that all the initial rankings are provided based on the experts' subjective view. After having presented the alternatives as well as the related attributes for the MADM maintenance problem, the specific steps followed in order to achieve the selection of the most appropriate maintenance type are explicitly shown in the next sections.

8.2.1 Rating stage

As described above, the rating stage of the different alternatives per attribute and expert involved in the MADM problem is demonstrated in this section. Initially, each attribute is allocated a relative importance factor *(RI)* concerning the importance that each attribute conveys in the decision-making procedure. In this respect, the highest/most important attribute is given a factor of 100, while the rest of the attributes are compared with the highest one and are assigned lower weighting factors. Following the above, each attribute is assigned a separate weighting factor w_i with $0 < w_i < 1$ as mentioned in the methodology section of this Chapter. The initial allocation of the mentioned factors is carried out by the selected group of experts, whose opinion is requested in the first place.

In terms of the group of experts participating in the MADM, they originate from different levels of the maritime industry and accordingly each expert's operational experience and expertise on the subject matter of maintenance approach selection has been considered. More specifically, the experts who participate and provide the performance ratings of the maintenance solutions with regards to the specific attributes are the technical manager of a shipping company (E_1), a superintendent engineer (E_2), a 2nd engineering officer (E_3) and a 3rd engineering officer (E_4).

At this point, it is essential to describe the role and responsibilities of each of the experts involved in the presented case study in order to clarify the experts' overall importance in the subject MADM process. With this in mind, the technical manager of a shipping company (E_1) is responsible for the overall technical supervision of a fleet of vessels as well as he retains the managerial overlook through the entire structure of the technical department of the company. He is also responsible for the budget allocation in the overall fleet of vessels that the company operates. The superintendent engineer (E_2), is accountable for a certain vessel or number of vessels with regards to their general performance as well as having some budgeting and management duties to perform. The 2nd engineering officer (E_3) follows the chief engineer's guidelines onboard the ship, while he/she is the actual supervisor of the jobs of the lower engineering personnel (e.g. 3rd engineer, oiler, wiper, etc.) carried out onboard the vessel. Finally, the 3rd engineering officer (E_4) is the lower ranked on the four experts within the structure of the shipping company and he attends the day-to-day operations of the ship, getting involved in various engineering tasks and gaining valuable experience in order to build-up his skills and knowledge.

Each one of the above experts is allocated different rating factors re_i as per the attribute they are asked to rank. The highest/most important rating factor assigned per expert E_i and attribute A_i is equal to one, while the rest are compared and categorised according to their importance/relevance with the top weighting factor. For instance, expert E_1 (technical manager) is assigned a factor *re* equal to 1 for the fifth attribute (top management) while expert E_4 (3rd engineering officer) is assigned a factor *re* equal to 0.1 for the same attribute. Then these factors are aggregated per each attribute providing a weighting factor *we*. The full details of the assigned rating (*re*) and weighting (*we*) factors for each expert and each separate attribute and alternative are presented in Table 8.2.

Table 8.2 Attribute and experts ranking and weighting factors

Attributes	**Relative Importance**	**w**	**E₁ re**	**E₁ we₁**	**E₂ re**	**E₂ we₂**	**E₃ re**	**E₃ we₃**	**E₄ re**	**E₄ we₄**
A_1	75	0.121	1	0.370	0.75	0.278	0.65	0.241	0.3	0.111
A_2	82	0.132	0.7	0.219	1	0.313	1	0.313	0.5	0.156
A_3	100	0.161	0.8	0.242	1	0.303	1	0.303	0.5	0.152
A_4	75	0.121	1	0.455	0.7	0.318	0.4	0.182	0.1	0.045
A_5	65	0.105	0.5	0.172	0.6	0.207	0.8	0.276	1	0.345
A_6	75	0.121	1	0.435	0.8	0.348	0.4	0.174	0.1	0.043
A_7	70	0.113	0.9	0.305	0.9	0.305	0.7	0.237	0.45	0.153
A_8	80	0.129	1	0.317	1	0.317	0.7	0.222	0.45	0.143

What follows next is the representation of the experts' answers by using the fuzzy linguistic expressions. In order to achieve the above, there are a number of different linguistic terms and their fuzzy weighting Scales available as retrieved from Chen and Hwang (1992). In any MADM process, one can employ either a combination of different Scales or just a single Scale to transform the linguistic terms into fuzzy numbers. For the present study, Scale 3 is selected to be employed, using five different ranking categories ('very low', 'low', 'medium', 'high' and 'very high') (Table 8.3). This is performed for various reasons. In the first place, Scale 3 is selected in order to maintain a simple and robust ranking type. More specifically, it is multifaceted enough to provide the experts with adequate space for ranking (five different options to select from one to five) whereas at the same time also create a robust enough fuzzy scale category, which will not confuse the experts with additional (and in some cases unnecessary) linguistic terms. The above-mentioned Scale is used for all the solutions as well as across all the attributes described.

Table 8.3 Fuzzy weighting scale used in the suggested approach

Scale 3

Linguistic term	**Fuzzy number set**
Very Low	(0, 0, 0.1, 0.2)
Low	(0.1, 0.25, 0.4)
Medium (fair)	(0.3, 0.5, 0.7)
High (good)	(0.6, 0.75, 0.9)
Very high (very good)	(0.8, 0.9, 1.1)

Moreover, the experts' answers to a sample questionnaire are achieved in order to obtain their view on the selection of the most appropriate maintenance approach (Appendix H). The questions distributed to the mentioned experts are directly associated with the most significant issues which are combined in order to achieve the best maintenance policy in the maritime context. The experts' responses are then transformed into fuzzy trapezoidal expressions which are eventually used for the aggregation process for each one of the different attributes mentioned in the previous section. Overall, the initial expression of the experts' opinion together with the respective standardised fuzzy numbers for each different alternative and attribute are summarised in Table 8.4 below.

Table 8.4 Experts' answers and respective standardised fuzzy numbers per alternative and attribute

		corrective maintenance (X1)				preventive maintenance (X2)				predicitive maintenance (X3)			
		E_1	E_2	E_3	E_4	E_1	E_2	E_3	E_4	E_1	E_2	E_3	E_4
A_1	Experts' opinion	high	very high	very high	very high	low	medium	medium	low	medium	low	very low	very low
	Standardised fuzzy number	(0.6, 0.75, 0.75, 0.9)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.1, 0.25, 0.25, 0.4)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.1, 0.25, 0.25, 0.4)	(0.3, 0.5, 0.5, 0.7)	(0.1, 0.25, 0.25, 0.4)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)
A_2	Experts' opinion	very low	very low	very low	very low	very high	medium	medium	very high	medium	very high	very high	high
	Standardised fuzzy number	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.8, 0.9, 1, 1)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.6, 0.75, 0.75, 0.9)
A_3	Experts' opinion	very low	very low	very low	very low	very high	low	medium	very high	low	very high	very high	low
	Standardised fuzzy number	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.8, 0.9, 1, 1)	(0.1, 0.25, 0.25, 0.4)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.1, 0.25, 0.25, 0.4)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.1, 0.25, 0.25, 0.4)
A_4	Experts' opinion	very high	very low	very low	low	high	medium	medium	high	very low	very high	very high	very high
	Standardised fuzzy number	(0.8, 0.9, 1, 1)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.1, 0.25, 0.25, 0.4)	(0.6, 0.75, 0.75, 0.9)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0, 0, 0.1, 0.2)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)
A_5	Experts' opinion	high	very low	medium	medium	medium	medium	high	medium	very high	very high	very high	very high
	Standardised fuzzy number	(0.6, 0.75, 0.75, 0.9)	(0, 0, 0.1, 0.2)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)
A_6	Experts' opinion	medium	very low	very low	low	medium	medium	medium	medium	high	very high	very high	very high
	Standardised fuzzy number	(0.3, 0.5, 0.5, 0.7)	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.1, 0.25, 0.25, 0.4)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)
A_7	Experts' opinion	medium	high	high	very high	very high	medium	medium	medium	low	very low	low	low
	Standardised fuzzy number	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.6, 0.75, 0.75, 0.9)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.1, 0.25, 0.25, 0.4)	(0, 0, 0.1, 0.2)	(0.1, 0.25, 0.25, 0.4)	(0.1, 0.25, 0.25, 0.4)
A_8	Experts' opinion	very low	very low	low	very low	very high	medium	medium	high	medium	very high	very high	very high
	Standardised fuzzy number	(0, 0, 0.1, 0.2)	(0, 0, 0.1, 0.2)	(0.1, 0.25, 0.25, 0.4)	(0, 0, 0.1, 0.2)	(0.8, 0.9, 1, 1)	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)	(0.8, 0.9, 1, 1)

8.2.2 Aggregation stage

In the aggregation stage, the experts' answers/ratings are combined for each attribute and each maintenance solution. In order to achieve this, the degree of agreement (or similarity function) S among the experts is estimated first by using the standardised trapezoidal fuzzy numbers as shown in Equation 4.18. Having performed the above, the agreement matrix (AM) is created next, followed by the average degree of agreement (AA) for each attribute shown in Equation 4.19. Accordingly, the relative degree of agreement (RA) is estimated (Equation 4.20) followed by the consensus degree coefficient (CC) as calculated by Equation 4.21. For the calculation of the CC the β factor is taken into account, which denotes the influence of the facilitator on the initial weighting factors for each attribute (w) as well as on the relative degree of importance (RA) and consequently on the whole aggregation process. In this case, β equals to 0.5.

Eventually the trapezoidal fuzzy number aggregation result (R) is also calculated as explained in Equation 4.22. In brief, an example of the summarised steps followed so far in the aggregation stage of the MADM process including experts' answers for the fifth attribute is shown in Table 8.5. Overall, the final aggregated results for experts E_1- E_4 are presented in Table 8.6.

Table 8.5 Summarised steps followed in the aggregation stage of the MADM process including experts' answers for the fifth attribute

	Corrective (X_1)	Preventive (X_2)	Predictive (X_3)
Experts (E)			
E_1	(0.6, 0.75, 0.75, 0.9)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)
E_2	(0, 0, 0.1, 0.2)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)
E_3	(0.3, 0.5, 0.5, 0.7)	(0.6, 0.75, 0.75, 0.9)	(0.8, 0.9, 1, 1)
E_4	(0.3, 0.5, 0.5, 0.7)	(0.3, 0.5, 0.5, 0.7)	(0.8, 0.9, 1, 1)
Degree of agreement (S)			
S_{12}	0.325	1.000	1.000
S_{13}	0.750	0.750	1.000
S_{14}	0.750	1.000	1.000
S_{23}	0.575	0.750	1.000
S_{24}	0.575	1.000	1.000
S_{34}	1.000	0.750	1.000
Average degree of agreement (AA)			
$AA(E_1)$	0.608	0.917	1.000
$AA(E_2)$	0.492	0.917	1.000
$AA(E_3)$	0.775	0.750	1.000
$AA(E_4)$	0.775	0.917	1.000
Relative degree of agreement (RA)			
$RA(E_1)$	0.230	0.262	0.250
$RA(E_2)$	0.186	0.262	0.250
$RA(E_3)$	0.292	0.214	0.250
$RA(E_4)$	0.292	0.262	0.250
Consensus degree coefficient (CC)			
$CC(E_1)$	0.207	0.226	0.219
$CC(E_2)$	0.194	0.240	0.233
$CC(E_3)$	0.286	0.239	0.260
$CC(E_4)$	0.313	0.295	0.288
Aggregation result (R)			
R	(0.3, 0.45, 0.47, 0.64)	(0.37, 0.56, 0.56, 0.75)	(0.8, 0.9, 1.0, 1.0)

At this point, it needs to be mentioned that the degree of agreement as well as the average degree of agreement values (S and AA respectively) for the fifth attribute regarding the third alternative (X_3) are equal to one. This is the case with some of the attributes primarily due to the fact that a single linguistic Scale (Scale 3) is used for all the attributes mentioned in this decision making problem. However, the most significant part of the aggregation stage is the final aggregation result (*R*) for each attribute and alternative shown. As can be observed in the case of the fifth attribute, the final aggregation results differ from one another while this is the case for the rest of the attributes as well. Bearing the above in mind, the overall final aggregation matrix for experts E_1- E_4 for all attributes A_i and alternatives X_j are presented in Table 8.6.

Table 8.6 Final aggregation matrix for experts E_1- E_4

	Corrective (X_1)	Preventive (X_2)	Predictive (X_3)
A_1	(0.74, 0.86, 0.93, 0.97)	(0.20, 0.38, 0.38, 0.55)	(0.11, 0.21, 0.26, 0.40)
A_2	(0.00, 0.00, 0.10, 0.20)	(0.52, 0.68, 0.72, 0.83)	(0.65, 0.78, 0.84, 0.91)
A_3	(0.00, 0.00, 0.10, 0.20)	(0.48, 0.62, 0.67, 0.76)	(0.49, 0.61, 0.66, 0.73)
A_4	(0.19, 0.24, 0.32, 0.41)	(0.45, 0.62, 0.62, 0.80)	(0.65, 0.73, 0.83, 0.85)
A_5	(0.30, 0.45, 0.47, 0.64)	(0.37, 0.56, 0.56, 0.75)	(0.80, 0.90, 1.00, 1.00)
A_6	(0.11, 0.20, 0.25, 0.39)	(0.30, 0.50, 0.50, 0.70)	(0.73, 0.85, 0.92, 0.97)
A_7	(0.56, 0.71, 0.73, 0.87)	(0.42, 0.60, 0.62, 0.77)	(0.07, 0.18, 0.21, 0.35)
A_8	(0.02, 0.06, 0.13, 0.24)	(0.49, 0.66, 0.68, 0.82)	(0.68, 0.80, 0.88, 0.93)

As explained above, the aggregation stage provides the necessary input for the following stage of the MADM process; that is the selection stage.

8.2.3 Selection stage

The selection stage is the final stage for carrying out the MADM process. It consists of two separate steps. The first one considers the defuzzification of the aggregated trapezoidal fuzzy values of the matrices developed in the aggregation step by using Equations 4.23-4.27 and summarised in Table 8.7. The second step assists in the ranking the different alternatives after the defuzzification has taken place by using the TOPSIS ranking method.

Table 8.7 Defuzzified aggregated values, normalised and weighted normalised ratings for experts E_1-E_4

		Corrective (X_1)	Preventive (X_2)	Predictive (X_3)
A_1	Defuzzified aggregated values (total score)	0.5287	0.6336	0.6746
	Normalised ratings	0.4960	0.5945	0.6329
	Weighted normalised ratings	0.0598	0.0717	0.0763
A_2	Defuzzified aggregated values (total score)	0.0909	0.6655	0.7717
	Normalised ratings	0.0889	0.6505	0.7543
	Weighted normalised ratings	0.0117	0.0858	0.0994
A_3	Defuzzified aggregated values (total score)	0.0909	0.6223	0.6144
	Normalised ratings	0.1034	0.7078	0.6988
	Weighted normalised ratings	0.0166	0.1138	0.1124
A_4	Defuzzified aggregated values (total score)	0.3016	0.6030	0.7542
	Normalised ratings	0.2981	0.5961	0.7456
	Weighted normalised ratings	0.0359	0.0719	0.0899
A_5	Defuzzified aggregated values (total score)	0.4708	0.5516	0.9091
	Normalised ratings	0.4048	0.4743	0.7817
	Weighted normalised ratings	0.0423	0.0496	0.0817
A_6	Defuzzified aggregated values (total score)	0.2634	0.5000	0.8415
	Normalised ratings	0.2599	0.4933	0.8302
	Weighted normalised ratings	0.0313	0.0595	0.1001
A_7	Defuzzified aggregated values (total score)	0.6915	0.5899	0.2353
	Normalised ratings	0.7365	0.6283	0.2506
	Weighted normalised ratings	0.0829	0.0707	0.0282
A_8	Defuzzified aggregated values (total score)	0.1373	0.6442	0.7960
	Normalised ratings	0.1329	0.6235	0.7705
	Weighted normalised ratings	0.0171	0.0802	0.0991

In the second step, the ranking of the different alternatives after the defuzzification phase is shown by using Equations 4.28-4.35. In this respect, the TOPSIS method is applied in order to obtain the overall rating of the three suggested alternatives (corrective, preventive and predictive maintenance type respectively). As explained above, the TOPSIS method is based on the initial identification of an ideal positive and negative solution and its comparison with the various suggested alternatives. The ideal positive solution derives from the best values of each attribute while the negative one originates from the worst values of each attribute. In this respect, the positive and negative ideal solution for each attribute and alternatives for the suggested maintenance decision-making selection are shown in Table 8.8.

Table 8.8 Positive and negative ideal solutions for the suggested attributes for all alternatives

Attributes	Positive ideal solution	Negative ideal solution
A_1	0.060	0.076
A_2	0.099	0.012
A_3	0.114	0.017
A_4	0.090	0.036
A_5	0.042	0.082
A_6	0.031	0.100
A_7	0.028	0.083
A_8	0.099	0.017

After having set the ideal positive and negative solutions, the distance of each one of the suggested maintenance alternatives from them (S_i^+ *and* S_i^- respectively) is calculated together with the final ranking C_i^+ of each alternative (Table 8.9).

Table 8.9 Distance (separation) of alternatives from positive and negative ideal solution

	Corrective (X_1)	Preventive (X_2)	Predictive (X_3)
Si+	0.173	0.061	0.081
Si-	0.081	0.152	0.172
Ci+	0.319	0.715	0.680
Final ranking	3	1	2

By observing Table 8.9, it is clear that the second alternative (Preventive maintenance - X_2) is the one with the shortest distance from the ideal positive solution (S_i^+) and the furthest one from the ideal negative solution (S_i^-) accordingly, thus ranked as the first maintenance alternative for the DG system of the motor cruise ship. Another significant observation is that the second (X_2) as well as the third (Predictive maintenance - X_3) alternatives are very close in terms of similarity degree from the ideal positive and negative solution. This denotes that although preventive (or planned) maintenance is the preferred maintenance solution for this decision making problem, predictive maintenance is gaining momentum and is considered as the next viable step in the maintenance approach onboard cruise vessels.

On the other hand, as shown in Table 8.9, alternative X_1 (corrective maintenance) is the one furthest away from the positive and closest to the negative solution indicating that corrective maintenance is the least preferred solution for this type of problem. In a more practical perspective, the result can be also verified by the maintenance sequence followed in the luxurious cruise industry (preventive or predictive maintenance being implemented the most). In this respect, the potential breakdown of vessel equipment or machinery is avoided as they lead not only to operational loss and repair expenditure but also to a knock-on effect on the reputation/business profile of the shipping company.

In addition to the above, a sensitivity analysis is performed in order to observe the influence of the β values in the MADM process and accordingly to the selection of the most appropriate maintenance solution. It is reminded that the β values reflect the facilitator's influence in the entire MADM process. A β value of zero denotes that there is no influence in the process while a β value of one denotes that the facilitator's choice on the initial weighting factors attributed to the experts is of major importance and thus, not objective. In this respect, the range of the β values is shown together with the ranking results for the three suggested alternatives in Table 8.10 and Figure 8.3.

Table 8.10 Sensitivity analysis regarding different β values

β value	Corrective (X_1)	Preventive (X_2)	Predictive (X_3)
0	0.3166	0.7128	0.6703
0.1	0.3171	0.7137	0.6725
0.2	0.3176	0.7144	0.6745
0.3	0.3182	0.7149	0.6764
0.4	0.3188	0.7151	0.6781
0.5	0.3194	0.7150	0.6796
0.6	0.3190	0.7145	0.6810
0.7	0.3177	0.7134	0.6823
0.8	0.3162	0.7114	0.6838
0.9	0.3147	0.7085	0.6853
1	0.3130	0.7048	0.6870

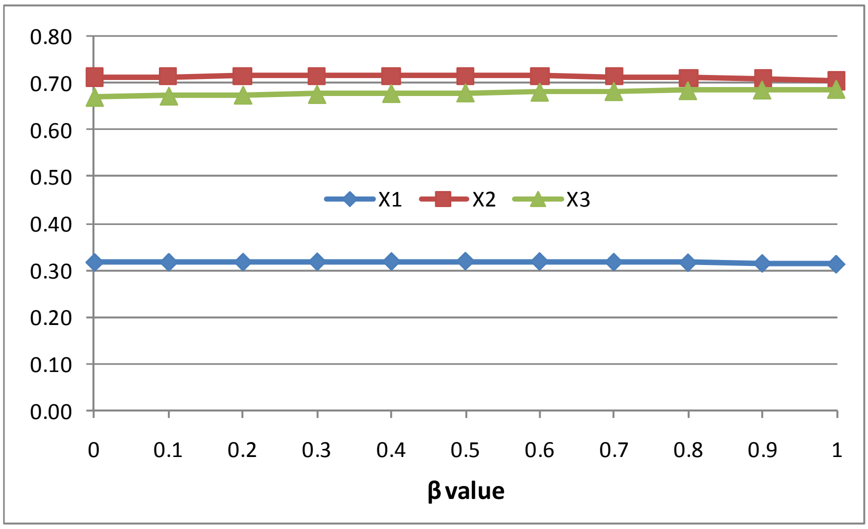

Figure 8.3 Graph showing the sensitivity analysis regarding different β values

As can be seen from both Table 8.10 and Figure 8.3 above, the ranking of the decision making approach does not change as the β values increase from zero to one. The latter shows that the influence of the facilitator in the entire process is of insignificant degree, thus assuring the objectivity of the MADM process for the specific decision making problem. Overall it can be said that the application of the FST in the maintenance multi attributive decision making environment as this is presented as part of the overall RCBM strategy shows very good adaptation to the specific characteristics of the maintenance problem in the maritime environment and thus it is concluded that it can be firmly used in the applications of the optimum maritime maintenance selection process.

8.3 Chapter summary

In the Chapter presented herein, the Fuzzy Set Theory has been used in a group MADM methodology in order to assist in the selection of the most suitable approach regarding the maintenance problem indicated in the previous Chapter and supplement the application of the RCBM strategy. This takes into account three separate stages i.e. the ranking, aggregation and selection stage. The recommended methodology complements the overall proposed maintenance framework shown in the present thesis in terms of dealing with a multi attribute decision making objective in the light of vague information as well as including the involvement of multiple experts' judgement. What follows next is the presentation of the overall conclusions, assumptions and recommendations for future research which are shown in Chapter 9.

9 CHAPTER 9 – DISCUSSION

9.1 Chapter outline

In this Chapter the overall discussion and review regarding the innovative RCBM framework is presented in the following sections.

9.2 Review of overall thesis

The present study has elaborated on the subject of reliability and criticality analysis of maintenance in general as well as being more specific in the case of the maritime sector. In this respect, the thesis has been initiated by stating the dominance of the maritime industry with respect to delivering its high-quality services in the transportation of goods and passengers worldwide. Furthermore, by crafting the introductory note in Chapter 1, the establishment of the primary research question complemented with the specific objectives through which this can be achieved is mentioned in Chapter 2.

Following the above, the next step is to ascertain the originality of the present study and is performed by carrying out a thorough and meticulous literature review on maintenance in both a generic as well as maritime context. This is achieved in Chapter 3, which is divided in three major sections. The first one (§3.3) refers to the examination of the overview of maintenance categories such as the corrective, preventive and predictive maintenance approaches. Furthermore, the outline of maintenance methods existing in other industrial sectors has been demonstrated. The latter includes approaches such as the Terotechnology model, Integrated Logistic Support (ILS) and Logistic Support Analysis (LSA), Business Centered Maintenance (BCM), Risk Based Inspection (RBI) and Risk Based Maintenance (RBM), Vibration Based Maintenance (VBM) and Condition Based Maintenance (CBM), Asset Management (AM), Total Productive Maintenance (TPM) and Reliability Centered

Maintenance (RCM) approach. The advantages and shortcomings of these approaches have been identified in order to explain the need for the new maintenance framework for the maritime industry which covers the aforementioned weaknesses.

Moreover, the second part of Chapter 3 (§3.6) has dealt with the existing maintenance regime in the maritime industry presenting an initial comparison with similar maintenance approaches in other industrial areas. The main broad categories, namely corrective, preventive and predictive maintenance have been examined, whereas predictive maintenance is further investigated in terms of the RCM, RBI (in shipping and offshore sectors), Condition Monitoring (ConMon) and IT applications. The above is performed in order to obtain a clear insight of the existing maintenance approaches currently available in practice and in the research field in the maritime industry as well as identify the gaps, which the suggested innovative maintenance strategy will further fulfil.

Moreover, in order to examine the various reliability and criticality tools and techniques that can be employed in the use of the suggested novel Reliability and Criticality Based Maintenance strategy, a third section has been developed elaborating on this aspect (§3.7). In this section, various approaches are discussed including qualitative and quantitative ones. In the first category, the Failure Modes, Effects and Criticality Analysis (FMEA/FMECA), Hazard Identification (HAZID), Hazard and Operability study (HAZOP), Structured What-If Technique (SWIFT), Bow Tie and Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis tools are encompassed. The second category presents the reliability tools and techniques of the Event Tree Analysis (ETA), Reliability Block Diagrams (RBD), Bayesian Belief Networks (BBN), Markov Analysis (MA), Monte Carlo simulations, the application of Fussy Set Theory (FST) in Multi Attribute Decision Making (MADM) problems and finally the Fault Tree Analysis and Dynamic Fault Tree Analysis (FTA/DFTA) and Importance Measures (IMs) as well.

Having examined the above and identified the research gap, Chapter 4 describes and presents in details the novel Reliability and Criticality Based Maintenance (RCBM) framework for the maritime industry. In it, the advantages of the TPM and RCM approaches with particular focus in the maritime sector are principally combined enabling the introduction of the new maintenance framework (§4.2-§4.4). Furthermore, the combination of reliability and criticality tools such as the DFTA tool is also presented using static and dynamic gates to represent the system structure under consideration (§4.5). In conjunction to DFTA, minimal cut set theory is also demonstrated on its application for the current selected case studies as well as the reliability IMs, which validate the results of the DFTA approach. The FMECA approach is also employed but complemented by a purpose-built criticality matrix. In addition to the above, the application of the FST in the maintenance MADM problem is also revealed in section §4.6.

The above are implemented with respect to the initial structure of the reliability and criticality analysis of the RCBM strategy demonstrated with more details in Chapter 5. In it, the applicability of the mentioned tools is carried out in terms of the presentation of two separate case studies. The first one (§5.3) refers to the main systems and sub-systems of Diving Support Vessel *"DSV A"* while the second one (§5.4) applies the RCBM strategy in the Diesel Generator (DG) system of a motor sailing cruise vessel. In the first case, the DFTA tool is used employing static and dynamic gates in conjunction with the application of minimal cut set theory and reliability importance measures so as to examine the reliability and criticality of the ship's systems. In the second case study, DFTA is supplemented with the FMECA criticality matrix tool providing insight in the reliability of the DG system of the vessel under consideration. In both cases, the original maintenance data stemming from the databases of the subject vessels are used, illustrating the actual repair and maintenance condition over a period of years.

In the case of *"DSV A"*, the above are described and explained explicitly in Chapter 6, in which the results of the mentioned case study are shown. The main systems identified for the subject vessel are the Power plant, the Propulsion, Lifting, Anchoring & Hauling, Water, Diving and finally the Safety system. Initially, the reliability results of the main systems are examined followed by the Probability of Failure (PoF) results of each one of the main sub-systems. Then, the Birnbaum, Criticality and Fussell-Vesely IMs are also studied, validating the results of the DFTA and identifying the most critical items and components of the vessel. The most critical items identified for each individual sub-system of *"DSV A"* are also presented and explained in details. Additional maintenance measures are suggested in terms of the introduction of SPARE gates in the DFT structure for each main system. The reliability index for each one of them is re-calculated in order to observe the influence of the suggested maintenance measures on the main system and sub-systems. Moreover, the availability index of *"DSV A"* when considered as a complete system is also calculated, thus providing valuable information on the improvement of the original condition of the vessel in terms of increasing in its operational availability.

For the second case study of the Diesel Generator (DG) system of a motor sailing cruise ship, the results of the reliability analysis are also shown and explained in Chapter 7. At first, the FMECA results for the subject DG are demonstrated so as to derive the primary conclusions regarding the criticality aspects of this system. Then, the DFTA tool is used and the reliability results of each individual DG are shown. These are followed by the analysis of the reliability IMs as described before, combined with the examination of the cut set results for the mentioned systems. The above assist in the identification of the most critical components of the DG system of the cruise vessel. Additionally, the reliability results of each one of the DGs before and after the introduction of 'SPARE' gates and events are also investigated and compared in order to address the potential for improvement of the DG system. Moreover, the critical items of all the DGs are compared in order to derive their differences and similarities and accordingly identify additional conclusions for the overall DG system. Furthermore, a cost assessment for the overall DG system is performed in order to observe the cost impact of the application of the suggested maintenance strategy as well as the overall benefit achieved.

The above strategy is supplemented in Chapter 8 with the implementation of the Fuzzy Set Theory in order to assist in the selection of the most suitable approach regarding the multi attribute decision-making maintenance problem indicated before. This refers to the second case study of the DG system of the cruise ship, embracing a broader aspect of the proposed innovative maintenance framework including a number of features not considered previously. The latter includes a number of intangible attributes such as the actual cost of a specific maintenance approach selected; the efficiency of the suggested maintenance type; the increase in the system reliability after implementation of the maintenance approach; the top management commitment towards implementation; the crew training cost involved when implementing a specific maintenance type; the company investment cost; the cost of spare parts inventories; and the minimisation of the operation loss that may occur when implementing a specific maintenance policy. The above are examined in the light of the three main maintenance approaches; that is corrective, preventive and predictive maintenance. A group of four experts with different levels of competence and experience is examined and ranked following the FST methodology of the three distinctive stages i.e. fuzzy set ranking, aggregation and selection stage. In this way, the recommended methodology complements the overall proposed maintenance framework shown in the present thesis in terms of dealing with a multi attribute decision making objective combining vague information as well as including multiple experts' judgement.

9.3 Research contribution and achievements of research study

In this section, the contribution of the present study into the broad maritime industry framework as well as more specifically into the maritime maintenance context is presented.

In this respect the main contribution of this study is the proposal and establishment of a novel specialised maintenance strategy for the maritime industry based on reliability and criticality assessment thus increasing the robustness while at the same time minimising the cost elements of maintenance. The mentioned contribution is based on the integration of the existing condition of shipping companies and furthermore enhancing it with the integration of the enhanced technical and management aspects observed in Reliability Centered Maintenance (RCM) and Total Productive Maintenance (TPM). The novelty of the new RCBM framework lays in the incorporation of a broad field of parameters which are all important in the context of the maritime maintenance such as improved data acquisition, application of condition monitoring tools and coordination with current planned maintenance, reliability and criticality assessment, decision support platform, onboard and onshore training of personnel, lean cooperation with supply chain and seamless flow of information through a maintenance management system specifically based on the above parameters.

Furthermore, RCBM is a framework which overcomes the shortcomings of the existing maintenance practices applied in the maritime industry. The benefits stem from the minimisation of the corrective maintenance tasks, the enrichment of the preventive/planned maintenance with condition monitoring, improving the data gathering procedure, establishing a decision support platform thus transforming it into predictive maintenance, increasing the reliability index at a system/ship as well as at a component level, significantly reducing the maintenance cost.

It is important to notice that the novel RCBM strategy not only identifies the reliability of a given system and component but above all prioritises them according to how critical they are in the operation of the overall system suggesting the most appropriate maintenance measures based on the knowledge about reliability characteristics, equipment failures and their consequences.

An additional novelty of the established maintenance framework is the use of Dynamic Fault Tree Analysis (DFTA), which assists in modelling the ship as an entire system for the first time by using the time-influenced dynamic gates on top of the already established classical static gates. Another novel feature is the combination of different tools in order to investigate the system reliability and criticality. These pertain to the mentioned DFTA, cut set theory, reliability importance measures, FMECA with a purpose-built criticality matrix and the Fuzzy Set Theory all deployed in a multiple maritime maintenance decision making process.

9.4 Accomplishment of main aim and objectives

In this section of the present Chapter, the accomplishment of the main aim and objectives mentioned at the beginning of the thesis are presented. Initially, the research question with regards to the implementation and integration of a maintenance strategy based on reliability and criticality assessment has been answered through the proposed innovative maintenance framework. The latter has been supplemented with the application of the above-mentioned strategy on two separate case studies vessels in order to show its effectiveness and moreover validate a small part of the technical section of RCBM. In this regard, a number of objectives have been identified and pursued in order to shed more light into the entire procedure of realising the main aim.

More specifically, the first step towards the aforementioned main aim has been the examination of the existing generic maintenance methodologies and approaches as well as the ones already applied in various business areas and then more particularly in the maritime industry. The maintenance procedures applied in these sectors have been compared with the ones in the maritime sector and the similarities and differences among them have also been identified. The outcome of this comparison is the identification and classification of the existing gaps in the present maintenance methodologies shown in Chapter 4. In this respect, the need for an enhanced maritime maintenance framework has been established and further elaborated in Chapter 4. As a consequence the first objective of the thesis has been achieved.

The second objective of the thesis is related to the establishment of the innovative and integrated maintenance strategy for the maritime industry. In the first place, this is achieved by proposing and establishing the Reliability and Criticality Based Maintenance framework in its full extent. This includes the combination of both the technical aspect observed in the origins of the RCM and the managerial features observed in the TPM maintenance approach. Moreover, both of these aspects are incorporated into a continuous supply chain interaction which enables the combination of all the different novel RCBM features into a common working platform. This is the first part of the innovative maritime maintenance framework, which as is shown in Chapter 4, it has not been examined in the overall maritime sector before.

The next objective that has been achieved is related to the examination and application of the most appropriate reliability tools, which render feasible the examination of the system reliability and criticality in the implementation of the aforesaid maintenance framework.

The solution is the combination of different reliability and criticality tools and techniques. These include the FMECA tool with a purpose-built criticality matrix involving experts' judgement and the Dynamic FTA. The latter is furthermore engaged with the minimal cut set theory and reliability Importance Measures which are used in order to identify the most critical items of the system in question. This is done since DFTA allows for the specific and more accurate representation of the ship systems taking into account the actual time constraints, which as a total vessel system application has not been considered before elsewhere in maritime maintenance. Additionally, the FST is also employed in order to assist in the identification of the maintenance approach needed when dealing with a multi attributive problem such as the maintenance selection for a specific vessel. In this respect, a multitude of technical and especially non-technical features are included which have not been addressed before in the context of the maritime industry.

Moreover, a field study has been performed in order to assess and acquire the relevant data needed for the application of another part of the technical section of the RCBM strategy. The latter has been achieved through numerous contacts and interviews performed with ship operators and personnel both onshore and onboard. During this stage, it has been found that in the best of cases, the existing maintenance management systems still accumulate a vast amount of data without being able to further process and turn them into concise information.

Consequently, the crucial initial stage of data acquisition is transformed into a huge black hole for the current maintenance systems. This has been solved with the suggested RCBM strategy as a full integrated data gathering procedure has been established through the continuous monitoring of onboard equipment, also incorporating maintenance databases and manufacturers' data.

All the above identified tools and data gathered are used to fulfil the realisation of the following objective, which initially examines the application of a small part of the technical section of the novel RCBM strategy on the different systems of a Diving Support Vessel (*"DSV A"*) as well as on the Diesel Generator (DG) system of a motor sailing cruise ship. The novelty at this stage lies in the use of both static and dynamic gates for both case studies, which signifies a turn towards the time-dependent representation of the failures regarding the examination of various systems and their components.

Related to the last outcome, the next objective is accomplished by demonstrating the results of the case studies mentioned above. This includes the initial examination of the reliability levels of the main systems of *"DSV A"*. With the assistance provided from the implementation of the reliability IMs and the cut set theory, the most critical components are demonstrated and thus additional maintenance effort is suggested in terms of the dynamic 'SPARE' gates being used. The reliability of the main systems is then assessed once again and the improved results confirm the application of the additional maintenance undertaking. In a similar manner, the reliability results of the main sub-systems of the overall DG system are also determined. Additionally, the benefits in terms of the overall principal systems investigated are also shown. In this respect, it is observed that there has been significant increase of the availability of *"DSV A"* as well as of the overall reliability of the DG system. Moreover, with the application of the RCBM framework, the cost element of maintenance has been decreased significantly, allowing for another benefit stemming from this approach.

Having performed the above, specific suggestions regarding the maritime assets in question are provided at both generic as well as detailed level in order to improve the maintenance condition and subsequently the reliability of each main system and sub-system in both case studies performed. In the case of *"DSV A"* this is performed by describing specific maintenance measures for each specific system. At a more detailed level, the specific failure causes of the mentioned systems are addressed, suggesting optimal maintenance actions. In the case of the DG system, the supplementary maintenance measures include combination of planned inspections with the application of condition monitoring tools as part of a predictive maintenance approach.

The outcomes of the proposed approach suggest the improvement of the overall reliability and availability of *"DSV A"*. More specifically, the reliability index of the Power plant system has increased to more than 5 months from the original condition. Regarding the Propulsion system, it has extended its high reliability profile up to 30 months of operation while the LA&H system has improved up to 12 months of operational capability. Regarding the Water system, corrosion problems have restricted its reliability improvement to two months of operation. On the other hand, for the Diving system reliability has improved up to another 9 months of operation. In the case of the Safety system, increase of up to 10 months of operation has been achieved too. In terms of the overall system availability, it has shown good results extending the overall vessel availability to the next Special Survey interval.

For the DG system, improvement has been achieved in all individual DGs. In this respect, DG 1 has improved its reliability index by almost 42% up to 34 months of operation while DG 2has more updated results of 49 months of reliable function (increase 29%). This is the case for DG 3 as well (46 months improved reliability condition-31% increase) and DG 4 with 48 months and 26% increased reliability compared to the initial condition. DG 5 is even more enhanced retaining its high reliability results up to 54 months (increase of 42%). Overall, when examining the total DG system reliability, it is enhanced by more than 40% compared to the prior condition. In addition to the above, the cost assessment of the different maintenance approaches shows that predictive maintenance is the most favourable option. As shown, when condition monitoring tools are used, a reduction of the overall cost of up to 1.5 million pounds sterling is achieved when comparing predictive maintenance with the corrective one. In the case of comparing predictive maintenance with the preventive one, a decrease of almost £600,000 is also accomplished.

The last assessment is extended furthermore with the use of the Fuzzy Set Theory to address the problem of selecting the most appropriate maintenance approach for a specific vessel, thus achieving the last objective of the present thesis. The problem in question refers to the DG system of the cruise vessel mentioned before. It comprises a multi attribute decision making process based on the subjective estimation provided by a group of experts with varying experience and expertise. The alternatives suggested include the corrective, preventive and predictive maintenance categories, from which the experts need to provide their judgement. This approach follows a certain path of different stages including the ranking, aggregation and finally the selection stage by using the well-known TOPSIS ranking method. Eventually, the results of this approach suggest that the preventive maintenance type should be considered first in the case of the DG system of the cruise ship, followed closely behind by the predictive maintenance solution. The latter denotes the changing trend in the application of maintenance practices in the maritime industry, as shipping companies move from the traditional corrective maintenance regime to a more scientific and structured preventive and moreover predictive approach as the present thesis highlights.

9.5 Assumptions of the present thesis

In any research undertaking, it is usually the case that certain assumptions and limitations are present, thus enabling but not restricting the implementation of the research study. This is the case with the thesis at hand, in which the following assumptions apply. The initial set-up regarding the DFT structure of the systems presented in the two case studies has been performed bearing in mind the availability of data at the specific period of the data collection activity. This means that the overall system structure may not be complete in terms of including all the individual items and components of *"DSV A"* as well as the DG system of the cruise ship. In this respect, more attention has been drawn to the fact that the data gathering procedure includes actual failure events of specific equipment onboard both vessels rather than generalised/assumed values assimilated from engine manufacturers and/or equipment databases.

Moreover, the details about the specific components and systems that have failed as well as the mentioned failure causes could be at a higher level highlighting the need for further elaboration towards this direction. This, in turns, is related to the maintenance management procedure being carried out onboard the two vessels. More specifically, the data collection activity should have been more thorough in order to capture the detailed information and record the failures/underperforming events occurring in different systems onboard the vessel.

9.6 Chapter summary

In this Chapter the overall discussion and review regarding the innovative RCBM framework has been presented. Moreover, the research contribution and achievements of this research study have been shown together with the achievement of the main aim and objectives. Finally, the assumptions which have been employed for the accomplishment of the thesis have been also described leading to the next Chapter of the thesis in which the final conclusions are highlighted.

10 CHAPTER 10 - CONCLUSIONS

10.1 Chapter outline

In this Chapter the concluding statements regarding the innovative RCBM framework are presented next.

10.2 Conclusions

As has been demonstrated, the RCBM framework places maintenance in the epicentre of maritime operations and fulfils the existing gap by establishing an integrated maintenance approach based not only on the asset reliability but furthermore on the asset criticality index. Overall, the concluding statements of this research study are presented next. More specifically:

- ✓ The presentation of the RCBM strategy has been enabled through the initial identification of the advantages and shortcomings of the current approaches regarding maintenance in a generic as well as a specific (maritime) context. The detailed overview of the current approaches has also clarified the need for a new maintenance strategy and has moreover facilitated the introduction of the RCBM framework.
- ✓ In this respect, with the introduction of the novel RCBM strategy, maritime maintenance has been addressed at both a strategic and application level combining the managerial and technical aspects of maintenance into one interrelated dynamic entity moreover showing the direct link with a decision support platform and establishing a close cooperation with the supply chain stakeholders
- ✓ Case studies based on the proposed RCBM indicated that RCBM can improve the reliability of the ship by 40%. This also proves the benefits of the suggested strategy. It is believed that the benefits will be further enhanced when the full maintenance framework is implemented
- ✓ Consequently, in order to implement the RCBM strategy, the most appropriate reliability and criticality analysis tools and techniques have been examined and finally the Dynamic FTA (DFTA) together with the FMECA with a purpose-built criticality matrix have been selected to assist in the application of the novel maritime maintenance framework. It is proven that the DFTA provides significant benefits

compared to the rest of the reliability tools by employing dynamic time-influenced gates to model the systems under consideration and moreover systematically investigate the criticality index of systems and their components.

- ✓ Furthermore, when the above are applied in the case study of a Diving Support Vessel *"DSV A"*, they assist in the examination of the initial reliability results of the main systems and identify the major contributing (critical) failures and components. In this way, the analyst is capable of addressing the specified failures and critical events by suggesting additional rectifying maintenance measures, which are then introduced in the main system which is modelled as mentioned before. Likewise, the reliability index of the main system and sub-systems is improved as well as the availability of the top system extended to the next extensive maintenance survey performed as per Flag State and Class society's regulations and guidelines.
- ✓ The proposed strategy can be applied to the entire system as well as sub-systems as it has the capability and flexibility to adapt to both cases
- ✓ Relevant to the application of the RCBM strategy in the case of the DG system of a motor sailing cruise vessel, the critical components for the operation of the entire DG system as well as for the sub-systems (individual DGs) have been identified and remedial measures have been suggested. The above analysis is furthermore extended by introducing the cost assessment of the application of different maintenance approaches in the subject case study. In this regard, it is revealed that predictive maintenance reduces the maintenance cost of the examined DG system by up to 1.5 million pound sterling through the lifetime of the vessel compared to the corrective and preventive maintenance methods.
- ✓ Moreover, the enhancement of the RCBM strategy for the selection of the most appropriate maintenance approach has been achieved in the case study of the DG system with the engagement of the Fuzzy Set Theory. In this respect, the selection of the maintenance approach has been transformed into a multi attribute decision making selection problem employing experts' judgement rating a number of different attributes of varying significance in order to come up with the optimum maintenance methodology. The latter has demonstrated that preventive as well as predictive maintenance are the most suitable ones, complementing the results of the financial analysis mentioned above.
- ✓ Fuzzy Set Theory which includes experts' input clearly denotes that preventive and predictive maintenance are much more appropriate compared to corrective

maintenance in terms of top management commitment, maintenance cost, maintenance effectiveness, onboard crew training, company investment, system reliability, spare parts inventories, minimisation of operation loss

- ✓ By utilising the proposed RCBM strategy, preventive and predictive maintenance approaches reduce the maintenance cost while improve the overall reliability and availability
- ✓ The RCBM strategy can be further enhanced when combining the above with a web-based application through which the automatic data acquisition and elaboration can take place, thus enabling real-time decision support actions.

11 CHAPTER 11 - RECOMMENDATIONS FOR FUTURE RESEARCH

11.1 Chapter outline

In this Chapter the recommendations for carrying out further research regarding maintenance in the maritime context are suggested next.

11.2 Recommendations and further research activities

Overall, the present thesis has introduced, established and demonstrated an innovative framework for addressing maintenance in the maritime industry in order to assess the reliability of the systems and sub-systems of a ship and identify the criticality level of individual components. Additionally, the RCBM framework demonstrates the data acquisition and gathering process, develops a decision support onboard platform, enhances personnel training, involves management commitment and introduces the novel ship-company-supply chain interaction. Nevertheless, there are some parts of the present thesis, which can be enhanced furthermore by suggesting additional research in the areas mentioned next.

For the data collection and analysis procedure, the employment of more specific and complete datasets as well as drilling into the information regarding more details for the failure causes of specific equipment and system components can be helpful. This is dependent on the resources available including the existing shipping company database system/software in use, the availability of machinery components failure statistics as well as the cooperation with the company personnel tasked with the above such as technical managers, superintendent engineers and maintenance crew. To that extent, better communication and cooperation among the onshore and onboard personnel is necessary in order to perform the maintenance optimisation sequence.

The present innovative maintenance framework can be also applied and improved through the collaboration with original machinery and equipment manufacturers. The enhancement of the overall approach can be also achieved through research projects either at a national or international level. This is the case of a recently initiated EPSRC funded project (Low Carbon Shipping), in which a maintenance parameter is being examined bearing in mind the minimisation of ship generated emissions (carbon footprint of the ship) as well as the optimisation of the maintenance routine onboard the ship. The full benefits of the RCBM framework can be achieved by taking a further step ahead in the data retrieval, storage and elaboration of the information gathered from the PMS as well as from the daily routine of the ship's maintenance plan would be a web-based application. In this case, it would include provisions for spare parts inventory, real-time monitoring of the maintenance implementation with access from onshore personnel (technical manager, superintendent engineer) and potentially from onboard personnel (chief engineer, captain).

Regarding the DFTA and FMECA reliability tools, modelling of the entire ship hull structure, machinery and navigation equipment would be also beneficial as well as examining the reliability and criticality of their systems and sub-systems identified in the first place. Further on, other reliability tools can be employed for future research activities either in micro or macro scales. More specifically, the Monte Carlo simulation tool can be employed in achieving the required failure rates in order to address the data acquisition process and moreover assist in modelling the structure of systems while examining the details of the reliability and criticality importance of the components being used. On the other hand, the Markov Analysis and the Bayesian Belief Networks can assist in the modelling of a larger system such as the overall hull structure and machinery space/area combining attributes from smaller/lower sub-systems. This was a tool which was tried in the first place for the modelling of the entire DSV and DG system but failed due to restricted computer capability leading to the software 'crashing'. Therefore, enhanced software and hardware capacity is a prerequisite when addressing more complex systems such as a vessel at its full extent.

The application of the FMECA approach can be extended to cover an entire ship system such as *"DSV A"* in order to examine the full potential of involving experts' judgement in combination with purely technical models in order to derive the optimal maintenance result. Furthermore, the full benefits of the RCBM strategy can be achieved through the full integration of the technical and management aspects of the approach with the current situation in a shipping company further enabling full condition monitoring environment, data acquisition and gathering, automatic criticality analysis, decision support platform onboard, training of onshore and onboard personnel and seamless integration and cooperation with the supply chain stakeholders.

A further step ahead in the present study performed herein, would be also the integration of the relationship between maintenance and human element onboard ships. This is especially the case when considering that the number of crew onboard the ships tends to be minimised for a number of reasons. The latter includes the ever more reduced number of persons following the seafarer's career as well as the modernisation and automation of engine and machinery equipment onboard ships. The last issue comes in addition to concerns especially in the case of naval vessels and merchant ships in which the numbers of maintenance crew has decreased significantly.

In addition to the above and especially in the case of the MADM methodology, which employs the FST for the identification of the most appropriate maintenance approach, it can be expanded in a number of different ways. As the original framework for the selection process is already provided, the group of experts can be expanded to include other relevant stakeholders such as the captain and chief engineer of a ship, the owner of the shipping company as well as a cadet to cover an even wider range of experts from the shipping industry including experts' financial, managerial and technical knowledge into it. Furthermore, the initial ranking stage of the different attributes and alternatives can be examined in the light of the application of the Delphi or Analytical Hierarchy Process (AHP) method to address the initial phase of rating the alternatives per each attribute. Another recommendation would be to address more alternatives suggested for the initial selection process by including the sub-divisions of preventive and predictive maintenance. These may comprise the overhaul and repair types of preventive maintenance as well as the continuous and interval-based types of predictive maintenance mentioned in the RCBM framework.

In addition to the above, an online application of the above stated MADM methodology can be created in order to enhance its application using FST in a broader spectrum of functions regarding ship maintenance. This can be achieved by using the Java programming language tool to model the MADM, including a variety of alternatives, attributes and number of experts enabling at the same time real time updates in the group of alternatives and attributes available according to the decision maker's preference.

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APPENDICES

Appendix A - Qualitative and quantitative risk and reliability tools and techniques

Appendix B - MTBF values used for the case study of *"DSV A"*

Appendix C - Dynamic Fault Tree structure for *"DSV A"*

Appendix D - Dynamic Fault Tree structure for *"DSV A"* with SPARE gates

Appendix E - Dynamic Fault Tree structure for examining the overall availability of *"DSV A"*

Appendix F - Dynamic Fault Tree structure for the entire DG system

Appendix G - Dynamic Fault Tree structure of the DG system with SPARE gates

Appendix H - FMECA table for the DG system

Appendix I - Questionnaire used in the fuzzy set case study

Appendix A – Qualitative and quantitative risk and reliability tools and techniques

A.1 Qualitative risk and reliability tools and techniques

Appendix A demonstrates the presentation of the main qualitative reliability tools and techniques available in order to carry out the reliability and criticality analysis.

A.1.1 FMEA / FMECA

Failure Modes and Effects Analysis (FMEA) is a reliability analysis qualitative systematic method for comprehending a particular system or process (Teng 1996). The overall aim of FMEA is to review the system under investigation in order to provide details on how to identify failures and their causes as well as to determine the end results of the failures occurring. FMEA is a bottom-up approach which assists in mapping the overall failure events of a system or process. It is also used to pinpoint the items or processes that may need potential improvement at a design stage regarding the safety and operation characteristics of an item, sub-system or system. FMEA may be applied at the initial stage of a reliability analysis of a main system or part of it but also at any other interim stage in order to update the existing reliability exercise. As it is shown in Table 1, FMEA consists of the following elements:

- Failed item: The item or component which has failed
- Failure event: The event that lead to the failed item
- Failure cause: The initiating failure cause
- Effects of the failure: The effects at a local (immediate effect) and global (secondary effects) level
- Detection method used to identify the failure event
- Prevention mode: What could have been done to prevent the failure from occurring
- Repair time: The actual repair time of the failure event
- Unavailability: The total time out of operation (including initial breakdown, inspection, repair, testing and restarting the item)
- Remarks: Any kind of useful remarks identified during the initial inspection, maintenance and repair procedure

Table 1 Sample FMEA for an auxiliary ship engine table

Failed item	Failure event	Failure cause	Effects		Detection method	Prevention method	Repair time	Unavailability	Remarks
			Local	Global					
Oil mist detectors	blocked	No vacuum (vacuum breaks), filter chocked, faulty, valve chocked/damaged	unable to detect oil mist	stop engine, explosion	failure alarm	regular "zero setting", calibration	1hr	1.5-2 hrs	replace by spare (at least one/dg)
Cylinder heads 1-6	leakage, overheating	cracks, faulty exhaust valves, improper combustion	high temp alarm, smoke detection/alarm	stop engine	high pressure/temp alarms	proper monitoring of oil, exhaust & water pipes	2 hrs	3-4 hrs	proper maintenance
Governor	erratic function	electronic/mechanical control failure	cannot operate/malfunction load share	stop engine	frequency meter, kilowatt meter	lube oil replenish, maintain electronic circuits	2 hrs	3 hrs	
Valves, fuel injectors	blocked valve and/or injectors	Lack of maintenance, poor fuel quality, fuel temperature not correct, oil leakage on valve, not proper fuel injection/combustion	Load share for relevant cylinder, insufficient oil combustion, excessive smoke	Deferential temperature of exhaust gas	High deferential temperature indicated local or at control room monitors visual inspection	Overhauling/inspection and parts replacement according to manufacturer's instructions	1/2 hr	1 hr	spare fuel injectors ready for use
Turbocharger	bearing failure, seizure	lack of lubrication, excessive carbon deposits, cracked blades, inlet filter chocked, not sufficient air pressure, surging	bearing damage, turbine damage	lower output, high fuel oil consumption	high exhaust temp, reduced efficiency, low scavenge pressure (surging)	monitoring bearings, exhaust temp, scavenge pressure & temp	6hrs	depending on turbine condition (cleaning with chemicals, etc. - 12-24hrs	
Fuel system, valves, piping	Rupture of pipe, leakage, sludges/water in the line	poor quality diesel/HFO, cat fines, sludges (MDO)	oil spillage, hot spot creation	fire in E/R, genset failure, blackout	visual, loss of power, high temp deviation	good purification, filter cleaning, fuel treatment	1/2 hr	depending on situation	

According to Kumamoto and Henley (1996), the objectives of carrying out an FMEA, which at the same time constitute its benefits when applied, are to:

- Identify all items/components that might be influenced by any initiating failure events and depict their effects within a described system
- Classify the identified failure modes according to their criticality in the system under investigation
- Identify prevention methods that will assist in avoiding the initial failure events
- Identify the detection methods that will help mitigate the effects of the failure causes
- Be used as a basis for a thorough maintenance plan

On the other hand, FMEA can be time consuming (especially in the case of large systems). The detailed nature of an FMEA can be both a benefit and a weakness in terms of the over-extension of the analysis carried out. Another challenge is that each failure mode of the system or process under investigation is considered independent as the analysis concerns individual failure modes and their effects on a system. In the case that failure causes depend on a series of events or are the outcome of multiple failures, then other methods can also be complementary employed such as the FTA, RBD and MA.

Regarding FMECA, it is an expanded version of the classical FMEA as it has been described and developed in detail for the US DoD in the military standard 1629A as early as 1980 (US DoD 1980). This handbook includes definitions of the maintenance and reliability related terms and describes the requirements for FMECA presenting worksheet tables, functional and reliability block diagrams, graphs in relation to the criticality classification and examples of various cases. Ideally, it should be carried out by a team of experts which will have the knowledge and experience of the design features, operation and maintenance of the system to be analysed (Kontovas et al 2006). Complementary to the above, the team should be aware of any constraints applied such as environmental, health and safety and others originating from regulatory bodies so as to enhance the adequacy of its results.

A.1.2 Hazard Identification (HAZID)

As its name suggests, the Hazard Identification (HAZID) approach is used to identify the potential situations which may cause harm to people (working personnel and the public), the environment, the asset under examination as well as to the business itself in terms of the generation of bad reputation. It forms the initial step for the introduction of the risk analysis/assessment and can be used in the examination of hazards related to a physical situation (vessel approaching the quayside), an activity (e.g. diving operations) or a material (oil spill and potential fire/explosion). In this respect, HAZID is conducted in a qualitative way in order to create a list of potential hazards, which will also assist in identifying the measures for mitigation, prevention or controllable acceptance of risks created from the identified hazards. In order to initiate the HAZID approach, a facilitator should lead the hazard identification meeting(s) and have good knowledge of the approach to be followed and the system under consideration. Moreover, the scope of the hazard identification needs to be clearly defined so as to avoid confusion and misinterpretation of the potential hazards to be included in the approach. The group of experts assembled to carry out the hazard identification of the given asset, activity or operation should also be experienced with particular expertise on the various systems/processes examined. They should also avoid the over-estimation or censoring of information over a specific hazard. On top of the above, HAZID should also draw upon the use of past incident reports and lessons-learnt from previous related hazardous operations

HAZID can be also employed concurrently with a risk matrix in order to prioritise the potential hazards arising or engulfed in the system examined. In this way, the hazards can be ranked and prioritised accordingly. Moreover, HAZID is a powerful and well-applied tool especially in the case of the offshore oil and gas industry. As has been already mentioned, its strength lies in the use of multiple experts' judgement, drilling into the core of the potential existing hazards as well as identifying measures for addressing any undesirable events. Besides from the above, it may assist in the identification of hazardous events that have not been existent to that time. On the other hand, its shortcomings lie in the specific nature of its application. That is, latent drawbacks may refer to having difficulties in reaching full consensus regarding the hazards identified by the group of experts in the first place as well as lagging in information and experience especially in the case of novel design features.

A.1.3 Hazard and Operability study (HAZOP)

The Hazard and Operability (HAZOP) study is another way of identifying potential hazards in the functionality of a system. It differentiates from the HAZID approach in terms of being specifically carried out in the process plants classifying problems regarding the safety and the operational environment of a system under examination (NTS 2001, NTS 1998). The latter may include a fluid or a thermal system, especially the ones present in the offshore process oil and gas (e.g. oil transfer system, evacuation procedures) as well as the chemical industry. In relation to the HAZID approach, HAZOP may include the following steps (ABS 2003b-Table 2):

- Setting up the initial HAZOP team
- Identify the boundaries of the system under examination
- Prepare and perform the assessment
- Evaluate the results and
- Document the overall assessment

Table 2 Example of HAZOP study for the Compressed Air System of a vessel (adapted by ABS 2003b)

Item	Deviation	Causes	Consequences	Safeguards	Risk Ranking (Consequence, Likelihood)	Recommendations
1.1	High flow		No mishaps of interest			
1.2	Low/no flow	Plugging of filter or piping (especially at air intake)	Inefficient compressor operation, leading to excessive energy use and possible compressor damage	Pressure/vacuum gauge between the compressor and the intake filter	Medium Risk (Consequence: Medium, Likelihood: Medium)	Make checking the pressure gauge reading part of someone's daily rounds
		Rainwater accumulation in the line and potential for freeze-up	Low/no air flow to equipment and tools, leading to production inefficiencies and possibly outages	Periodic replacement of the filter		Replace the local gauge with a low pressure switch that alarms in a manned area
				Rain cap and screen at the air intake		

As previously mentioned, HAZOP is another broadly used approach, greatly relying on the expertise of the team performing the study. The particular group of experts need to originate from various disciplines relevant to the examined system while they also need to recognise both the technical and human related hazards. However, there are also a few shortcomings stemming from the application of this assessment as well such as; its dependence on the team and expertise of the group of experts performing the study; the thorough description of the process under investigation and finally the time consuming element of this approach.

A.1.4 The Structured What-If Technique (SWIFT)

The Structured What-If Technique (SWIFT) is another approach pertaining to the use of hazard identification methods. It is a mind-mapping activity which enables a relatively smaller team of experts to perform the hazard recognition activity. The element of flexibility that it possess, distinguishes it from the HAZID and the HAZOP approaches although it retains its structured and full capability. Its structure is similar to the ones described before (Figure 1). In this case, a group of multi-disciplinary experts with broad experience of the system to be analysed is employed as well, while also using checklists in order to identify potential threats.

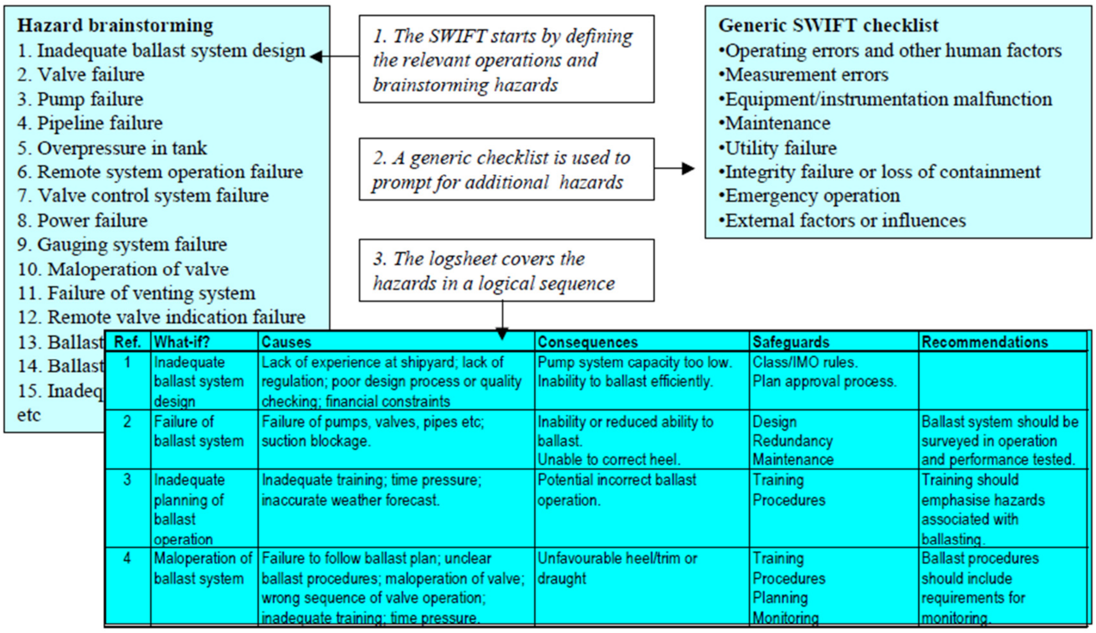


Figure 1 Example of SWIFT approach (DNV 2001)

In terms of the advantages and gaps identified in this approach, these are similar to the ones mentioned for the previous hazard identification assessments such as use of experienced group of experts and being a well-structured approach. Moreover, it is flexible enough to be applied to any system operation while it is not as time consuming as the other two approaches and takes into account the human factor as a source of potential threats. Regarding its weaknesses, its outcome heavily relies on the expertise of the team of experts involved in the original assessment while the need for preparing checklists in advance may be a time-consuming activity.

A.1.5 Bow Tie Analysis

The Bow Tie Analysis is another approach in order to address the qualitative risk and reliability of systems under consideration. In particular, it combines the use of Fault Tree as well as Event Tree in one single and simple to use diagram in order to identify the causes and consequences of an undesired event which is shown in the middle of the diagram (Figure 2).

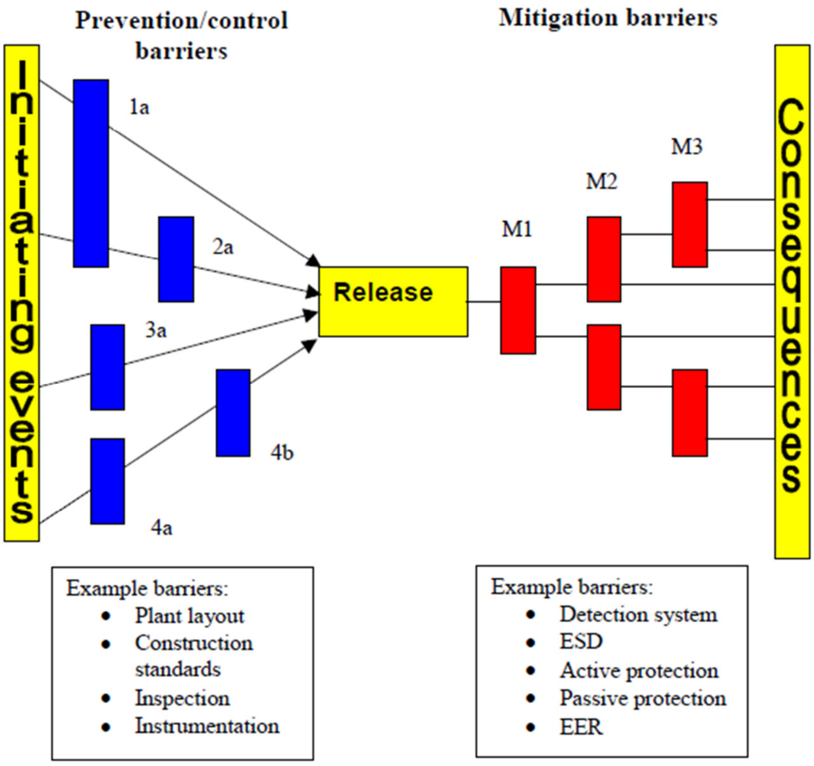


Figure 2 Example of Bow Tie Analysis diagram (HSE 2006)

In the left hand-side, the diagram consists of the potential threats (initiating events) identified while their consequences are shown in the right-hand side. Safeguards are being employed in both sides shown as safety barriers which prevent the occurrence of both the initial events and their outcomes as well. The Bow Tie Analysis can be a useful tool for qualitative examination of unwanted situations due to its clear graphical representation of initial threats, consequences and safeguards. It is also simple to understand and communicate to non-technical personnel/stakeholders as well as the associating safeguards to the management system are also clearly depicted. On the other hand, it can be ineffective in the case of complicated systems examined while it needs to present good balance of prevention measures for both sides of the diagram.

A.1.6 Strengths, Weaknesses, Opportunities and Threats (SWOT)

Strengths, weaknesses, opportunities and threats (SWOT) analysis is decision making tool which assists in the evaluation of an entire project/system. It takes into account the specific objectives of the project/system under examination by considering the internal (strengths and weaknesses) as well as the external (opportunities and threats) factors that influence the initially stated objectives (Arslan and Er 2008). It can be performed at the initial stage of a decision-making process by a single expert or most preferably by a team of experts (Figure 3).

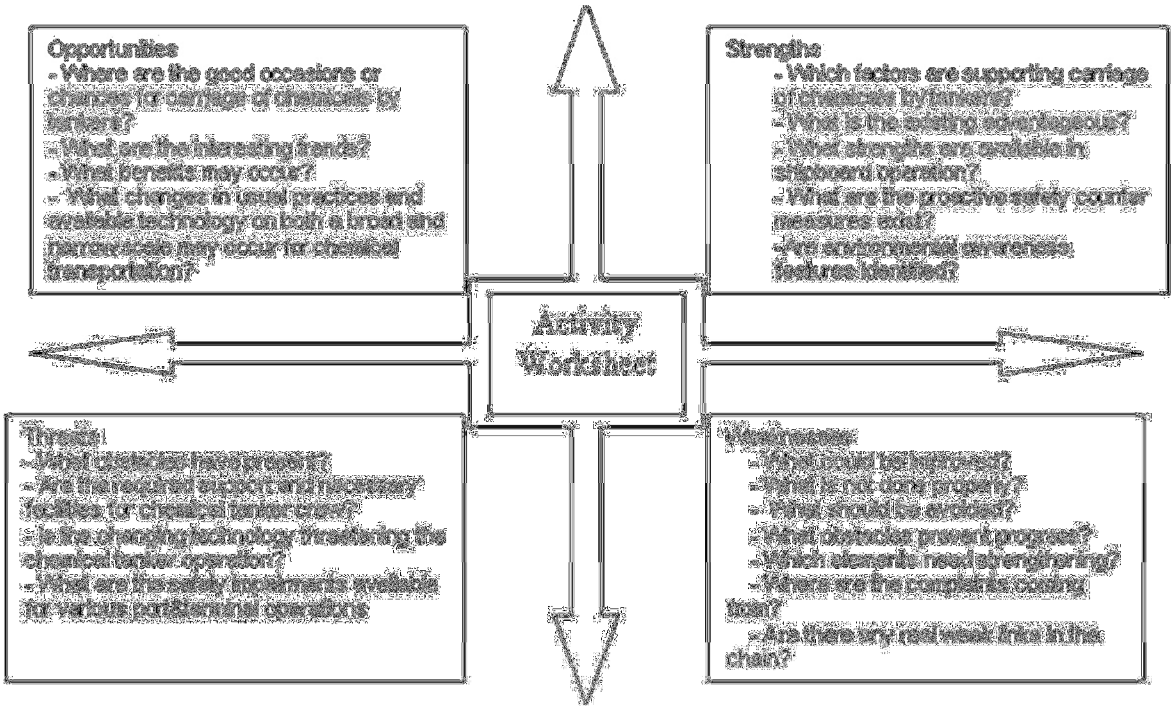


Figure 3 Example of SWOT analysis tool used in the case of carriage of liquid chemicals from chemical tankers (Arslan and Er 2008)

As mentioned before, by employing the SWOT analysis tool, all the internal and external factors affecting a specific decision-making process are considered, especially when bearing in mind the safety and human-related complications of such complex systems. It can be easily implemented by an expert with sufficient knowledge on the system examined and can take into account past information and analysis results as well as expectations based on the analysis of the subject system. However, an inherent limitation of this approach is that the various factors considered are not assessed in a quantitative way. Moreover, it is difficult to establish which of them is more important when compared with another one in order to make a decision. The latter is overcome with the combinatorial use of SWOT analysis with other techniques such as the Analytical Hierarchy Process (AHP), thus providing a quantitative estimate of the different influencing factors identified in the first place (Chang and Huang 2006).

A.2 Quantitative reliability tools and techniques

In this section the presentation of the main quantitative reliability tools and techniques available in order to carry out the reliability and criticality analysis is demonstrated.

A.2.1 Event Tree Analysis (ETA)

Event Tree Analysis (ETA) is another major reliability tool broadly used for the identification of the risks originating especially in the case of technical systems. It is modelled starting from an initial undesired event/failure (shown on the left side) and then proceeds with the description of several branches denoting the failure aftermath possibilities (shown on the right side), most usually in a binary way (Figure 4). The various questions asked during the creation of the Event Tree are placed on top of the tree structure while the positive answers are placed above the negative answers. Eventually, conditional probability values are assigned to each of the branches created with the summation of all the values of each branch being one. In order to calculate the probability values for the end-events of the Event Tree, multiplication of all the intermediate values takes place, with the summation of all the values of all outcomes being one as well.

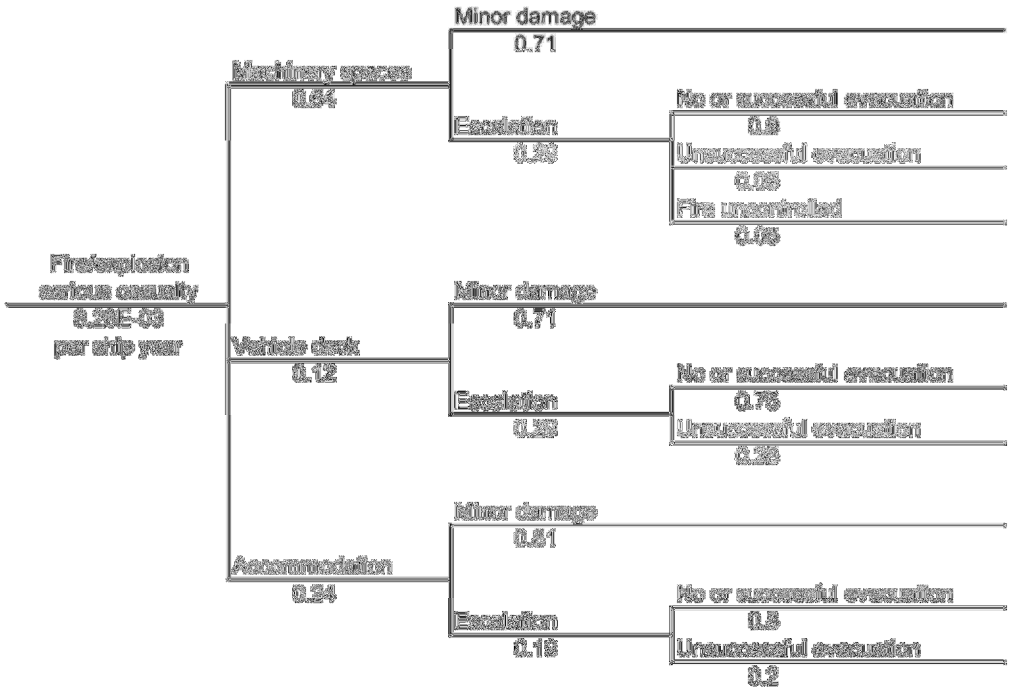


Figure 4 Example of ETA regarding fire onboard a ship (Konovessis and Vassalos 2007)

ETA can be carried out by a small team of experts and does not need the number of experts involved as in other risk and reliability techniques (e.g. HAZID, HAZOP, SWIFT). It is a broadly accepted and used approach in the maritime industry since its straightforward and clear graphical interface makes it useful in the understanding of the system examined. It is also useful when investigating the consequences on a system when a series of multiple failures occur. On the contrary, potential shortcomings of this approach are related to its restricted use when employing non-binary consequences (i.e. multiple failure incidents under the same branch/question) while all the failure events are considered independent from each other. Although it is used in a variety of cases, it can also be too simplistic when no direct answers can be provided for the questions asked under each branch (e.g. human element contribution to failures is more complicated than the examination of a technical system).

A.2.2 Reliability Block Diagrams (RBD)

Reliability Block Diagrams (RBD) is another technique used for carrying out the reliability analysis of a system. They are based on the initial formation of a set of blocks which follow a logic diagram sequence and represent the system under consideration. The blocks are then assigned failure or success values according to their contribution in the overall system.

Subsequently, its reliability can then be calculated when attributing the relevant reliability values to the different blocks (Figure 5). Moreover, the calculation of the overall system availability can be performed when assigning a certain repair value on each specific block. At this point, it is important to notice that when preparing an RBD, the order of failure occurrence of the individual blocks is not of importance.

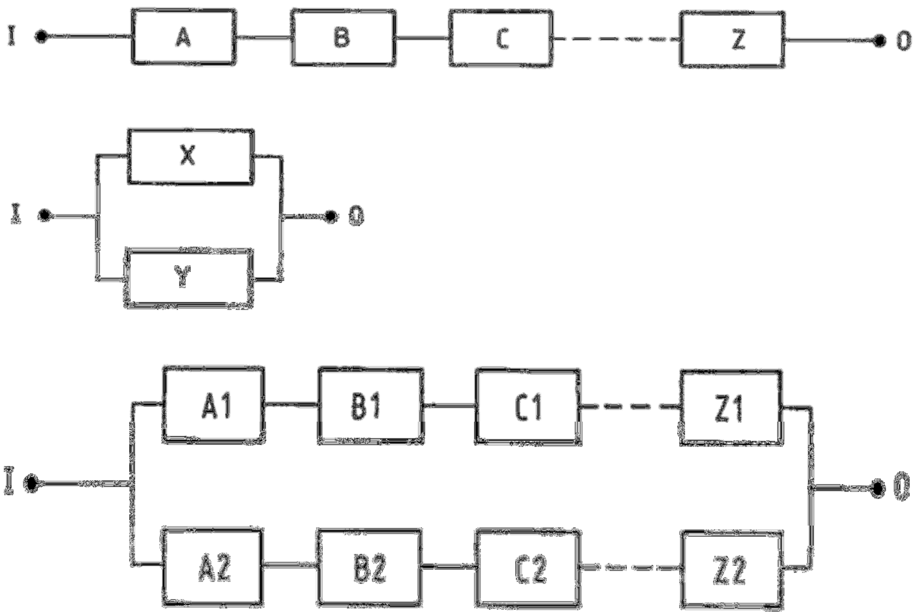


Figure 5 An example of a series, parallel and a combination of the two RBD system configurations (BS/ISO 5760 2007)

The advantage in the use of the RBD is that it provides the analyst with the initial information on the functional structure of the system examined in a clear way as each block represents a given element of the system examined. RBD can also be used when the order of block preference is pre-set and is quite straightforward. On the on other hand, this can be a shortcoming as in the case that a system in which the sequence of failure of its elements is important, cannot be modelled with RBD. Other disadvantages include the use of binary states (failed or working states) while it is not possible to use multiple state conditions. Furthermore, the partial failure of a block in the RBD can be an issue on the way to be modelled successfully. In this respect, the RBD structure can be compared to the FTA structure in terms of the representation of the different system elements as well as their interrelations (e.g. the RBD series structure is similar to the FT ‘OR’ gate, the RBD parallel structure is similar to the FT ‘AND’ gate). Their major difference is that the FT structure can represent multiple and complex system failure states, including various sub-systems and end-events thus representing the original system failure with more accuracy.

A.2.3 Bayesian Belief Network (BBN)

A Bayesian Belief Network (BBN) is another tool employed in the calculation of the reliability of various systems. It is represented as a direct acyclic graph which consists of a set of nodes (variables) showing the different system states and a given set of arrows (edges) which represent the probabilistic dependence among the variables and interconnect the nodes (Figure 6). In the graphical representation of BBNs, the nodes from which an arrow originates are called the ‘parent’ nodes (e.g. X1 is the ‘parent’ node) while for the ones to which the arrow ends are called the ‘child’ nodes (e.g. ‘child’ node Xn). Moreover, ‘root’ nodes signify that there are no arrows leading to them (e.g. X3 in this case).

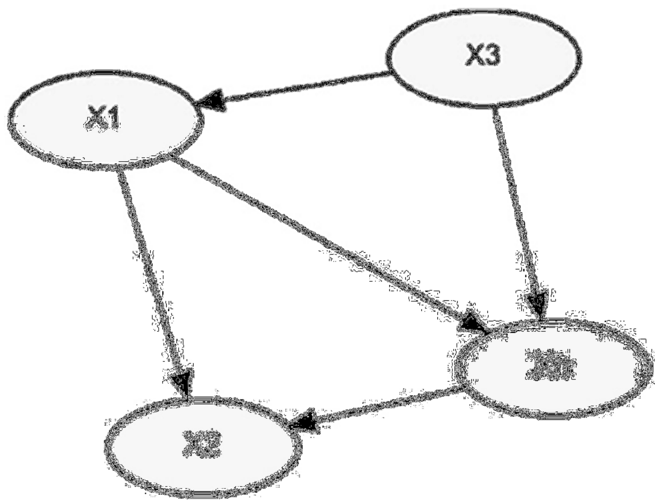


Figure 6 An example of a simple BBN (Trucco et al 2008)

Moreover, with the use of BBN different scenarios can be calculated regarding the reliability of a certain statement or inquiry, depending on the initial system set up (e.g. system reliability, cost element). In relation to the above, each node is then assigned conditional probabilistic values with respect to the ‘parent’ nodes that this is related with. In this way, the overall system probability can be estimated. Advantages of the BBN approach refer to the simplicity and usefulness of the graphical representation of the overall system, the ability to model systems in which complex and uncertain, non-deterministic information is present due to partial system knowledge, inaccurate information as well as the use of subjective and actual quantitative information. BBN can be also combined with other approaches (e.g. FTA) or extended (e.g. influence diagrams, decision trees) in order to overcome any difficulties regarding the information available in the first place as well as achieve the outcome that the decision-maker would like to investigate. However, a disadvantage of BBN is that great care needs to be taken when addressing the interrelation/causality of the various nodes (variables) among them as they may lead to unrealistic causal relationships, especially in the case of extended networks.

A.2.4 Markov Analysis (MA)

Markov Analysis (MA) or else state transition diagram is employed when the dynamic conditions of a system are examined. Dynamic conditions may represent the changes in the temporal order of the failure events of a system. MA can be also used to examine the condition of a system under multi-faceted maintenance procedures, failures depending on common causes, degradation, complex repair processes and other sequence dependent failures (Dhillon 2006).

The way of building a Markov model is based on establishing the various states and transitions of the system in question as well as providing the transition rates for each transition path (Villemeur 1992, Pil et al 2008). States represent the condition of the system at specific time intervals and can be good or failed. This depends on the capacity of the specific state in comparison to the original state capacity set up before the analysis starts. In the case of performance degradation of a given state, the new condition is called a degraded state. The assumption that is used in the calculation of the Markov models is that the state transitions are dependent on the current conditions each time and do not depend on previous calculation results. This means that the transition rates are only dependent on their current state and not on the previous ones (Figure 7).

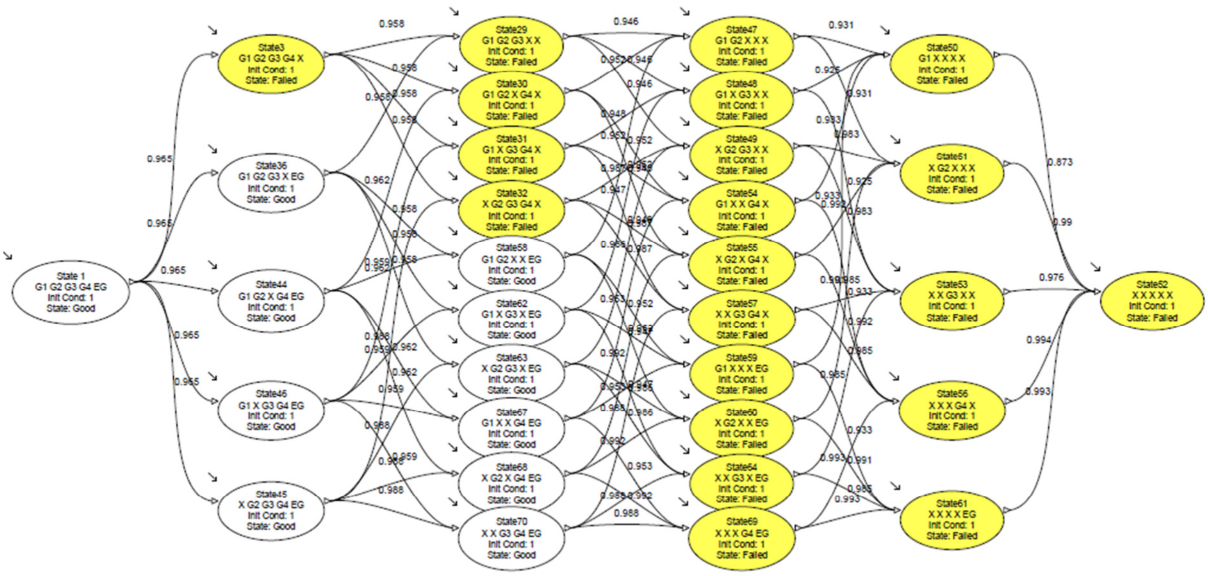


Figure 7 Failure and repair transition rates in a Markov state diagram of a ship DG system

The initial state of a Markov diagram is a good one, meaning that all components of the specific state are in good operational condition. Consequently, the last state is the one in which all components are in failed condition. In between these two states different variations of good, failed or degraded states may exist, which will describe in the best way the given system.

In order to set up a Markov model, all the different states (good, failed, degraded) must be created first and their transitional interdependencies drawn. Then, failure rates need to be used as inputs to the transitions from one state to the other. If a component belonging to a state is repairable, then a repair rate can be assigned to this state and another transition arrow can be drawn from this particular state back to the previous one. Likewise, all transition arrows are assigned failure rates at specific time points and the reliability calculations of the overall system can be performed.

In addition to the above, large Markov models need to be provided with all the possible states and transition conditions in order to be fully described. This is a laborious task as all states and conditions are manually inserted, which ultimately may lead to the creation of a very large Markov model with a lot of different elements and subsequently different states. Moreover, they may require extensive computational calculation time to be performed.

Before starting building a Markov model, there are certain parameters that need to be set up. At first, the goal of the analysis should be established. That is, whether the system to be analysed is investigated for its probability of failure before time *t*, its availability for the same time interval, the frequency of failure or any other specific aim. Then, the boundaries of the system need to be defined as well as present graphically the good, intermediate and failed states. The initial overall good state is shown in the left hand side of the diagram while the last and overall failed state is shown in the right hand side. All the states are joined by arrows with failure transition rates following the left-to-right direction and repair transition rates following the opposite (right-to-left) direction. After finishing the construction of the diagram, the transition states are populated with the numerical figures corresponding to the good, intermediate or failed state.

In this respect, it is obvious that with MA it is fairly easy to model the occurrence of system failures even in the case when complex systems are investigated. The graphical representation of the state diagram is another advantage of this approach while it provides both for the failures as well as the repair events/times for the subject system which complement the reliability analysis performed. In this way, several failure conditions can be described based on the initial state diagram. On the contrary, in the case that an extended number of states are used, powerful software and hardware capability is needed in order to carry out the probabilistic calculations. Moreover, the failure and repair rates employed by this approach are assumed to be constant over the time domain.

A.2.5 Monte Carlo simulation tool

Monte Carlo simulation is a way of representing the analytical calculations regarding the failure rates or MTBF used in the assessment of the reliability of different systems with statistical calculations. It is based on the creation of values originating from statistical simulations which can replace the lack of sufficient information employed for a system under investigation. Additionally, the overall system structure needs to be designed/represented first in a clear and comprehensive way. Then the Monte Carlo simulations can be used to populate the probabilistic values in the various system states which are initially modelled with the help of other reliability tools such as RBD, FTA, MA. In this way, the Monte Carlo simulation tool considers not only failure rates or MTBF but also repair rates as well as the presence of spare elements. Moreover, it can provide the analyst with results such as system reliability and availability, system repair time and the effectiveness of measures applied to calculate the above.

In this respect, the advantages of employing the Monte Carlo simulation tool lies in the use of values originating from a big sample of statistical distributed results in the light of otherwise insufficient number of data used. It is straightforward to employ and adjust according to the needs of the analysis performed and it is broadly applicable in various cases. On the other hand, a potential limitation may be the specific use of statistical models in order to achieve the values required. In this case, a large number of simulations may be needed to be performed, in which case the use of sensitivity analysis in order to measure the data variability is also required. Moreover, significant capability for software and hardware equipment is also needed.

A.2.6 Fuzzy set theory (FST) in a Multi Attribute Decision Making (MADM) problem

Fuzzy set theory (FST) was initiated by Zadeh (1965), extending the Boolean logic of real numbers (in which 0 represents false and 1 represents truth) by introducing values for partial truth statements; that is truth statements between 0 and 1 in order to address the fuzziness of imprecise answers to questions being asked. Since then, there have been various authors and researchers describing and providing further contribution to the FST including Zimmermann (1991), Chen and Hwang (1992), Ross (2004) and Zadeh (2008) among others. Simply described, FST can be defined as a way to approach the vagueness of human nature. In a more detailed way and when MADM problems are concerned, the following need to be considered:

- Attributes may be assigned crisp or fuzzy (linguistic) values
- Decision makers may form a diversified group with varying range of experience and expertise on the subject field/industry
- There may be a variety of different solutions/alternatives to choose from with vague and imprecise characteristics
- There may be incomplete and imprecise information available for the different solutions suggested

MADM is about making the best choice among a number of offered alternatives each of which is constrained by a certain number of attributes (Chen and Hwang 1992). The general model of MADM is presented in the following matrix:

$$\begin{array}{c} \\ A_1 \\ A_2 \\ \\ \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} X_1 & X_2 & & & X_n \end{array} \\ \begin{pmatrix} x_{11} & x_{12} & \cdots & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & \cdots & x_{mn} \end{pmatrix} \end{array}$$

where:

$A_1, ..., A_m$ = finite set of attributes

$X_1, ..., X_n$ = finite set of solutions / alternatives

$X = \{X_m \mid m = 1, ..., n\}$

$A = \{A_n \mid n = 1, ..., m\}$

As mentioned above, FST has a broad field of applications and there are various studies, which demonstrate its usage on MADM problems. Despite the fact that the detailed and in-depth coverage of the literature review of FST is not part of this dissertation, an introduction in the FST applications in MADM problems is carried out in the following paragraphs in order to highlight the extent and popularity that FST usage has achieved among different researchers and industrial sectors.

In this respect, Lin and Wang (1997) suggest the use of the FST in combination with the traditional FTA in order to model the safety operation of a robot-motion in an aircraft wing drilling system in the manufacturing context. Moreover, Sharma et al (2007) suggest the combination of fuzzy set decision making with other well-known reliability tools such as FMEA and Petri Nets (PNs) in order to achieve the best outcome in terms of maintenance prediction analysis. Initially, the standard FMEA is set up followed by the creation of PNs in order to model the relationship and functions among the various failure events. Subsequently, this is coupled with FST so as to represent the managerial and other implications (i.e. human element interference, maintenance efficiency) that are also part of the maintenance process.

The entire approach is applied in the case of a paper mill and assists in the analysis of the behaviour of its systems.

Additionally, Wang et al (2007) also address the issue of selecting the best maintenance approach for a power generation plant by using the multi criteria decision making approach in a fuzzy environment. In their paper, they employ a fuzzy modification of the classical Analytical Hierarchy Process (AHP) in order to rank the best maintenance method. The new approach takes into account several attributes related to maintenance optimisation such as personnel training, spare parts inventories, technical reliability and production loss among others. As part of the AHP, they also take into account the safety, cost, added value and feasibility considerations and conclude by identifying the best applicable maintenance approach for this sector.

In another paper by Al-Najjar and Alsyouf (2003), fuzzy multiple criteria decision making (FMCDM) is applied in order to compare and identify the best maintenance approach in the case of the roll bearings of an industrial plant. In their paper, they examine the application of a variety of maintenance methodologies such as failure based maintenance, preventive maintenance, RCM, TPM and vibration-based maintenance and assess them with the help of FST. Yuniarto and Labib (2006) also present another use of the FST by employing a decision making grid to prioritise maintenance strategies for the operation of different systems. In their case, they examine various maintenance policies in conjunction with the fuzzy set theory of a failure-prone manufacturing control system in order to achieve the optimal preventive maintenance action for the subject system.

On the other hand, in a paper by Carasco et al (2002) the authors suggest that expert systems have some disadvantages such as inconsistent questions asked to the experts in the first place and subsequently wrong responses and solutions suggested based on previous/past knowledge. However, these difficulties can be surmounted by precise declaration of the original question, specific and thorough definition of its attributes, and careful selection of experts and moreover of the person who will facilitate and implement the whole process.

In the maritime industry, there are also a few applications of the utilisation of FST in cases that one is faced with multi criteria/attribute decision-making problems. In a paper by Wang (2000), the application of FST is examined regarding the implementation of the ship Formal

Safety Assessment (FSA) method. In his paper, the ship safety analysis is carried out by determining the failure events, which are attributed subjective and non-crisp evaluations from a group of experts. Riahi et al (2010) also examine the application of FST in investigating the seafarers' reliability. This is performed through the construction of an ideal frame of reference regarding the seafarer, the vessel in which he/she are employed and the environmental conditions under which the ship sails. The individual seafarer is then assessed compared to the original ideal boundary setting and ranked accordingly, thus enabling the suggestion of measures in order to enhance his/her performance onboard.

In the same field of the FSA, Dourmas et al (2007) also employ the fussy logic theory to assess the Hazard Identification (HAZID) approach as an initial step towards the ship FSA. They present a list of potential hazardous events, which need to be evaluated (e.g. collision, fire/explosion, navigation, loss of containment, ship related hazards and manoeuvring) in relation to a set of predefined criteria of both generic and more specific form. Linguistic terms are used in this case as well describing the evaluators' opinion on the subject criteria.

In another paper by Turan et al (2003) a risk assessment methodology is developed based on the use of FTA and fuzzy set theory. FTA is used to model the possibility of loss of life at sea when onboard a fishing vessel while fuzzy set theory is used to compliment the analysis of the accidents occurring with fishing vessels. At first the FTA is populated with numerical values already existing in the literature (e.g. available database) whereas any missing values are derived from the fuzzy set assessment, thus assigning linguistic terms in the various end-events of the FT responsible for the loss of life onboard fishing vessels.

A MADM model is also presented by Olcer and Odabasi (2005), applies the FST in a multi attribute decision-making selection problem. This is the case for the selection of the best propulsion/manoeuvring system of a passenger vessel in terms of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), manoeuvrability, noise and vibration, system reliability, propulsion power and arrangement requirement. A group of non-homogeneous degree of experts provide a ranking of the attributes mentioned according to the suggested solutions offered for evaluation. Following the fuzzy set methodology steps, the initial solutions are categorised offering a crisp measure for determining the optimal selection.

In all the above mentioned cases, after the initial implementation of the FST, there is a stage in which the various solutions/alternatives of the initial problem need to be categorised (Zanakis 1998). This is the ranking stage used in the MADM process and there are a few methods employed to do that. The most powerful and widely applicable is the Technique Ordered Preference by Similarity to Ideal Solution (TOPSIS) method. TOPSIS is one of the various ranking methods applicable in MADM selection problems. Its applicability is based on the ranking of each suggested alternative according to how close these are to an imaginary ideal positive solution and at the same time how far from an imaginary ideal negative solution. Subsequently, the alternative that is closer (or more similar) to the ideal positive solution and further from (or not similar to) the ideal negative solution is the one ranked higher than the other solutions and accordingly is the best one for the decision maker to choose. Its usefulness and broad utilization is denoted by the number of studies it is applied at as shown in Krohling and Campanharo (2011) and Kelemenis and Askounis (2010).

As it has been shown, the application of the FST in the case of MADM problems is extensive and includes a number of field studies. This is because in most cases there is vagueness of information, as well as a number of alternatives/solutions to select from with many attributes characterising each one of them, as well as the FST provides solutions in a clearly depicted way. Overall, FST is a dynamic and powerful tool, which is used in order to assist the decision maker with multi criteria problems. Overall however, the system boundaries need to be distinctive and the various attributes need to be defined adequately, while the final ranking method has to be carefully selected.

A.2.7 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a well-known reliability tool used in various research studies for different applications since its original introduction in reliability analysis in the ‘60s and ‘70s (Dhillon 2006, Kumamoto and Henley 1996). In this respect, FTA is presented with more details as follows. Overall, it is a deductive (top-down) method of analysis aimed at pinpointing the causes or combinations of causes that can lead to the defined top event.

In more details, Failure Tree (FT) is a detailed and organised structure consisting of a top event (or in technical terms top gate), intermediate gates/events and basic events showing the dependability steps and process under which the latter (basic events or causal factors) lead to the failure of a top event. Inversely, when the outcome of the analysis leads to the success of a top event/gate and the various basic inputs are success events, then the same tree structure is called Success Tree. The FT structure identifies all the independent factors which influence the occurrence of the top event/gate and consequently the reliability of the top event/system under investigation. The advantages of using the FTA in determining the reliability of a given system are that it provides a clear picture of the structure and interdependencies of the system in question as well as that it may include all the combinations of the failure causes of the observed system, either multiple or single point failures. Furthermore, it can provide both a qualitative and quantitative measure of analysis when numerical data are given (MTBF, failure and repair rates).

In the literature, there are also potential limitations in the use of FTA, especially in the case of large FTs. These include the need of an analyst with specific knowledge of the system under investigation. In this case, the expert's knowledge on the system to be analysed in order to carry out the FTA modelling is essential. Moreover, the FT building process and analysis of the results can be time consuming while each FT structure examines the failure occurrence of a single main/top event each time. Consequently, different top events have to be examined separately in the FT modelling structure.

On top of the above, FT structure hierarchy consists of various building blocks which describe the different levels of the analysed main system under analysis (Figure 8). The top level represents the identification of the main system comprising of various systems in the next lower level. Each one of these is respectively divided into sub-systems, followed by the equipment level. Until this point, the blocks are called gates. The lowest block level of the hierarchical structure includes the specific items or basic events of the FT, which define the final causal reasons for the failure of the top event.

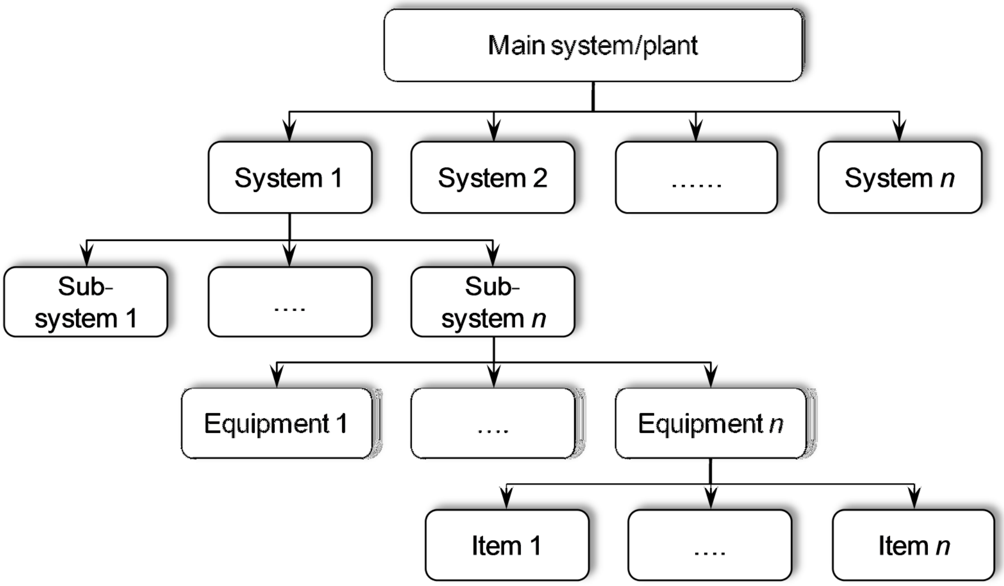
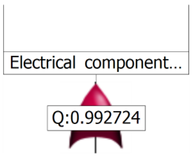
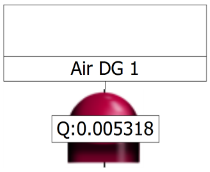
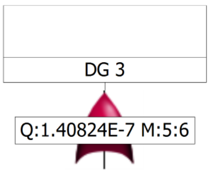


Figure 8 Hierarchical breakdown of FTA system

BS/ISO standard 61025 (2007) provides the detailed description of the definitions of the FT gates and events. Gates are described either as static or dynamic, hence the difference between Static FTA and Dynamic FTA (DFTA). In the case of the traditionally used static gates, the importance lies in the input values while the gates are not affected by the specific order of the inputs. With the use of dynamic gates in the DFTA however, the order in which the inputs are presented is essential for establishing the interdependencies among the various gates and events so as to obtain the reliability results of the FT structure. This is the main difference with the static FTA, which is moreover depicted through the detailed presentation of the various static and dynamic gates and events shown in Tables 3 and 4.

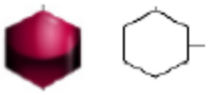
Table 3 FT structure gate types

Gate type/name	Symbol	Description
Static gates		
OR		The output occurs if and only if any of the input parts of the gate occur. The input parts can be intermediate gates, basic events or a combination of the two. The output can be the top event or any intermediate event. An OR gate should have at least two inputs
AND		The output occurs if and only if all the input parts of the gate occur. The input parts can be intermediate gates, basic events or a combination of the two. The output can be the top event or any intermediate event
Voting (VOT)		By using this gate, the output occurs when *m* out of *n* input events occur. When *m* is equal to *n*, the gate reacts like an OR gate. The input parts can be intermediate gates, basic events or a combination of the two. The number of inputs needs to be higher or equal to three. The output can be the top event of the FT or any intermediate event.
Exclusive or (XOR)		This gate is used if and only if one out of the two input events occurs and the other one does not occur as well. This gate can only have two inputs: intermediate gates, basic events or a combination of them. The output can be the top event of the FT or any other intermediate event.
NOT		With this gate the output event occurs if and only if the input event does not occur. Only one input is used for this type of gate
Not And (NAND)		This type of gate is a combination between a NOT and an AND gate. By using this gate, the output occurs if at least one of the inputs does not occur. The output can be the top event of the FT or any other intermediate event. On the other hand, the input parts can be intermediate gates, basic events or a combination of the two.

Not Or (NOR)

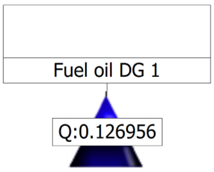
Similar to the description of the NAND gate, this gate is a combination of a NOT and an OR gate. In this case, the output occurs when all the input events do not occur. The output can be the top event of the FT or any other intermediate event. On the other hand, the input parts can be intermediate gates, basic events or a combination of the two

Inhibit (INH)



In this gate, the output event occurs when the input events take place as well as an input condition is satisfied. The output can be the top event of the FT or any other intermediate event. On the other hand, the input parts can be intermediate gates, basic events or a combination of the two

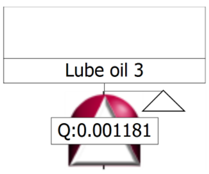
Transfer



This gate is used as a connector between different parts of the FT structure. In case of a FT being too big in size, the TRANSFER gate is used to represent part of the FT as a single gate, thus minimising the graphical size of the whole FT structure. It can be also used to represent the same gate structure in other parts of the main FT

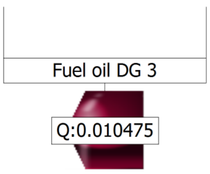
Dynamic gates

Priority And (PAND)



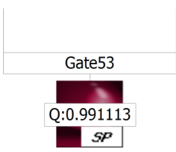
This is a dynamic gate and can be used if and only if all the input events occur in a specific order (from left to right) as presented in the FT structure. This means that for an input event to occur, its neighbouring to the left event needs to occur first.

Sequence enforcing (SEQ)



Another dynamic gate used if and only if all the input events occur in a specific order (from left to right) as presented in the FT structure. In this way, the left-most event occurs followed by the one next to it and so on. This gate is similar to the PAND gate and can be employed when the inputs are more than two

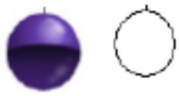
Spare

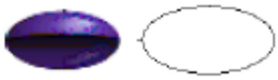


A SPARE gate is used to show that the output will occur if and only if all the input Spare events occur. The input of a

		SPARE gate can be a combination of primary (left-most event) and spare events (the ones next to the primary event). When the primary event fails, the spare events are activated in a left-to right order. The spare events may be distinguished by a dormancy factor (DF), which is a measure of the ratio between failure and operational rate of the spare events in the stand-by mode. In this way, a Spare gate may act as Cold spare when all connected spare events have a DF of 0, Hot when all the connected spare events have a DF of 1 and Hot spare if the DF is between 0 and 1
Functional dependency (FDEP)		This gate may be employed when the occurrence of the connected input events depends on the occurrence of a primary (or conditional) event. This gate has one trigger event and one or more dependent events. The separate happening of any of the dependent events does not influence the initial triggering event
Remarks		This gate is used for entering comments or remarks in a FT structure and can be the input of another gate providing more details about the influence of the specific gate in the FT. It does not contain any calculation data and therefore does not contribute to the calculation results

Table 4 FT structure event types

Event type/name	Symbol	Description
Basic		Basic events describe the final level/stage of a FT structure or branch of a FT and define the end of the analytical structure. They can be populated with MTBF or failure rates in order to carry out the reliability calculations of the FT
Repeated basic		A repeated event denotes that the specific event has exactly the same properties with another event already used in the FT structure
Undeveloped		This type of event is similar to a basic event but it also signifies that the event is not developed yet as it is not needed to do so (not necessary to explore the specific condition in the FT)
Spare		Spare events are similar to basic events but in addition they are characterised by a dormancy factor, which is the ratio of failure rate in the stand-by and operational mode respectively. A Spare event can only be used as an input for a Spare gate of a Functional Dependency gate and it can also have a spare group of identical spare components used in the FT. The primary event is initially active while the rest are in the standby mode and are activated when the primary input fails.
House		A House event is used when the analyst needs to make a part of the FT operational or non-operational by turning the event on or off. When the House event is on, the gate it belongs participates in the FT structure while when the House event is off, the corresponding gate does not participate in the calculations of the FT

Conditional		This type of event is used as a primary input for an Inhibit gate and it needs to occur for the other input events of the specific gate to occur

Some of the latest efforts to apply FTA in research studies are mentioned next, which also signifies the combinatorial use of different reliability tools and techniques. In this respect, Lampis and Andrews (2009) combine the classical FTA with BBNs in order to depict the failure causes of a water tank system. In their paper, they describe the way the FTA can be used to provide the initial setting for further examination with the help of BBNs. The latter also provide the modelling of all failure scenarios of the main system in one graphical representation.

Morello et al (2008) also present another application of FTA on gearboxes of commercial vehicles. They initially apply FTA in order to define a small number of events that significantly contribute and influence the overall sensitivity of the examined system. In a paper by Gupta and Bhattacharya (2007), the FTA is used in combination with Fuzzy Set theory in order to investigate their application in a conveyor system while Zaphiropoulos and Dialynas (2007) also employ the FTA tool in their research study. They combine it with RBDs so as to evaluate the reliability of electronic devices in the light of cost constraints.

In general, FTs can be utilised to carry out the analysis of a main system in two different ways: qualitatively and quantitatively. Qualitative analysis is performed by setting up the structure of combination(s) of gates and events while with the quantitative analysis failure rates, Mean Time Between Failures and minimal cut sets are used to evaluate the reliability and availability of the subject system (Dhillon 1999). In order to do that, one can employ either exact calculation method or calculation methods using cut set theory (Tang and Dugan 2004).

The exact calculation method employs the FT gate logic to calculate the probability of occurrence of the top or intermediate gates. This method provides accurate results but, in the case of large FT structures, it is very time consuming since the probability calculations have to be executed through the whole FT at each one of the different time points/intervals. Another challenge that might be present has to do with the reliability software used, which might crash under the overload of reliability calculations. In this case, cut-sets are used to overcome these obstacles.

A cut-set is any series of events that may cause the top event of a FT to occur. A minimal cut-set is a sub-group of the initial cut-sets, that is the shortest set of events that may lead to the realisation of the top event (Bedford and Cooke 2001). Therefore cut-sets are used to quickly establish the probability of occurrence of the top event in a FT. Depending on the size of the FT model, there can be several minimal cut-sets in place while the ones that have the fewest number of events will ultimately have the highest probability of occurrence.

Accordingly, the cut-set summation method computes the probability for each gate by summing up the cut set probabilities of the specific gate. This calculation method provides very good results when using small failure probability rates as inputs for the basic events of the FT. The probability of each cut set is calculated as the product of event probabilities. In addition to the above and in the case that the FT events have input values with big failure probability rates, the overall probability of the main or intermediate gates may show estimates greater than one (unrealistic values of gate probability). In such a case, other calculation methods can be employed such as the Cross Product and the Esary Proschan methods.

The Cross Product (CP) method calculates the probabilities of the FT gates by using the summation and product terms of the cut-set probabilities of the FT. For the Esary Proschan (EP) calculation method upper and lower bounds are calculated for the FT gates probability of occurrence using path sets. In this case, a path set is the opposite of a cut set, meaning that it forms a group of basic events in which if one of them does not occur, the top event (or gate) will not occur as well. In general, the EP method is a relevant method if the system is considered as coherent system so that the occurrence of an item failure always results in system degradation and each basic event appears in at least one minimal cut set (Kumamoto and Henley 1996).

A.2.8 Reliability Importance Measures (IMs)

In addition to the FT analysis described above, further assessment can be achieved with the use of reliability Importance Measures (IMs) can be performed. IMs are used to provide a ranking of the various end/basic events of a FT according to the level they contribute in the top event reliability. In this way, the analyst can focus his/her attention to the events that, if more effort is provided, they will increase the reliability of the main or intermediate systems. For example, IMs are estimated for the basic events of a FT and all gates, either the top or the intermediate ones, will have different ranking of events influencing their reliability and availability. There IMs which are employed more often in the evaluation of the reliability are the Birnbaum (Bir), Fussell-Vesely (F-V) and Criticality (Cri) IMs.

Birnbaum importance measure is the rate of change in the top event/gate probability when a change occurs in the availability of a basic event (Levitin et al 2003). Therefore, the ranking of events obtained using the Bir IM is helpful when selecting which end-event needs to be improved so as to concentrate the improvement effort on this event. Regarding the F-V IM, it is used when an event contributes to the failure of the top event but is not necessarily the most critical one (Beeson and Andrews 2003). F-V IMs rely on the minimal cut sets, which determine the shortest way the failure of the top event/main system may occur. For this to happen, at least one cut set including the specific event must occur. Additionally, the Cri IM shows the ranking of the end events of a FT according to how much their failure contributes to the failure of the gate they participate in (Andrews 2008). Moreover, it considers the overall probability of the top event occurrence due to an event A. Alternatively, the Cri IM modifies the Birnbaum importance measure by adjusting for the relative probability of basic event A to reflect how likely the event is to occur and how feasible it is to improve the event.

Appendix B - MTBF values used for the case study of *"DSV A"*

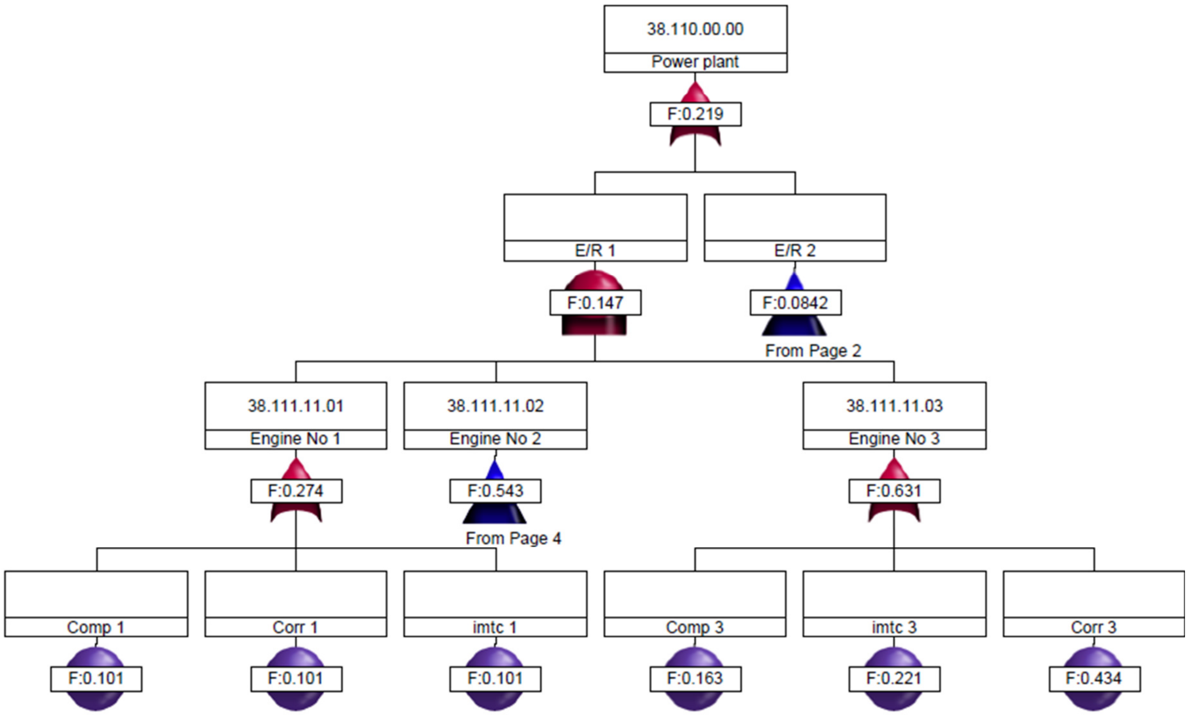
##	System	Component	Failure cause	MTBF (days)
1	Power plant	engine no1	comp	853
2			corr	853
3			imtc	365
4		engine no2	comp	853
5			corr	160
6			imtc	853
7		engine no3	comp	512
8			corr	160
9			imtc	365
10		engine no4	comp	853
11			corr	853
12			imtc	365
13		engine no5	comp	512
14			corr	640
15			imtc	365
16		engine no6	comp	512
17			corr	320
18			imtc	365
19	Propulsion	bow thruster fwd no1	fwt	426
20		bow thruster centre no2	fwt	640
21		bow thruster aft no3	fwt	512
22		power packs	comp	320
23			fwt	640
24			matf	853
25			mecd	853
26		azimuth thruster port no1	fwt	365
27			comp	160
28			ilub	853
29		azimuth thruster ctr no2	fwt	853
30			comp	853
31			ilub	853
32		azimuth thruster stbd no3	fwt	512
33			comp	160
34			ilub	853
35	Water	main cooling pumps	bloc	853
36			fwt	853
37		sea water valves & pipework	cor	512
38			crac	853
39		cathelodic protection	corr	640
40			fwt	640

##	System	Component	Failure cause	MTBF (days)
41		pump positive displacement	corr	853
42			mecd	853
43		Reciprocating pump	corr	853
44			mecd	853
45		emergency pump	corr	640
46			fwt	853
47		fire & deck wash	corr	640
48			fwt	853
49		circulating pumps	fwt	426
50		heat exchanger	bloc	640
51		tanks	corr	853
52		fresh water generator	cont	853
53			corr	512
54			mecd	640
55		pump	corr	853
56			fwt	640
57		potable water treatment	cont	853
58			fwt	640
59		valves & pipework	conn	853
60			corr	426
61		sewage treatment	bloc	640
62			cont	640
63			corr	512
64	Lifting	light cranes A	fwt	853
65			mecd	640
66		light cranes B	fwt	512
67			mecd	853
68		main crane A	cont	853
69			corr	640
70			matf	426
71		main crane B	cont	640
72			corr	640
73			matf	365
74	Diving	chambers	cont	512
75			fwt	320
76			wrcm	853
77		sdc structure	comp	512
78			cont	853
79			corr	853
80		sphl	comp	640
81			fwt	512
82			mecd	853
83		launch systems	comp	640
84			fwt	426
85			mecd	853

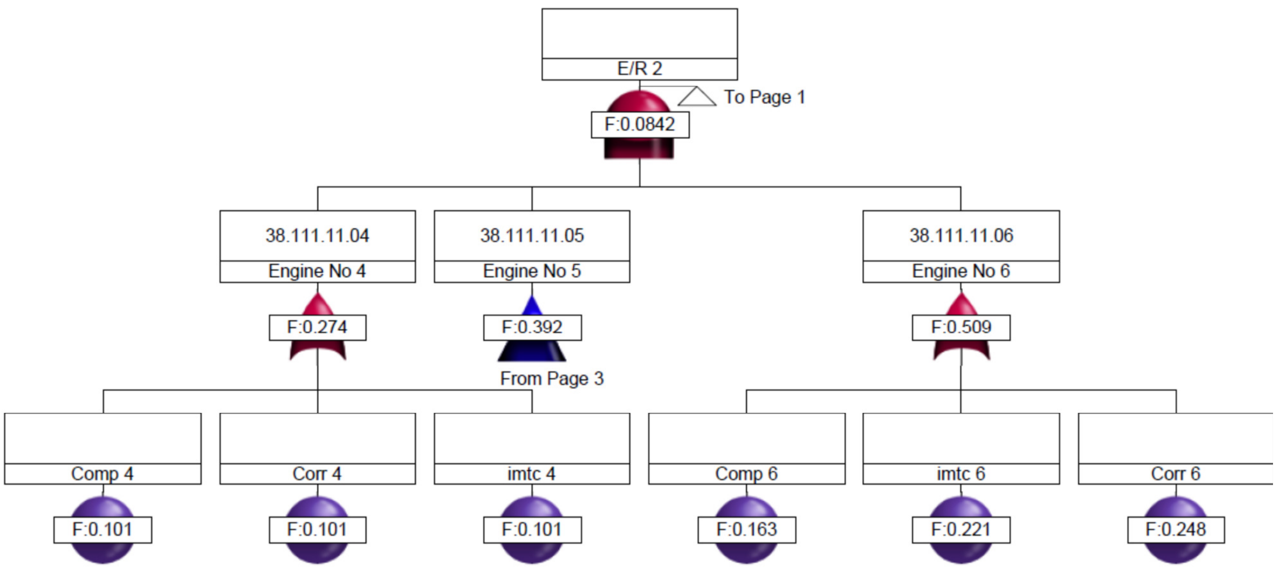
##	System	Component	Failure cause	MTBF (days)
86		compressors	comp	853
87			crac	853
88			fwt	640
89		electrical comms & cutouts	cabl	640
90			comp	171
91			fwt	512
92	Safety	fire fighting equipment	comp	853
93			corr	512
94		powered watertight doors	fwt	640
95		hydraulics	fwt	853
96		watertight hatches	fwt	640

Appendix C – Dynamic Fault Tree structure for *"DSV A"*

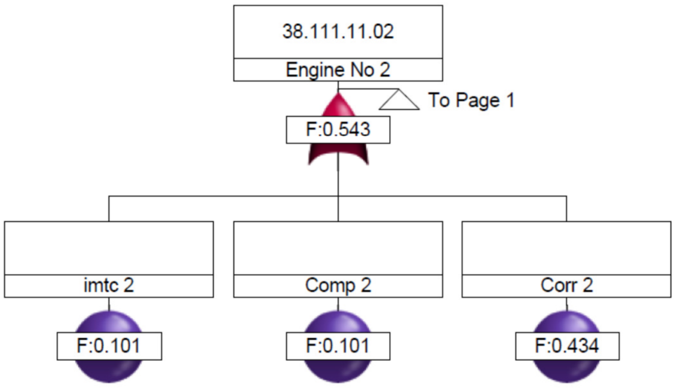
C.1 Dynamic FT structure for the Power Plant system



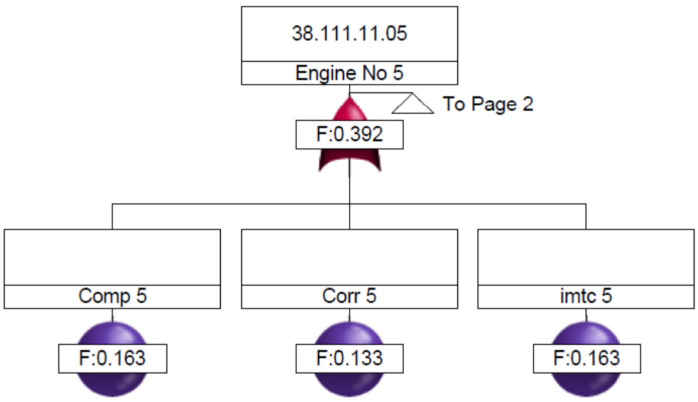
Dynamic FT structure for the Power Plant system (overall view)



Dynamic FT structure for E/R 2

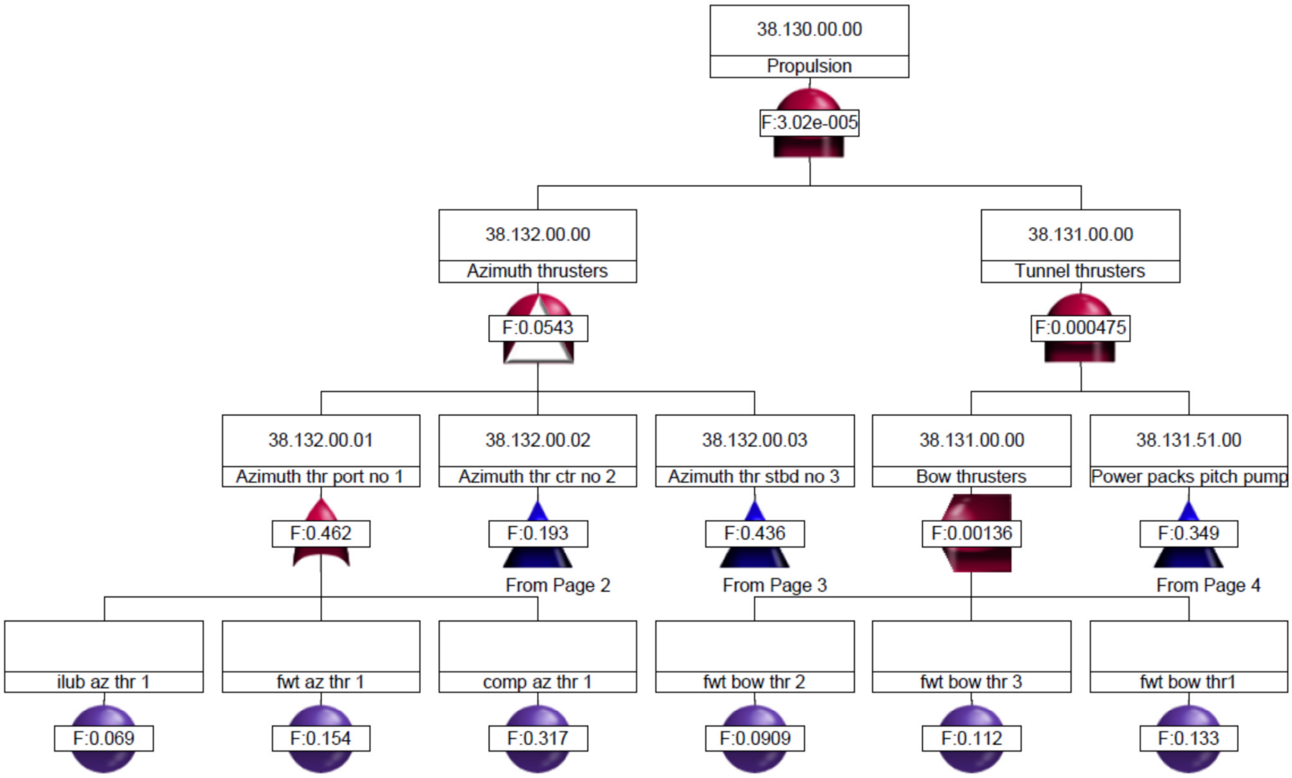


Dynamic FT structure for Engine No 2

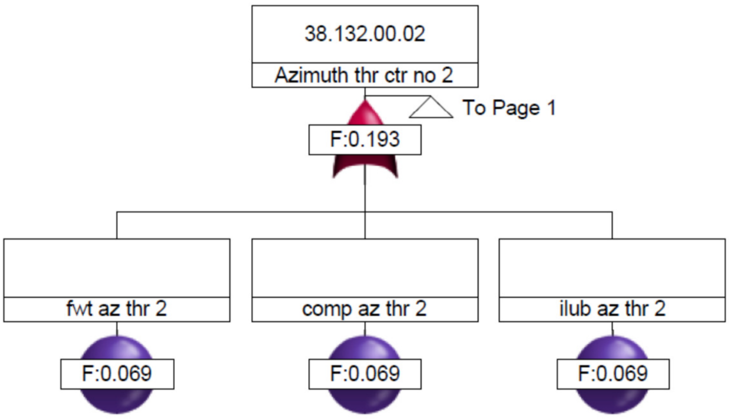


Dynamic FT structure for Engine No 5

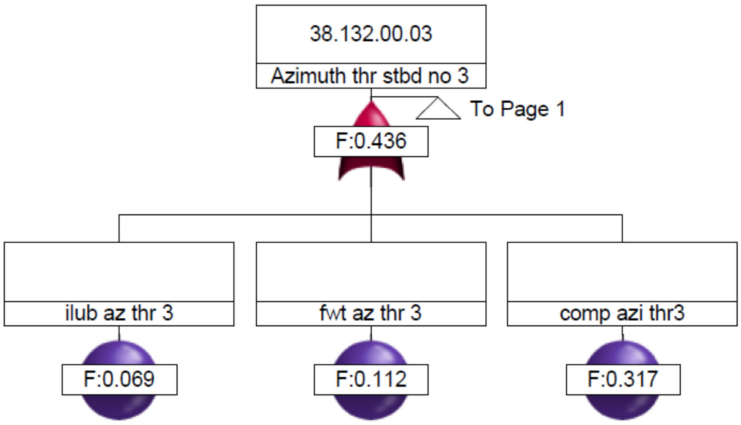
C.2 *Dynamic FT structure for the Propulsion system*



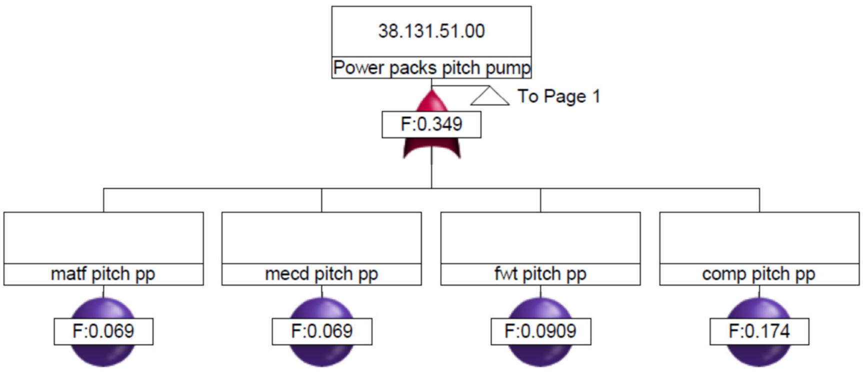
Dynamic FT structure for the Propulsion system



Dynamic FT structure for azimuth thruster centre No 2

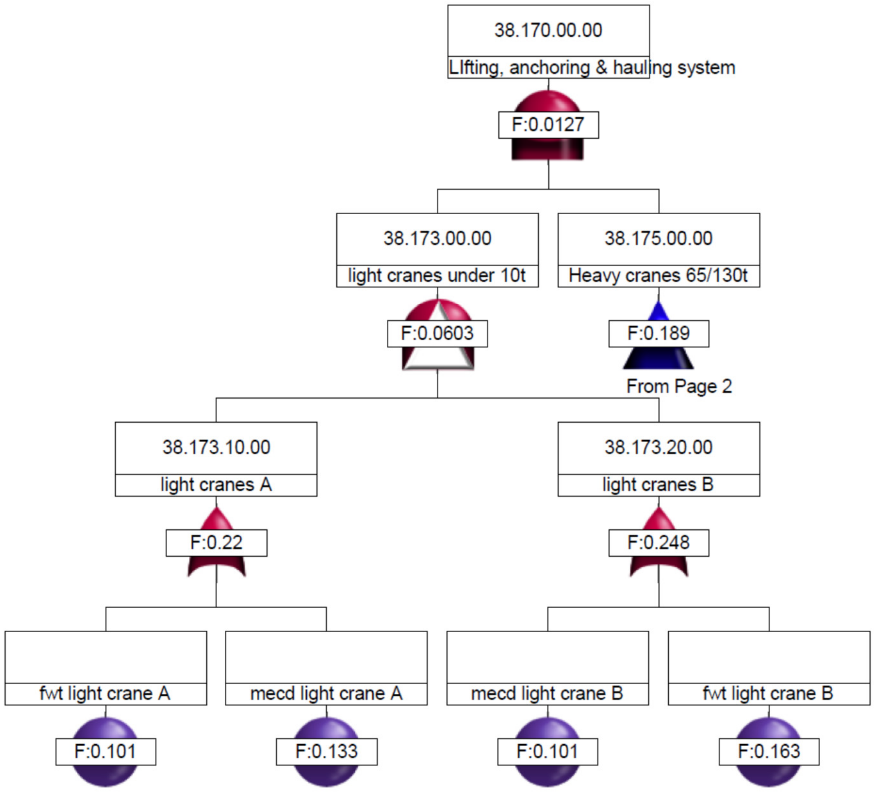


Dynamic FT structure for azimuth thruster starboard No 3

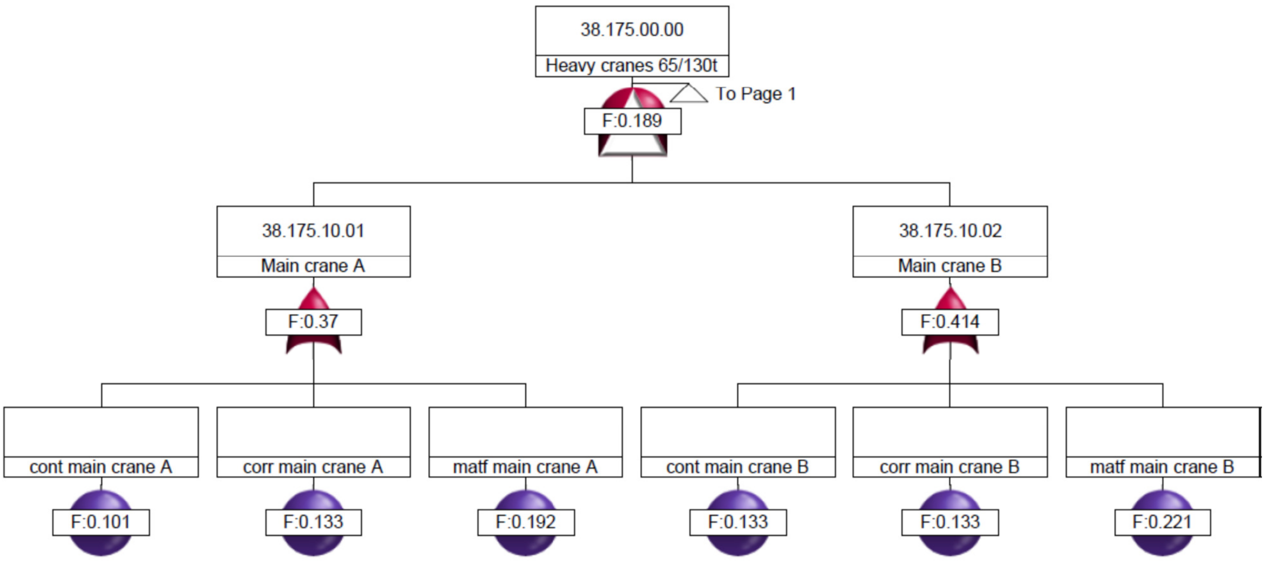


Dynamic FT structure for power packs pitch pump

C.3 Dynamic FT structure for the Lifting, Anchoring & Hauling system

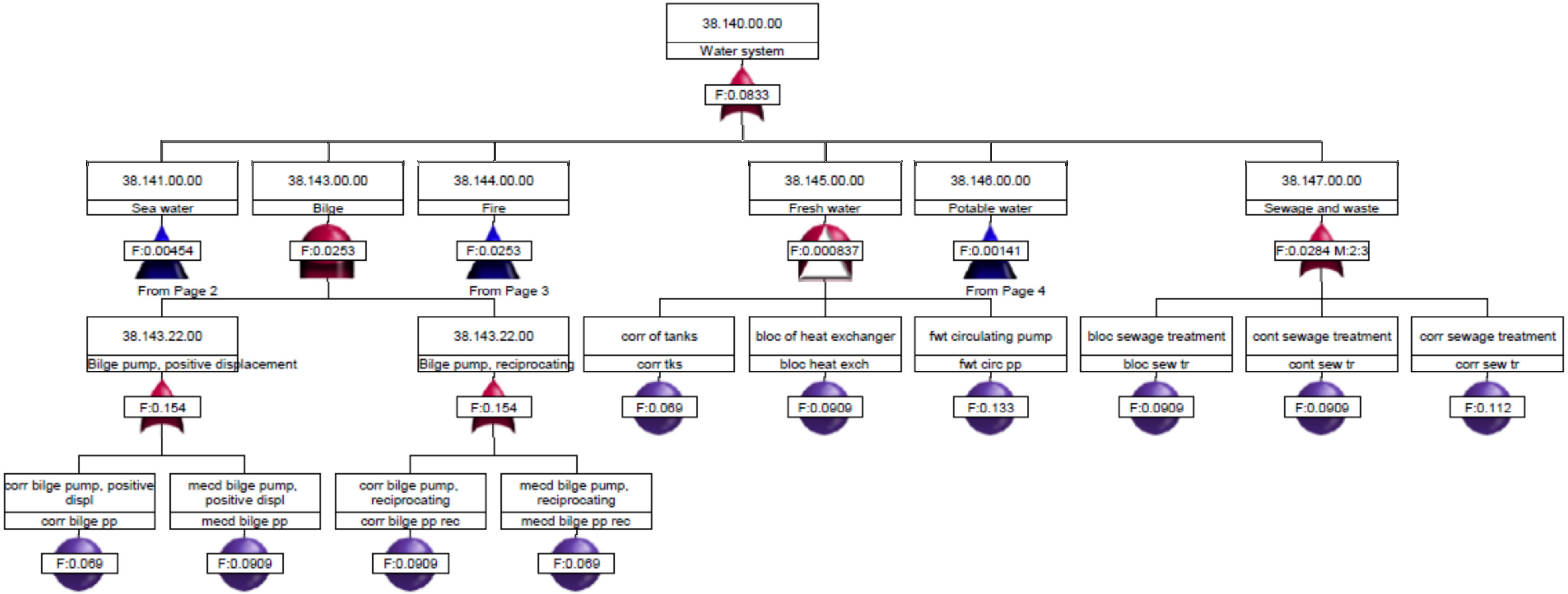


Dynamic FT structure for the Lifting, Anchoring & Hauling system (overall view)

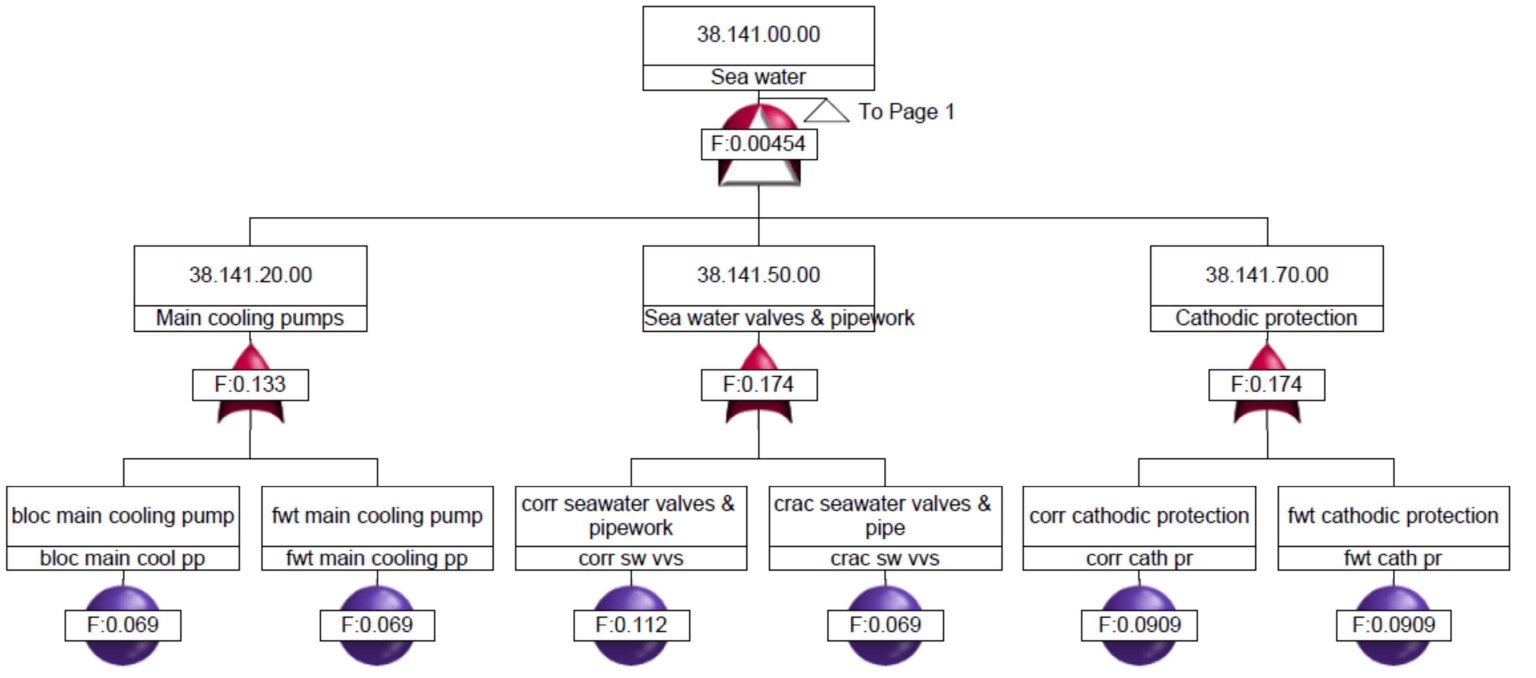


Dynamic FT structure for heavy cranes 65/130 tonnes

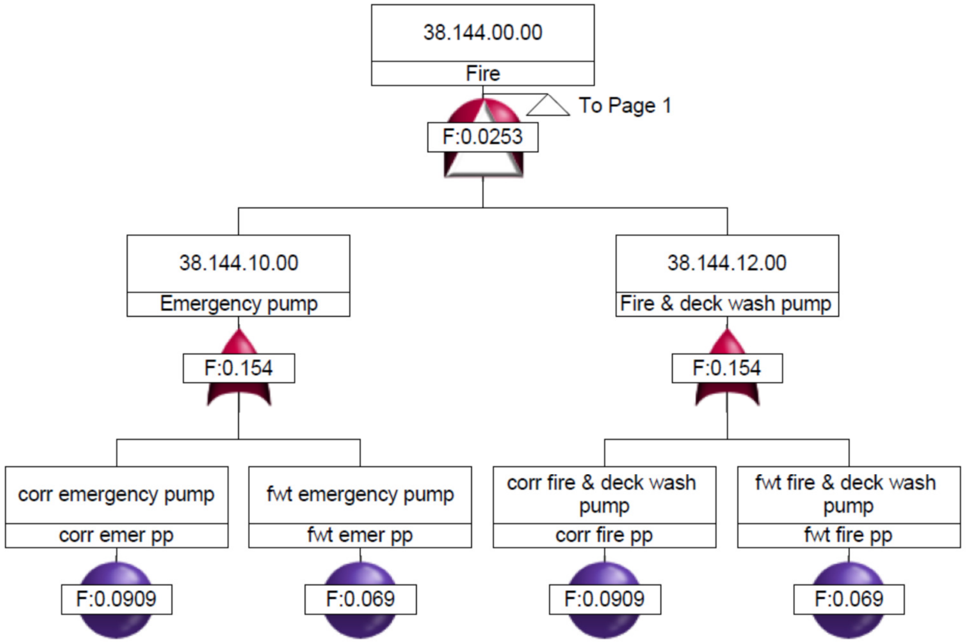
C.4 Dynamic FT structure for the Water system



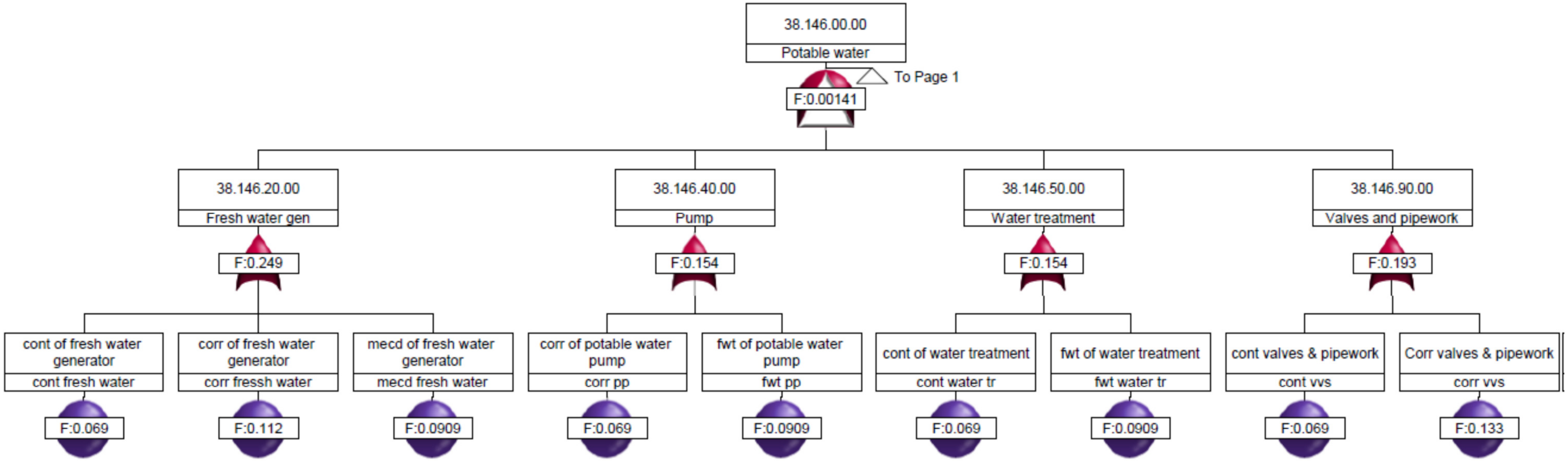
Dynamic FT structure for the Water system (overall view) including the bilge, fresh and sewage & waste sub-systems



Dynamic FT structure for the seawater sub-system

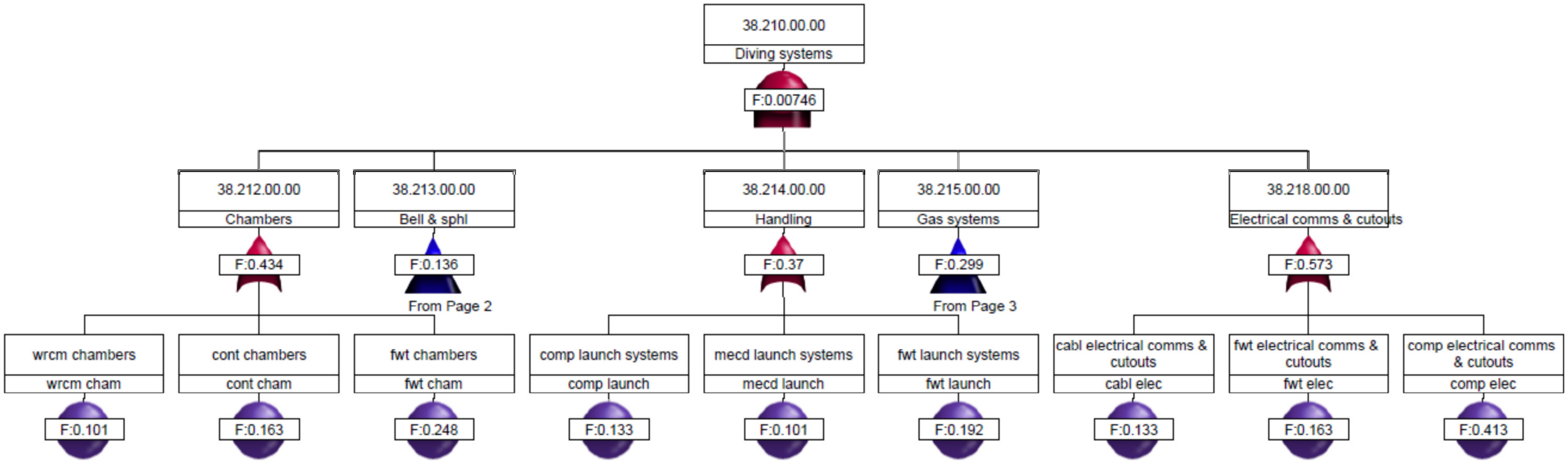


Dynamic FT structure for the fire sub-system

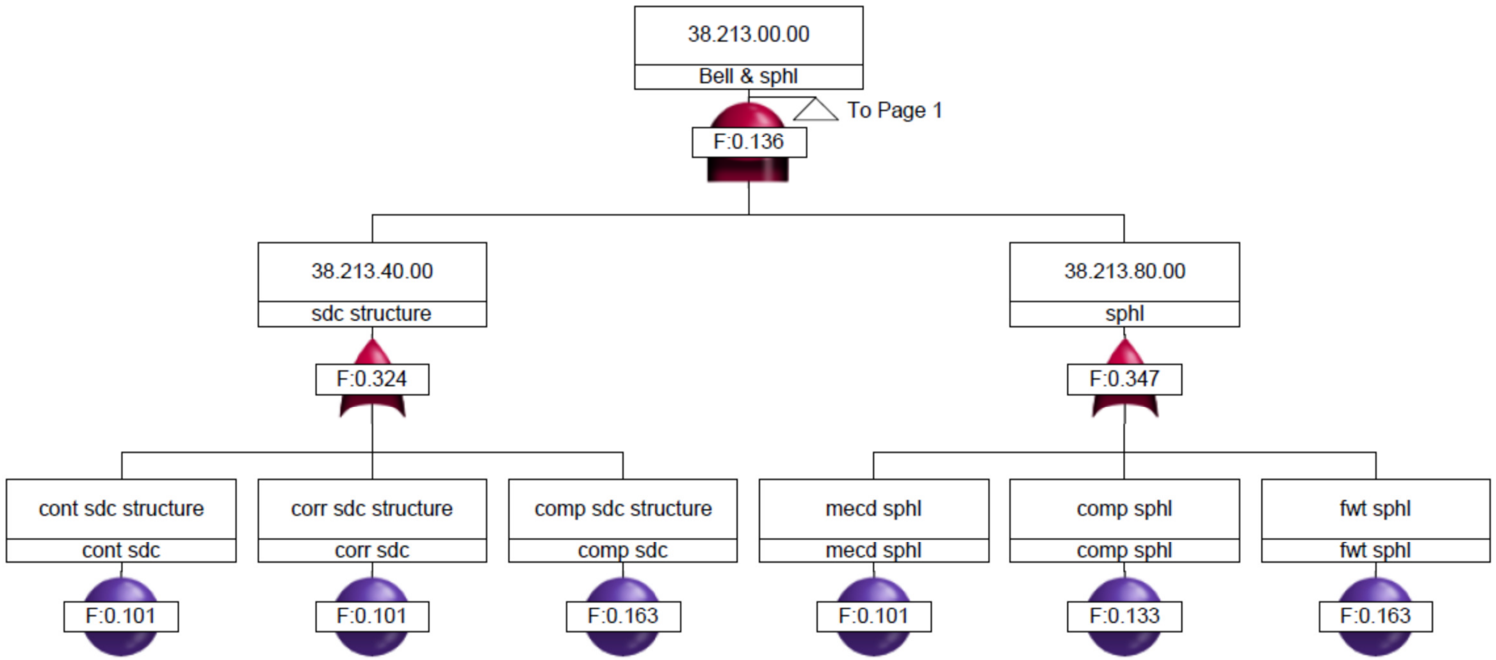


Dynamic FT structure for the potable water sub-system

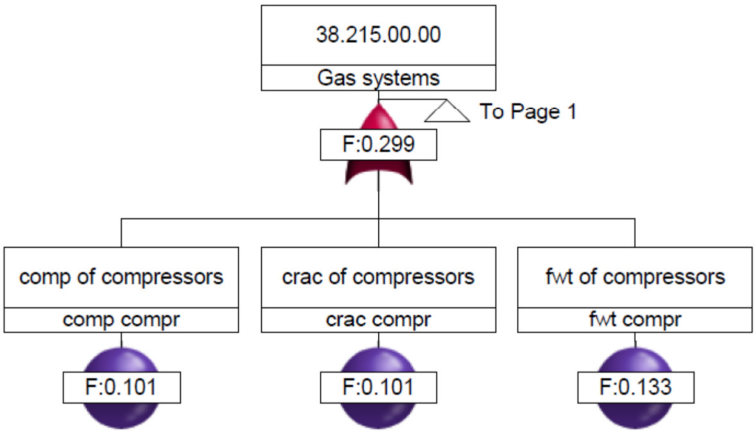
C.5 Dynamic FT structure for the Diving system



Dynamic FT structure for the Diving system (overall view) including the chambers, handling and electrical comms & cutouts sub-system

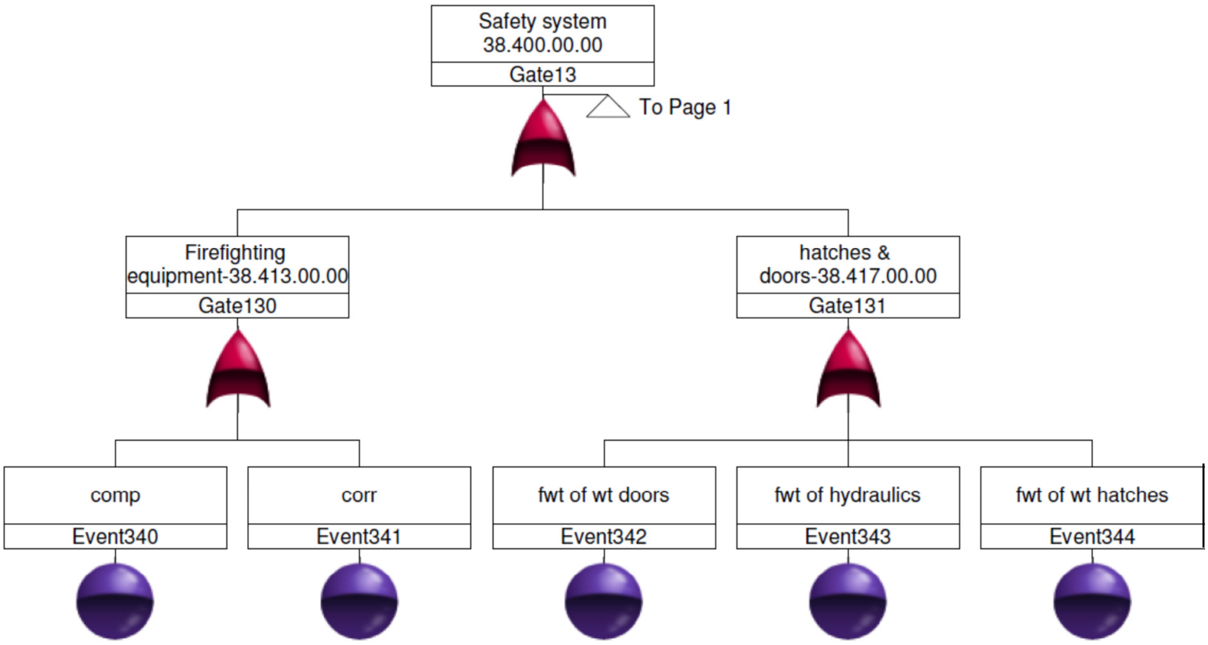


Dynamic FT structure for the bell & sphl sub-system



Dynamic FT structure for the gas sub-system

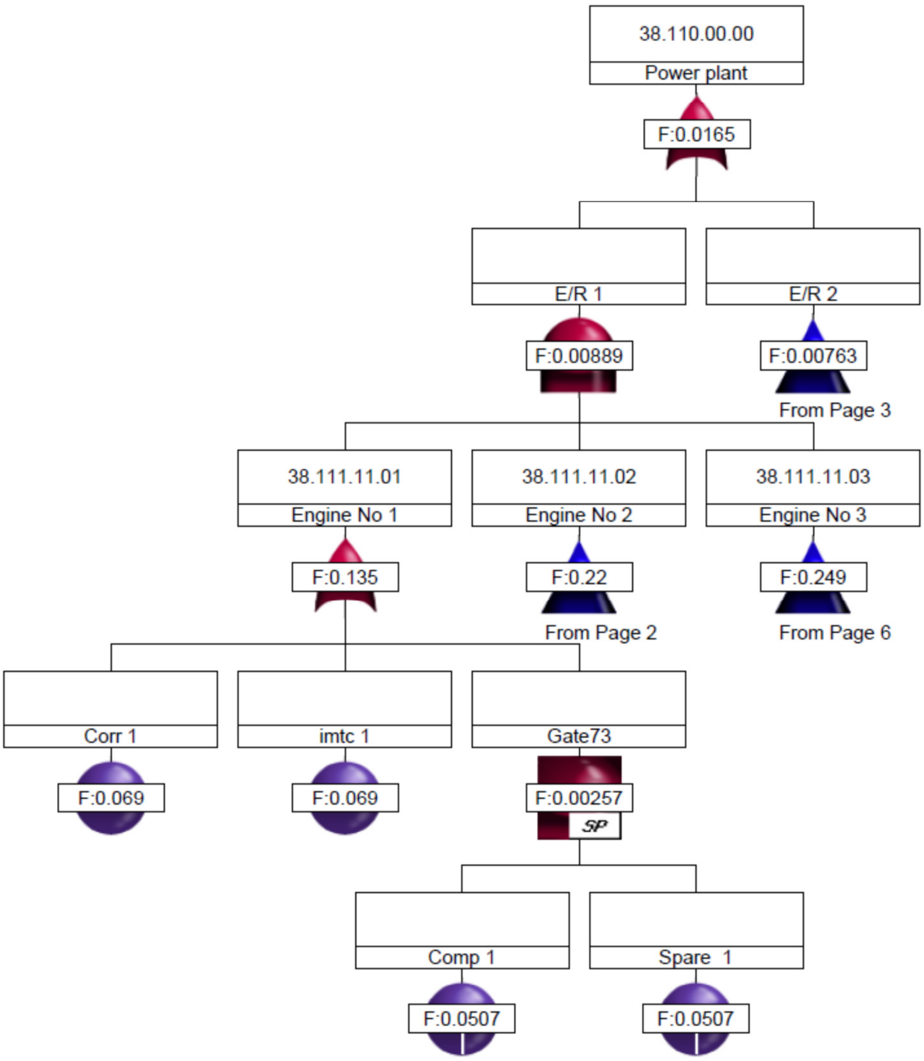
C.6 Dynamic FT structure for the Safety system



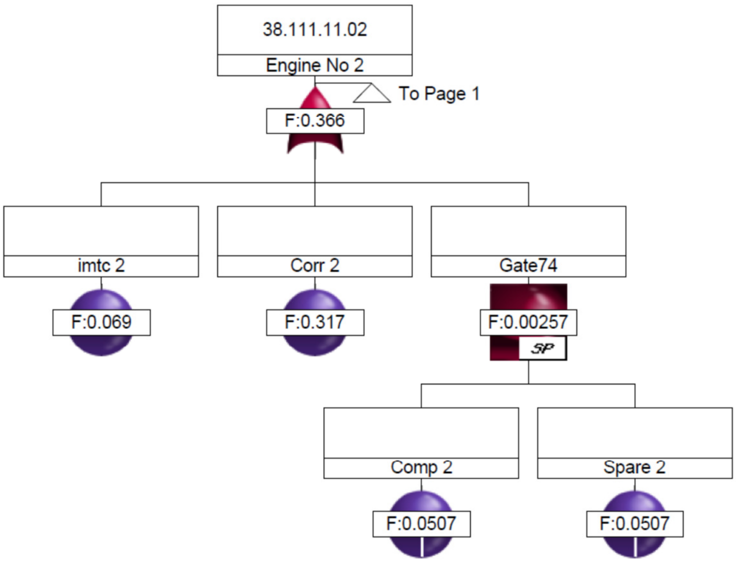
Dynamic FT structure for the Safety system (overall view)

Appendix D - Dynamic Fault Tree structure for *"DSV A"* with SPARE gates

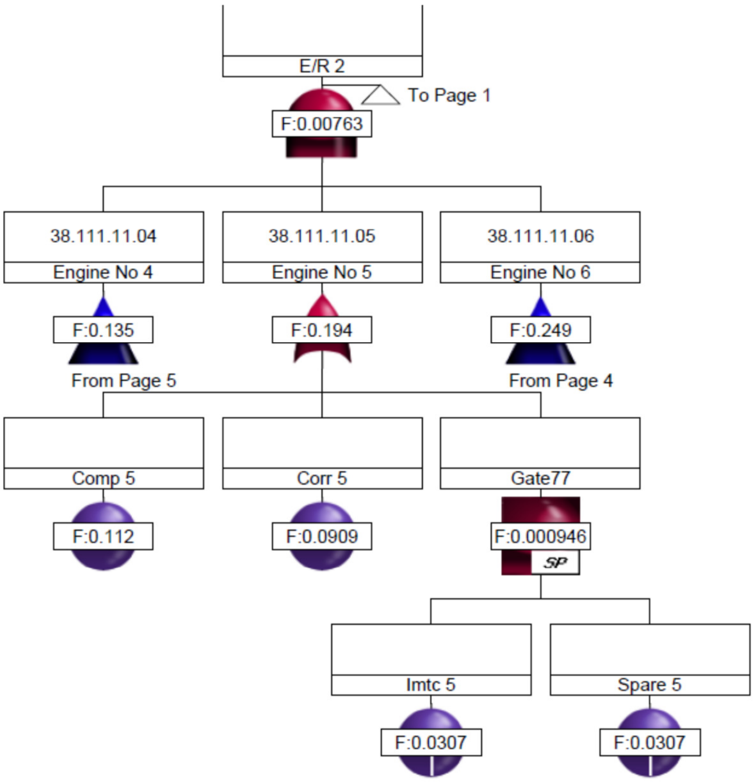
D.1 Dynamic FT structure for the Power Plant system with SPARE gates



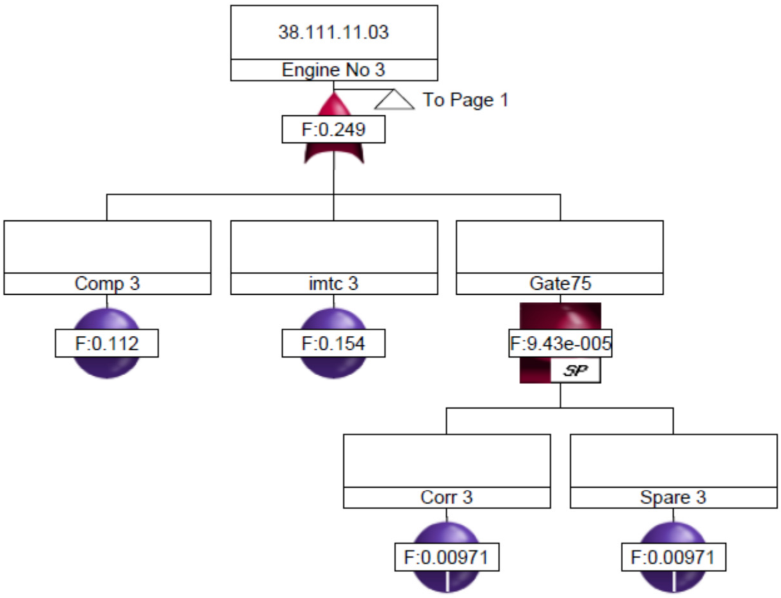
Dynamic FT structure for the Power Plant system (overall view)



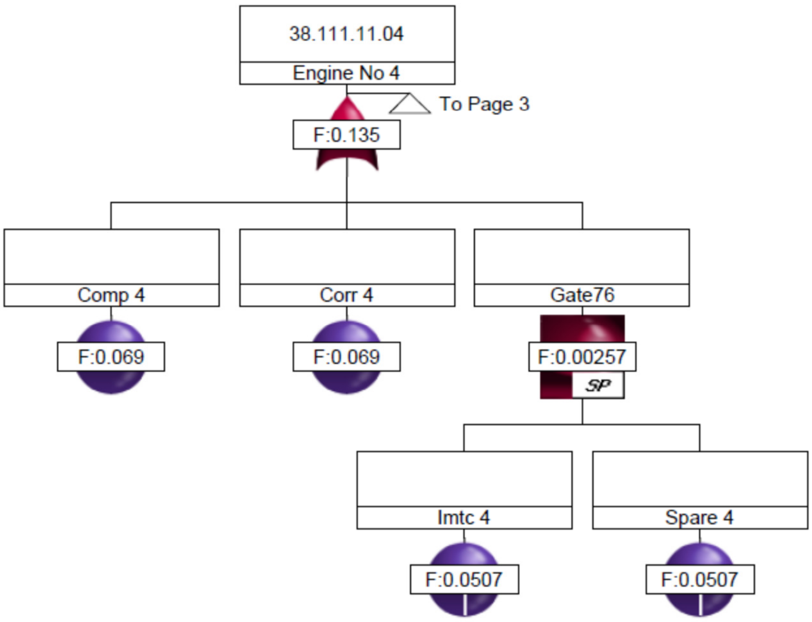
Dynamic FT structure for engine No 2



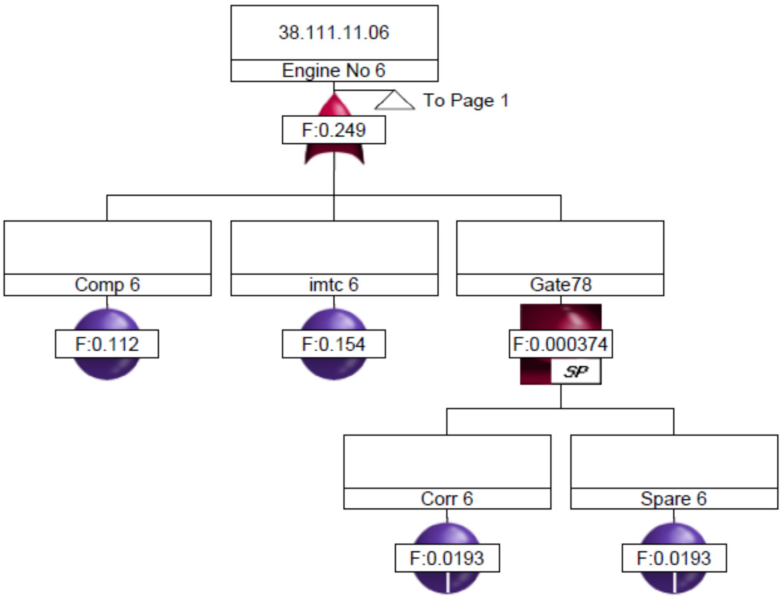
Dynamic FT structure for E/R 2



Dynamic FT structure for engine No 3

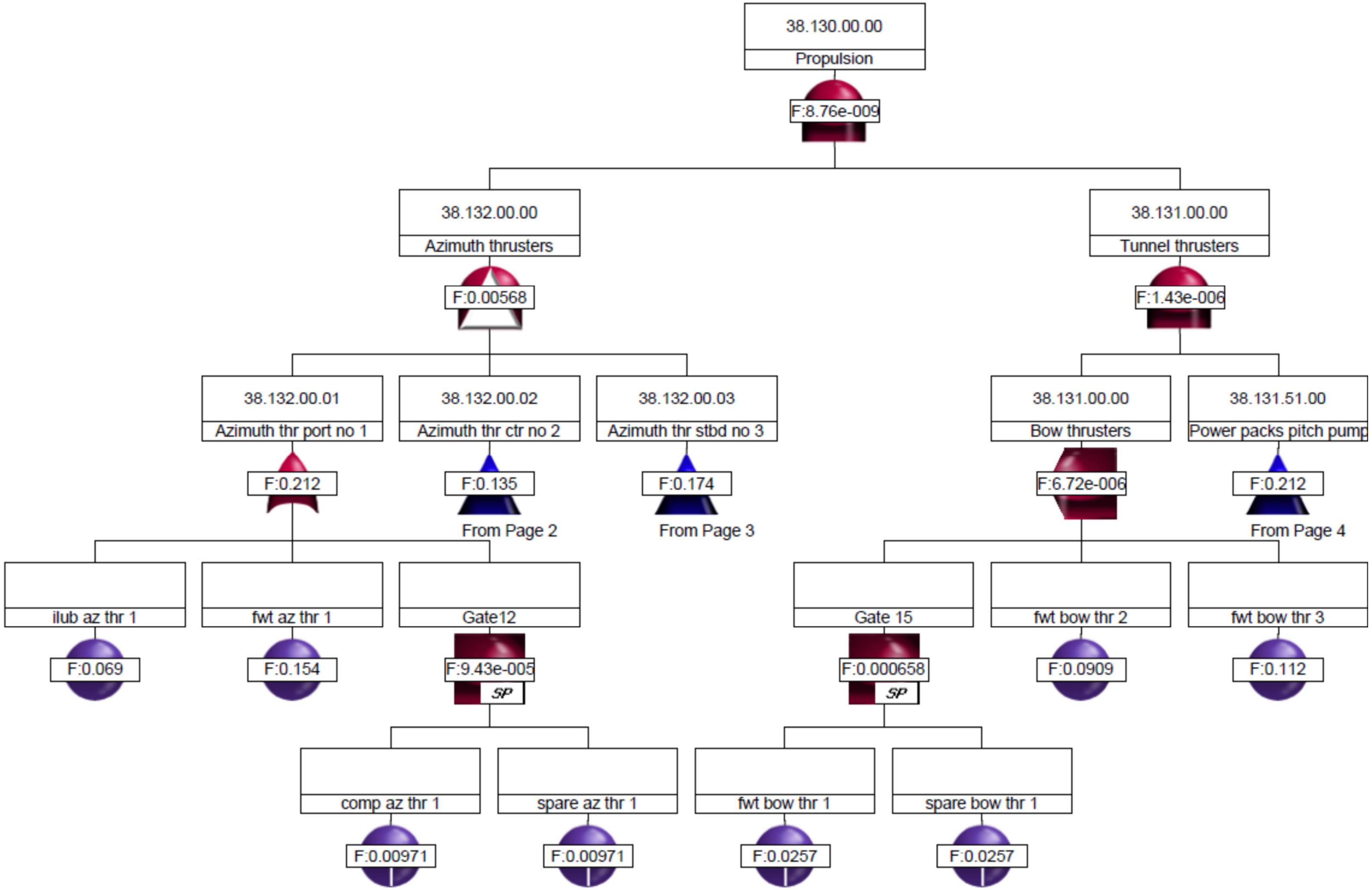


Dynamic FT structure for engine No 4

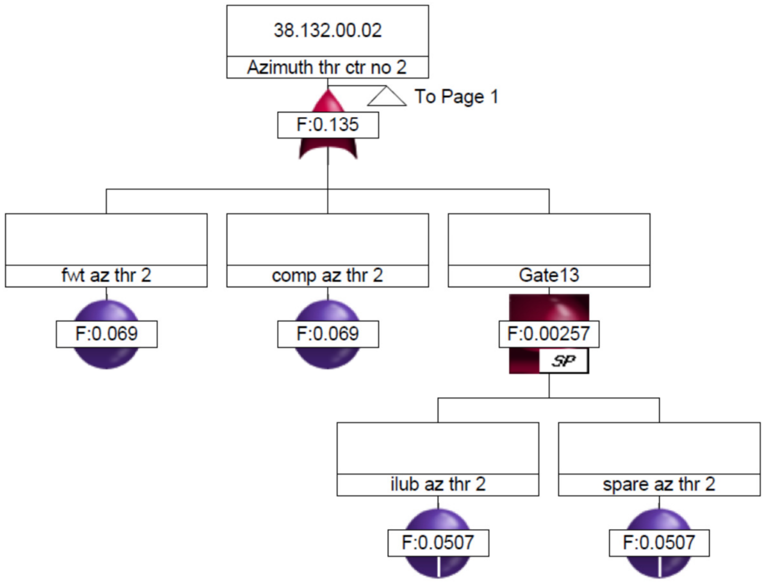


Dynamic FT structure for engine No 6

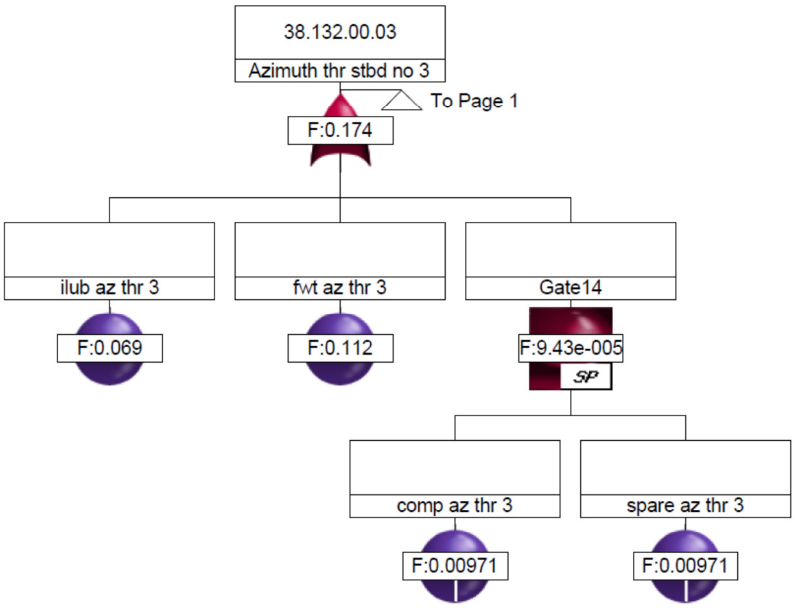
D.2 Dynamic FT structure for the Propulsion system with SPARE gates



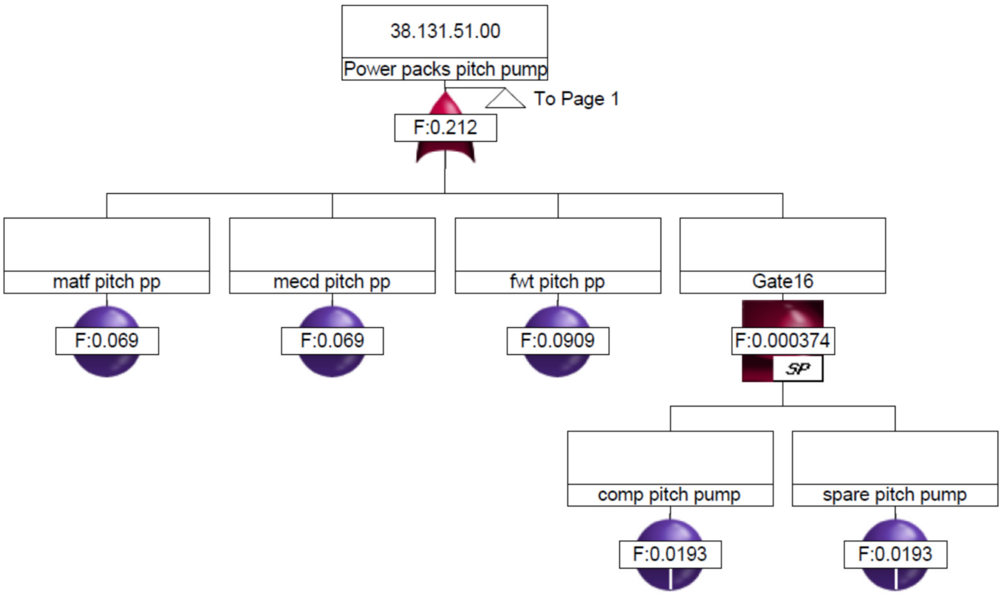
Dynamic FT structure for the Propulsion system (overall view)



Dynamic FT structure for azimuth thruster centre no 2

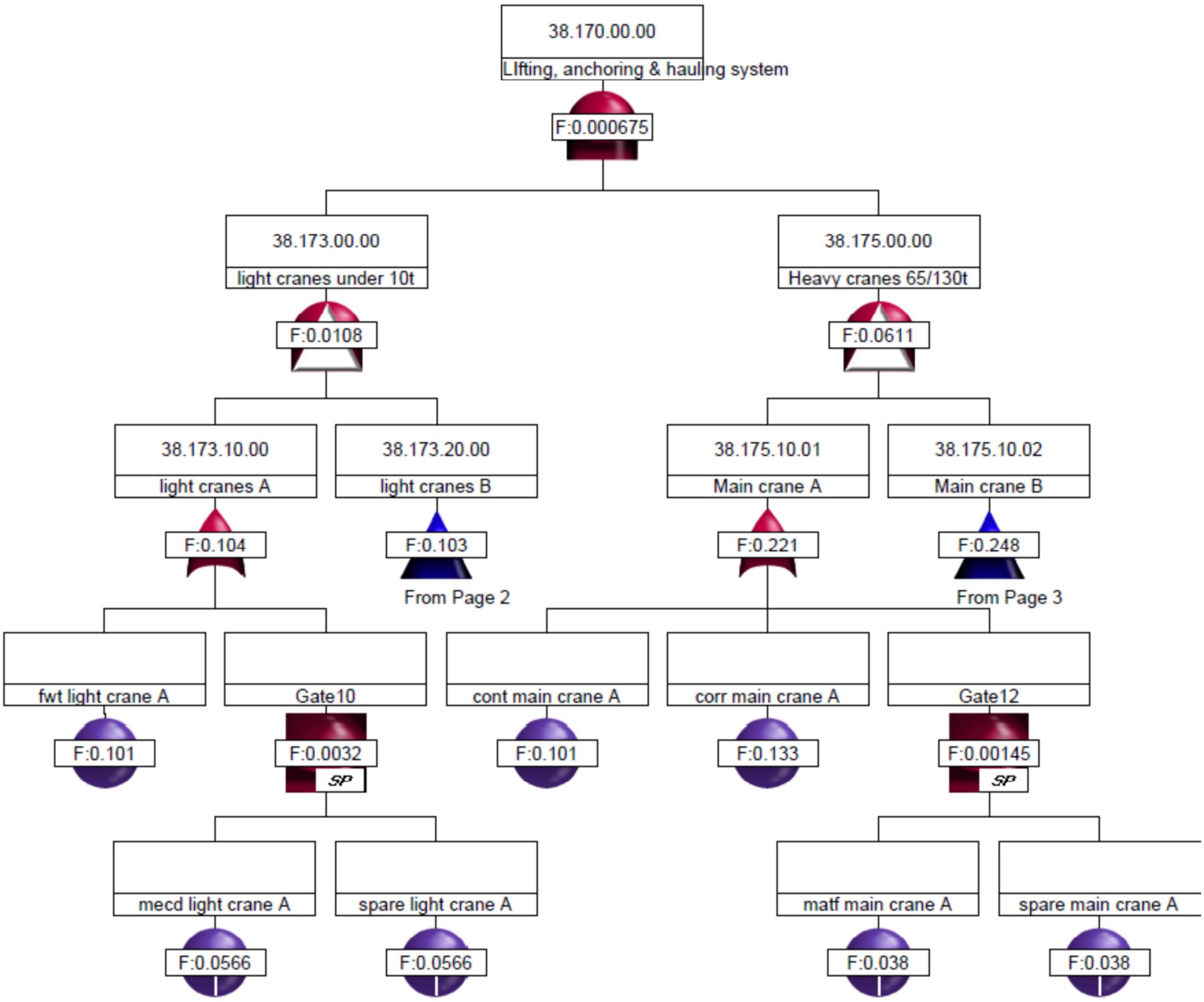


Dynamic FT structure for thruster starboard no 3

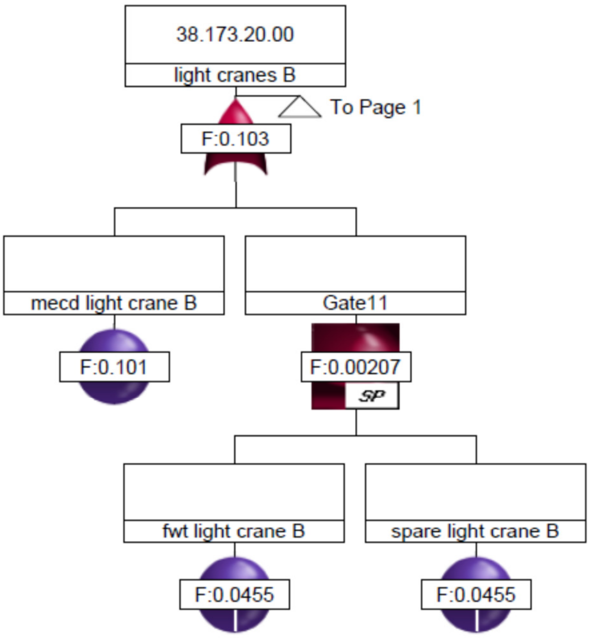


Dynamic FT structure for power packs pitch pump

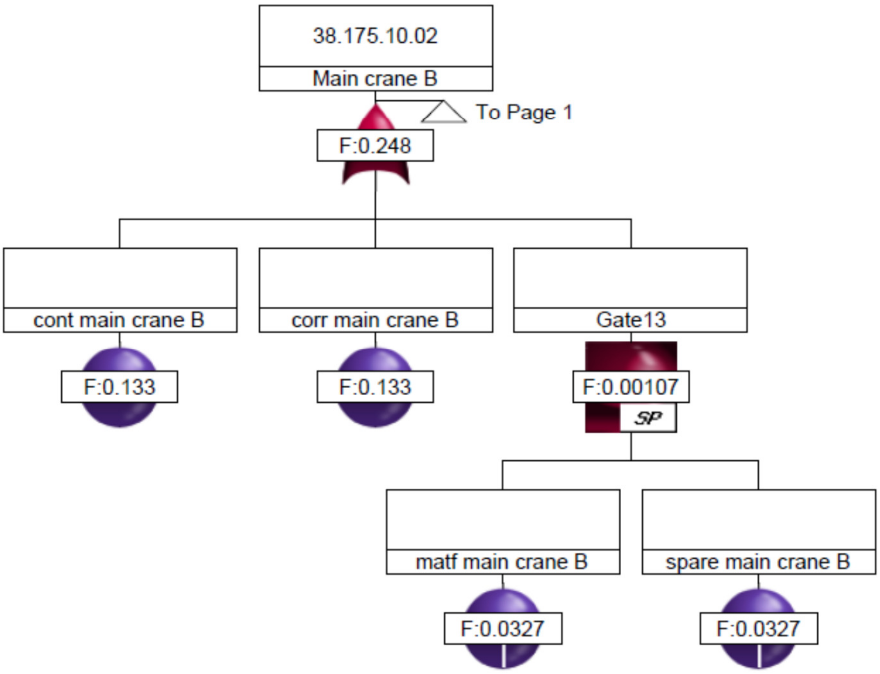
D.3 Dynamic FT structure for the Lifting, Anchoring & Hauling system with SPARE gates



Dynamic FT structure for the Lifting, Anchoring & Hauling system (overall view)

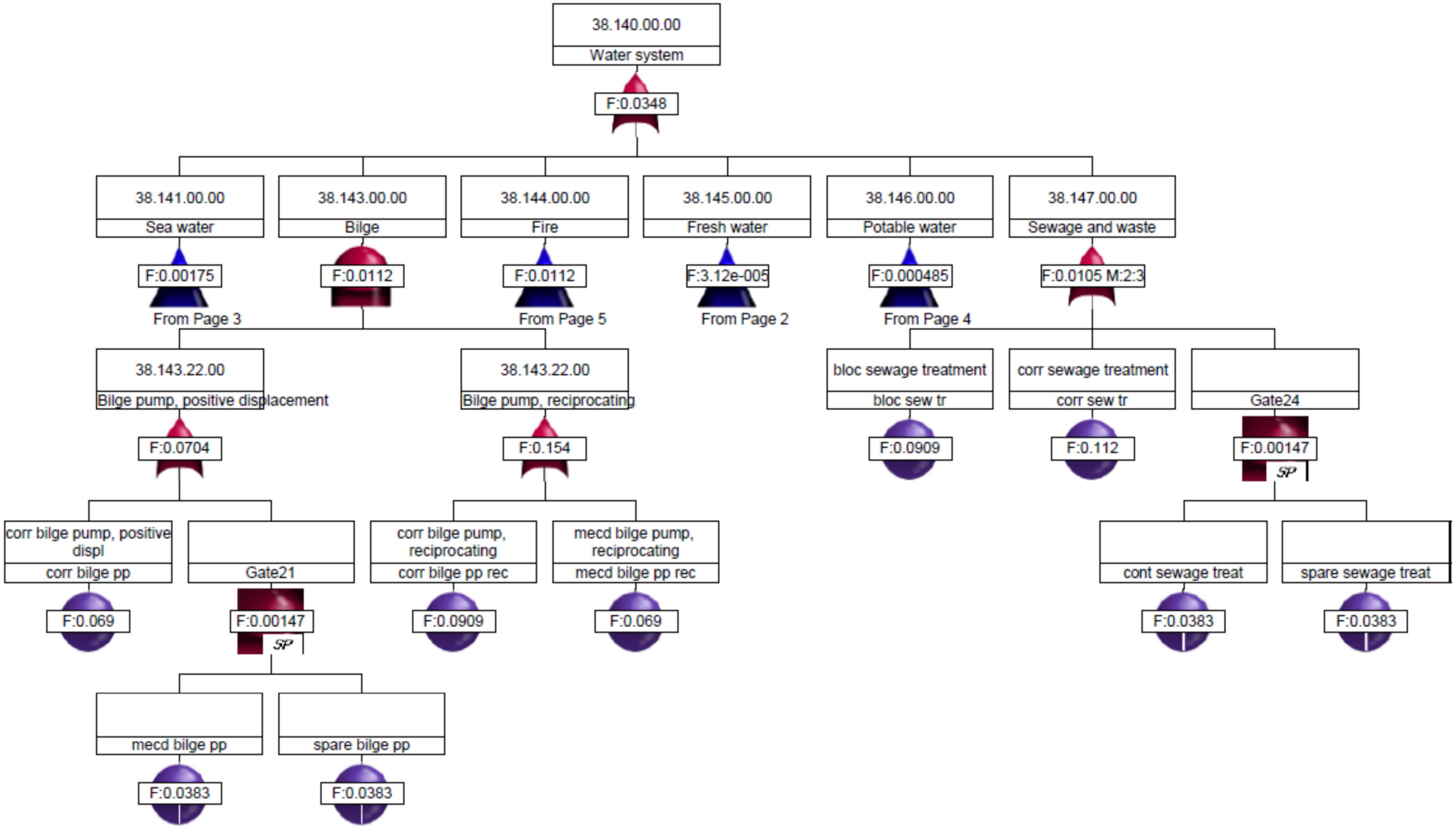


Dynamic FT structure for light cranes B

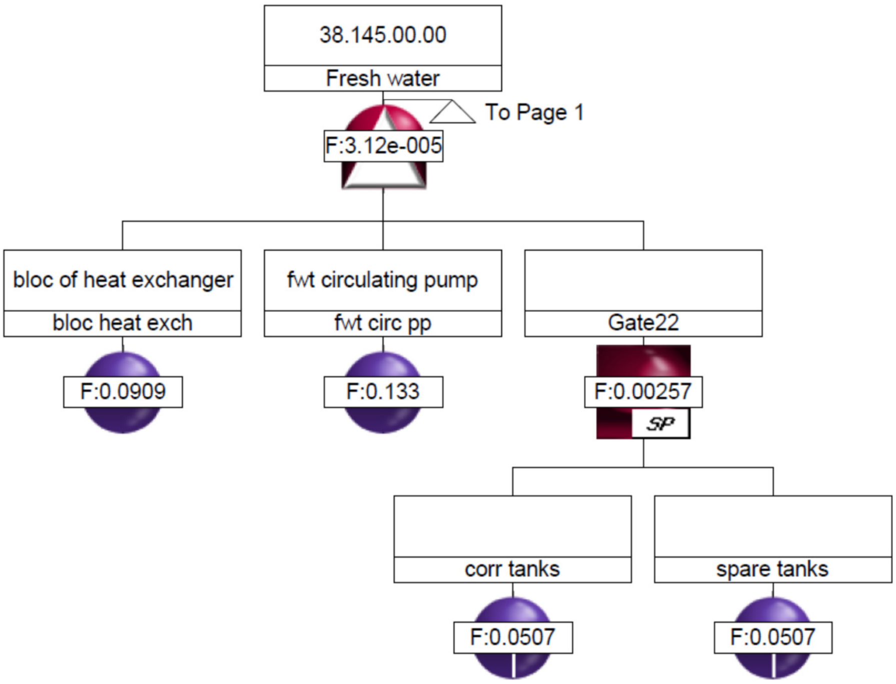


Dynamic FT structure for main crane A

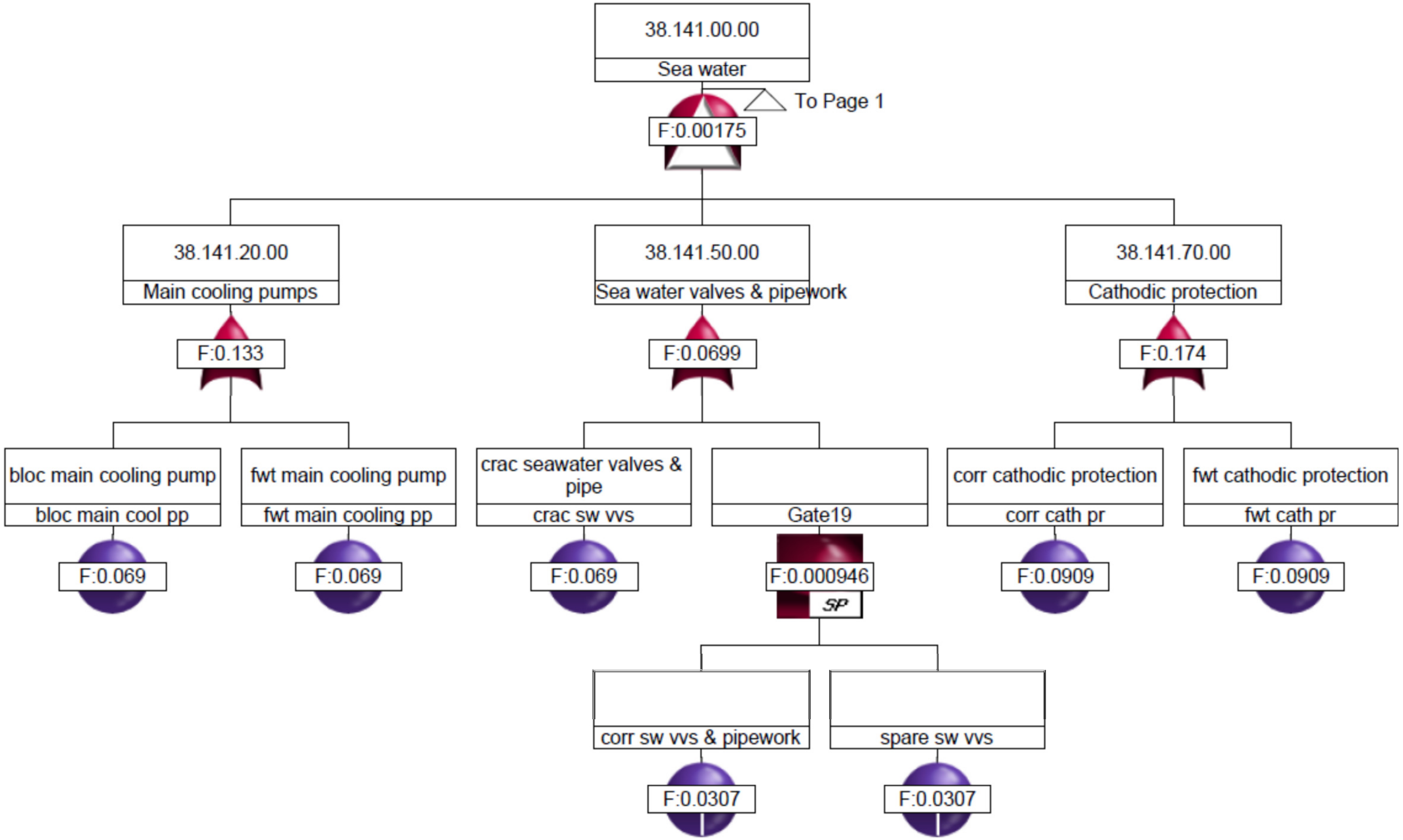
D.4 Dynamic FT structure for the Water system with SPARE gates



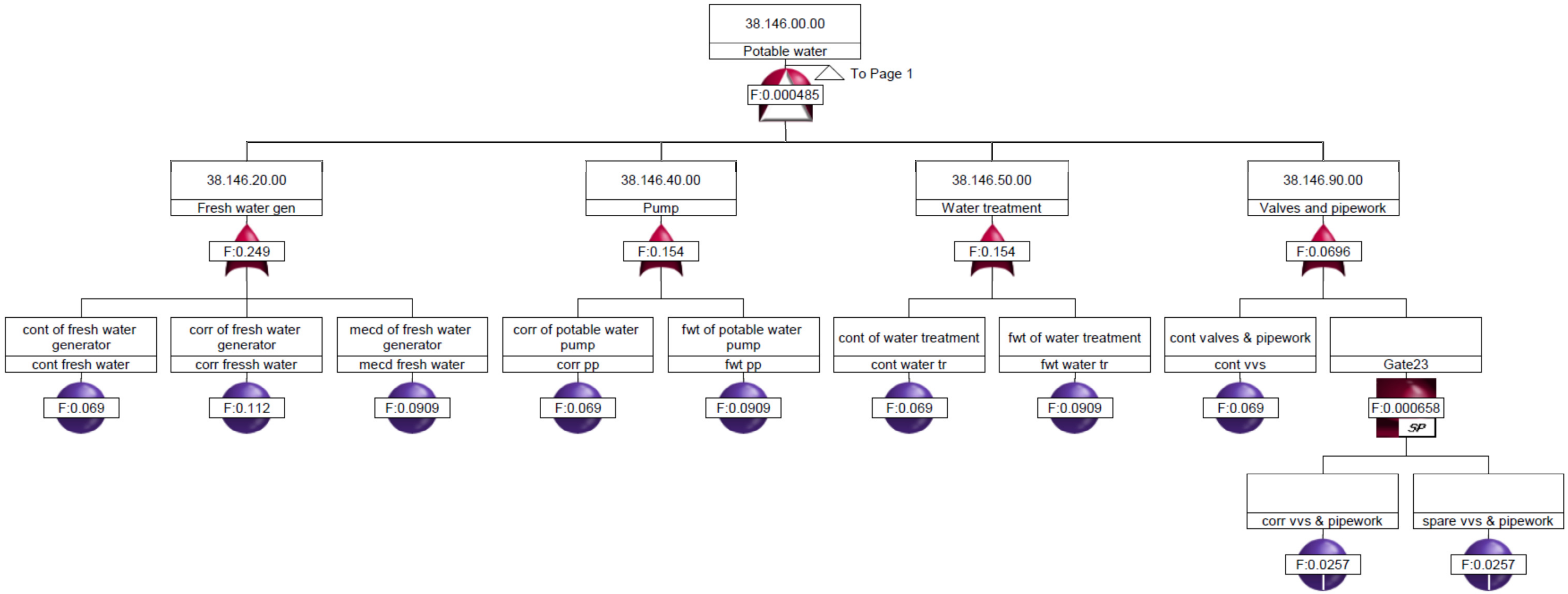
Dynamic FT structure for the Water system (overall view)



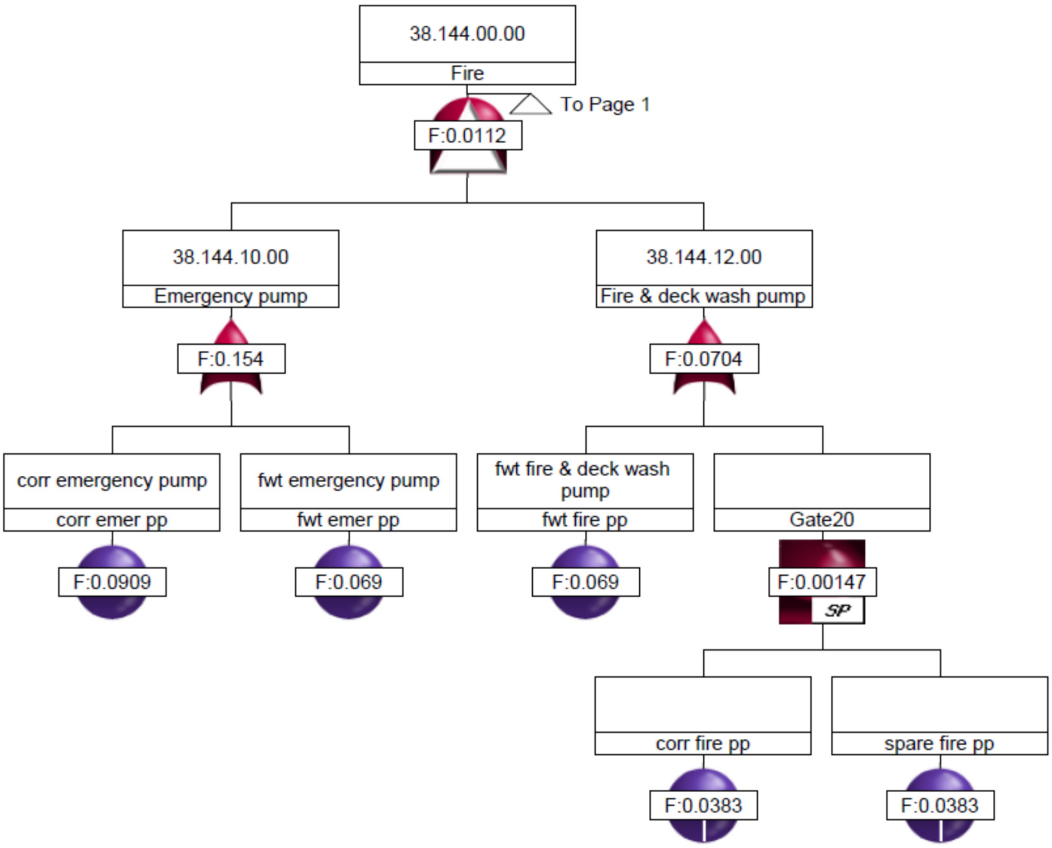
Dynamic FT structure for the fresh water sub-system



Dynamic FT structure for the sea water sub-system

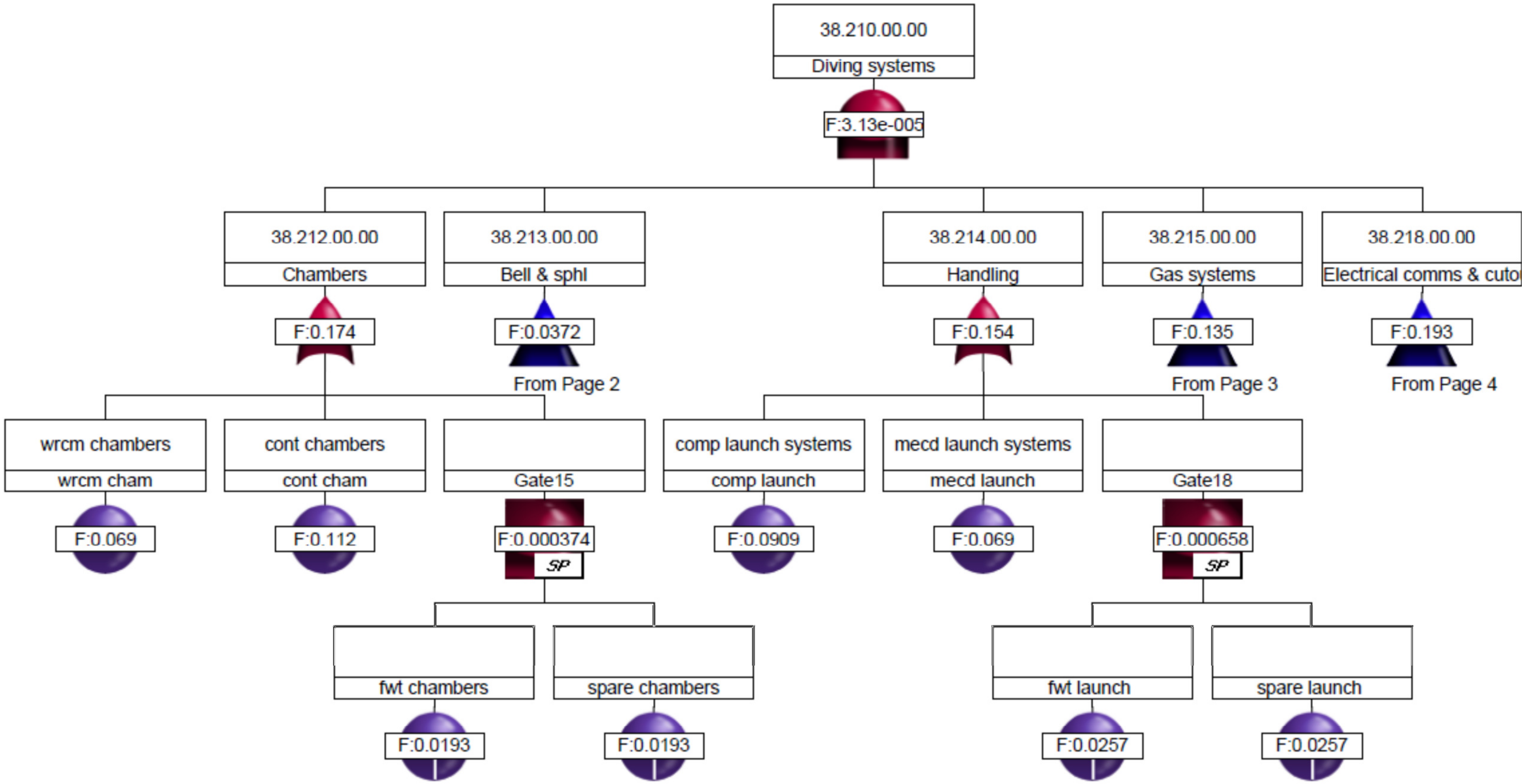


Dynamic FT structure for the potable water sub-system

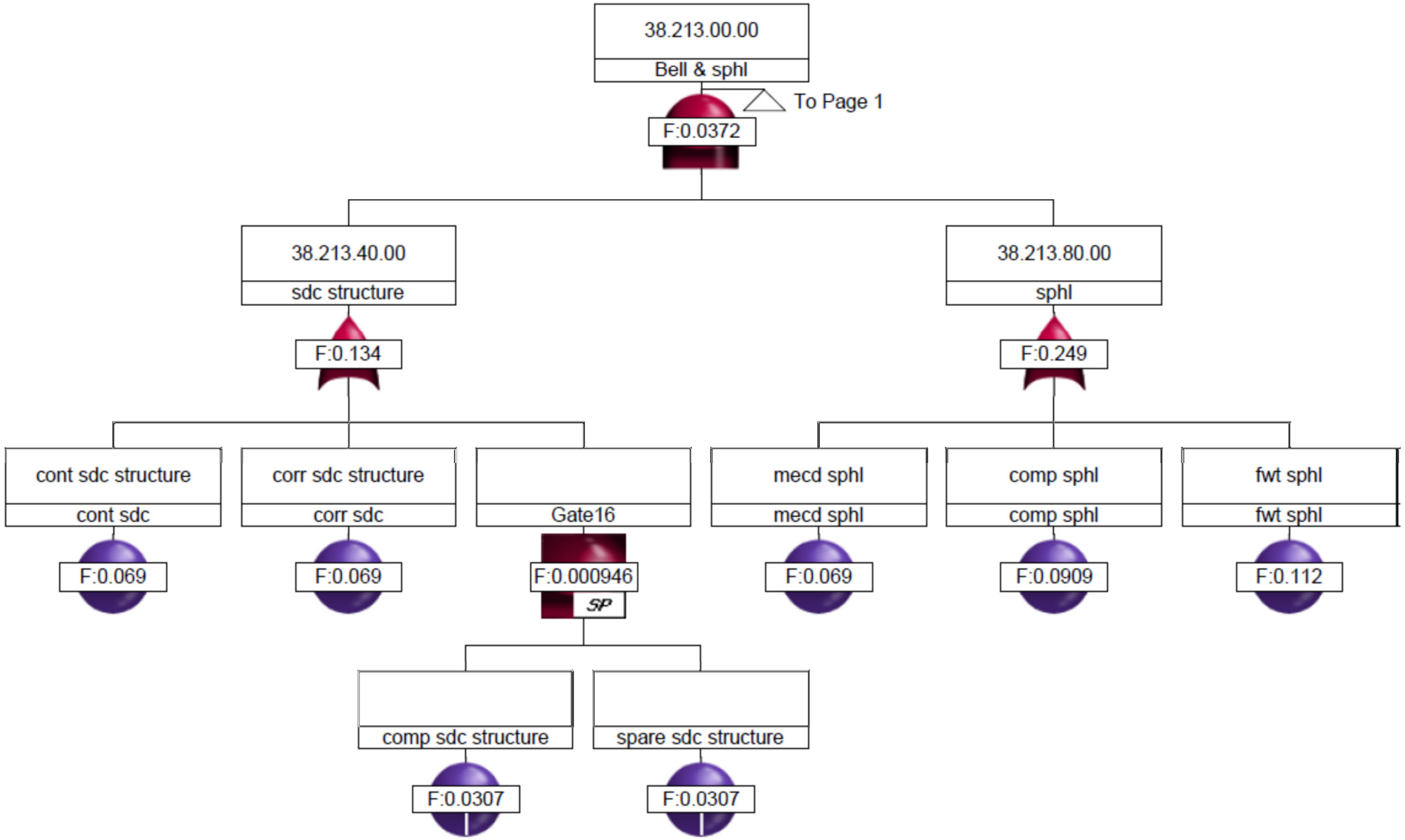


Dynamic FT structure for the fire sub-system

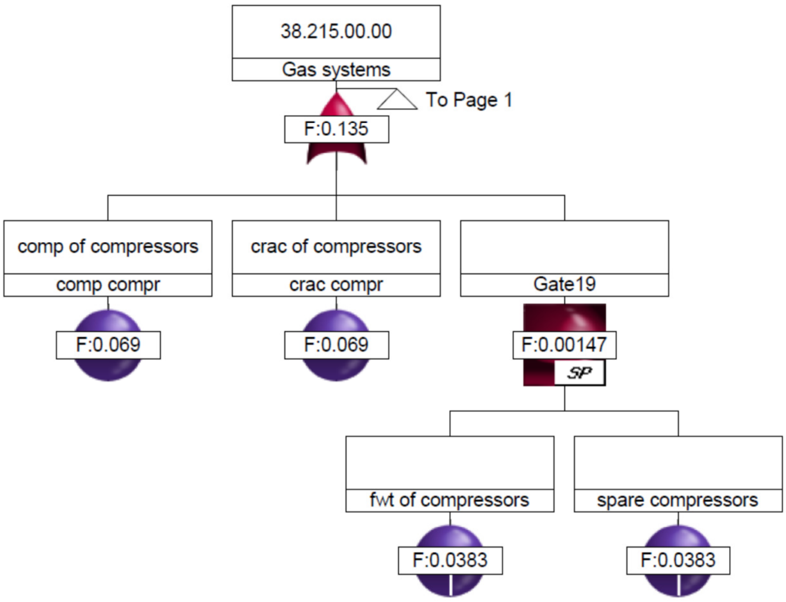
D.5 Dynamic FT structure for the Diving system with SPARE gates



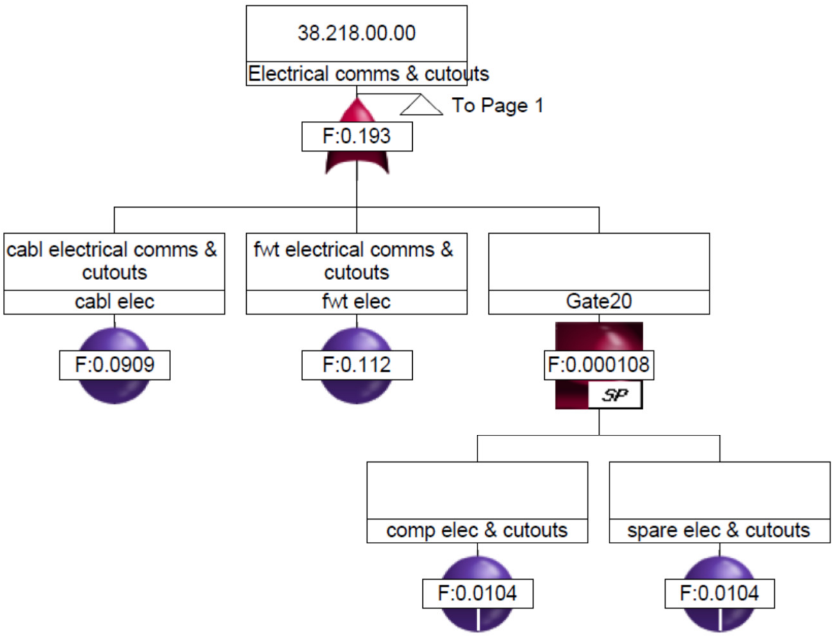
Dynamic FT structure for the Diving system with SPARE gates (overall view)



Dynamic FT structure for the bell & sphl sub-system

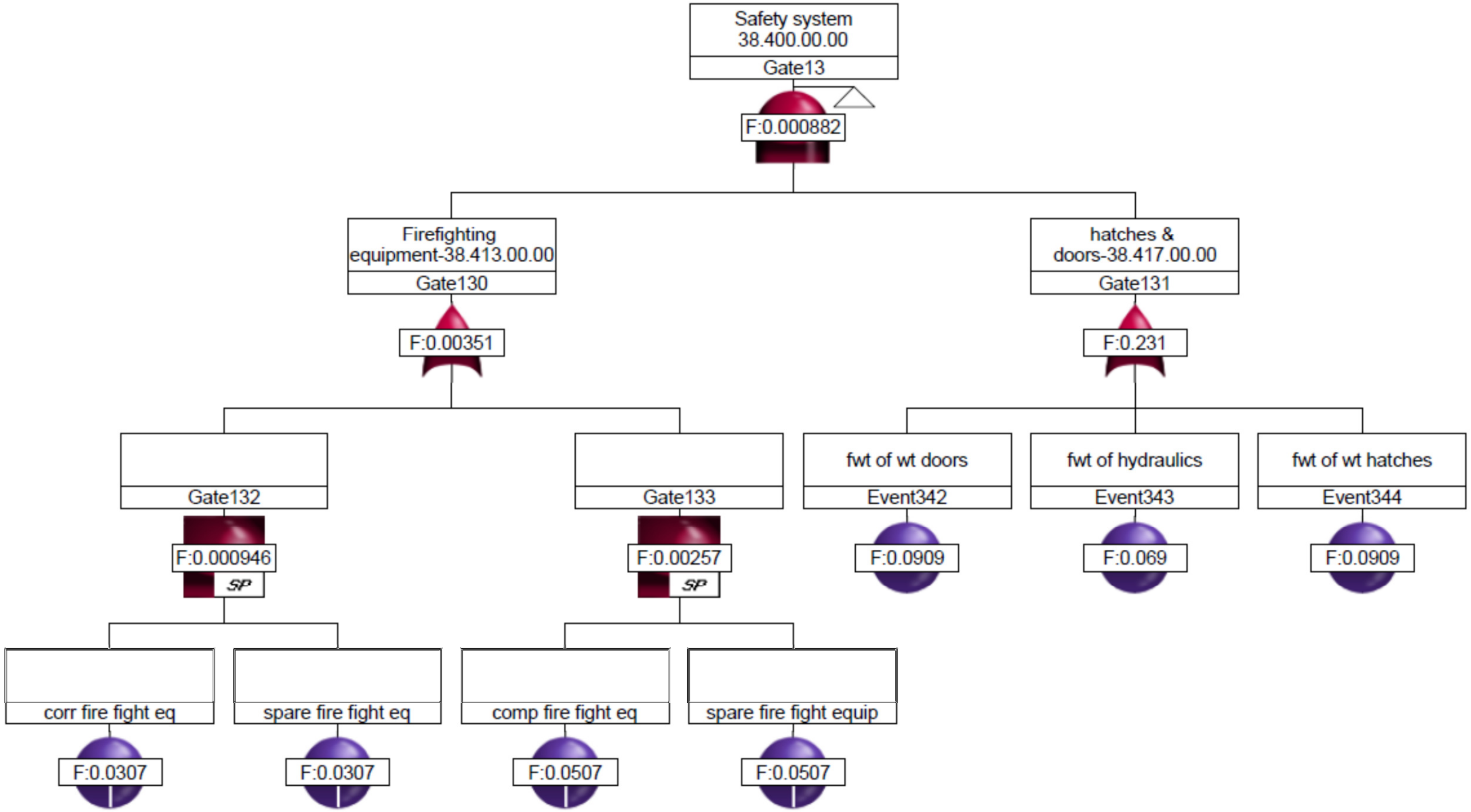


Dynamic FT structure for the gas sub-system



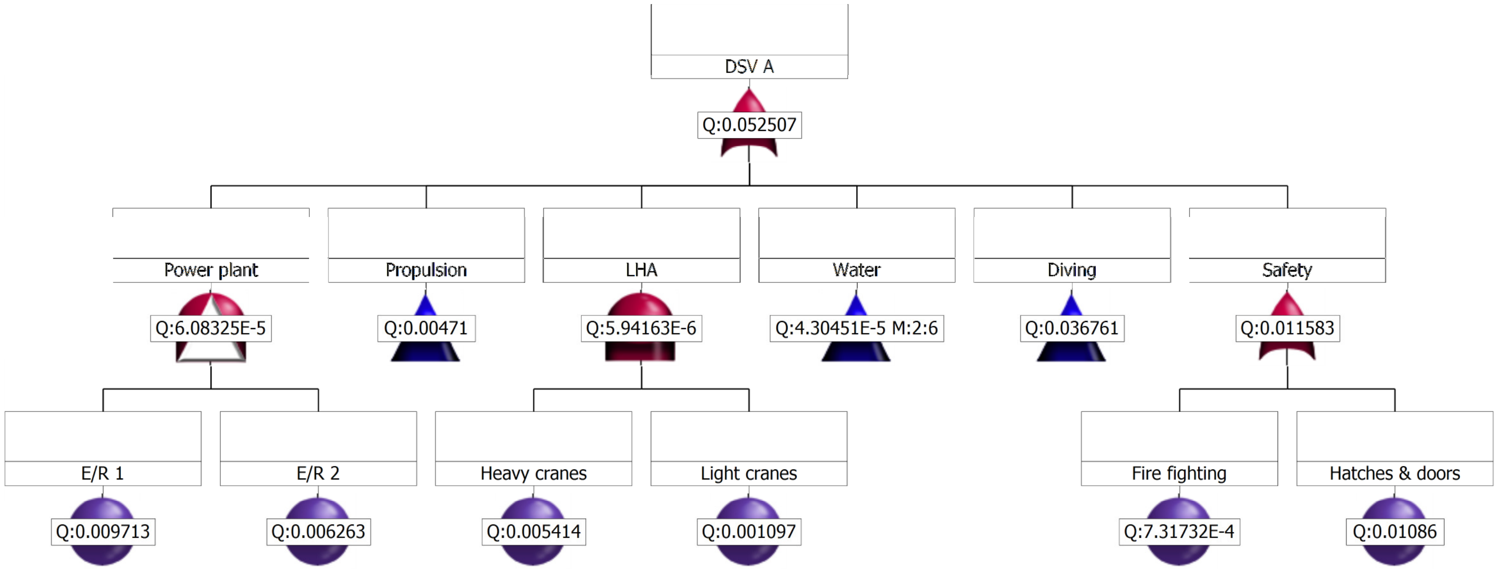
Dynamic FT structure for the electrical comms & cutouts sub-system

D.6 Dynamic FT structure for the Safety system with Spare gates

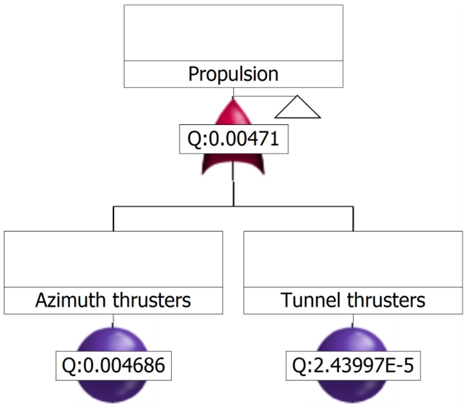


Dynamic FT structure for the Safety system (overall view)

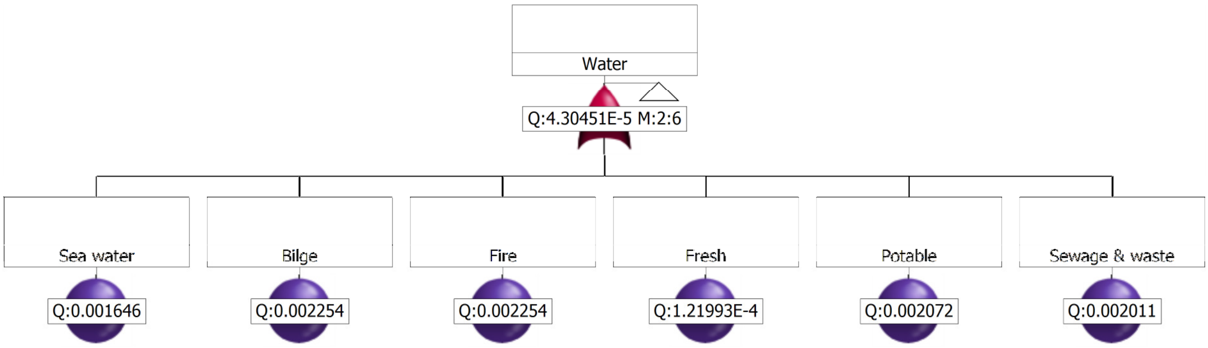
Appendix E – Dynamic Fault Tree structure for examining the overall availability of *"DSV A"*



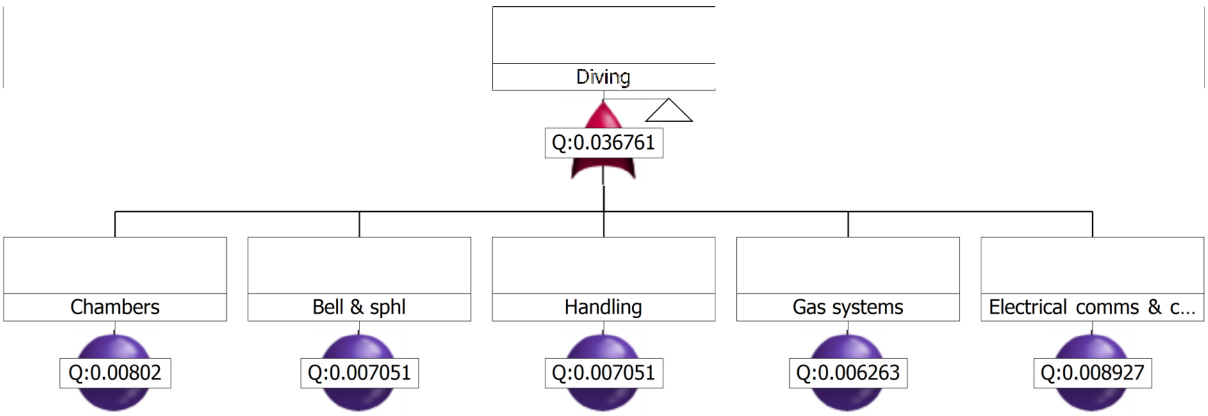
Dynamic FT structure for the examination of the overall availability of *"DSV A"*



Dynamic FT structure for the Propulsion system

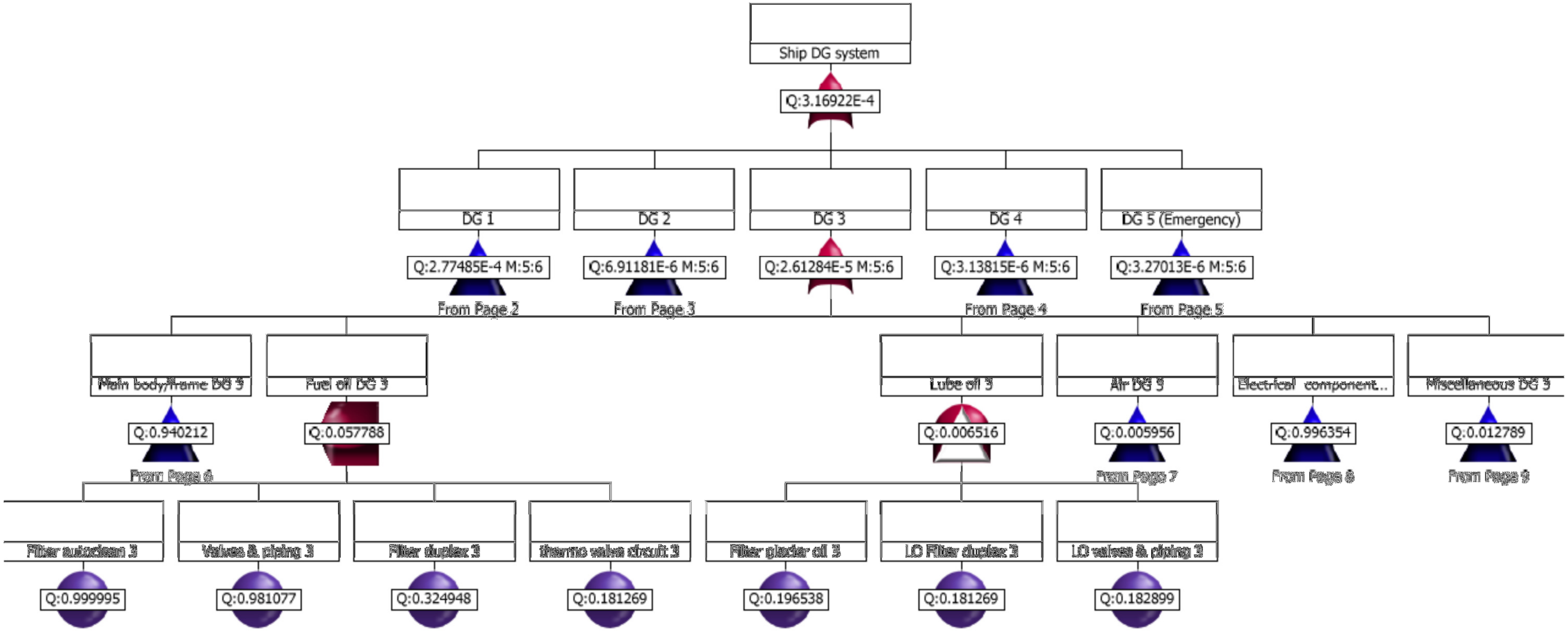


Dynamic FT structure for the Water system



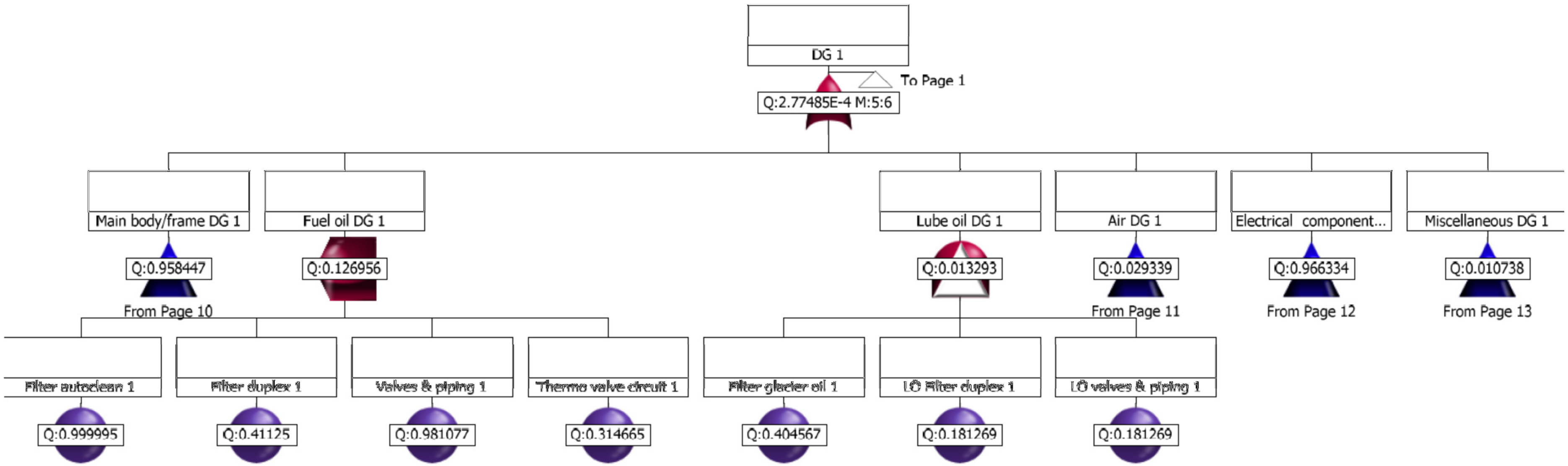
Dynamic FT structure for the Diving system

Appendix F – Dynamic Fault Tree Structure for the entire DG system

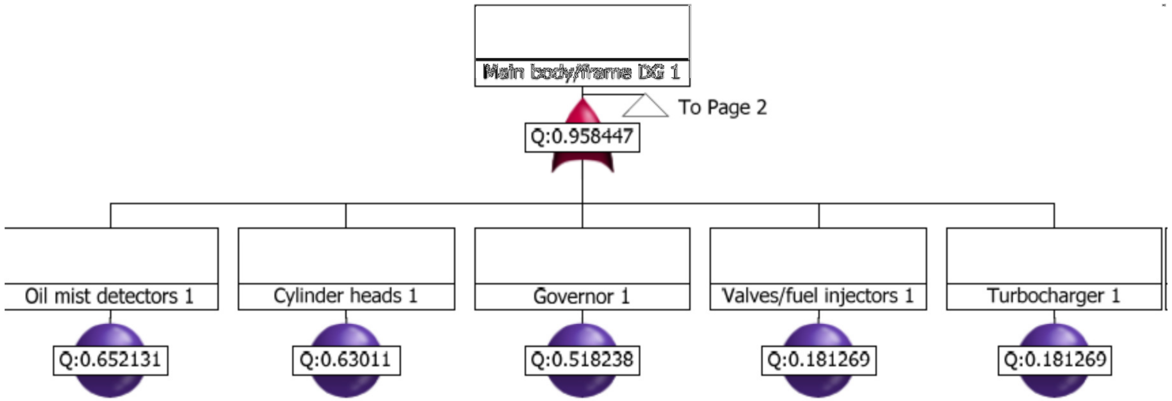


Dynamic FT structure for the overall DG system of the motor sailing cruise vessel

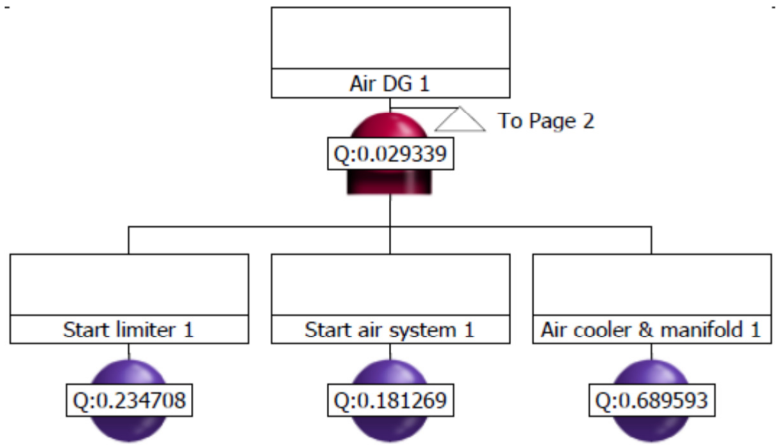
F.1 Dynamic FT structure for DG 1



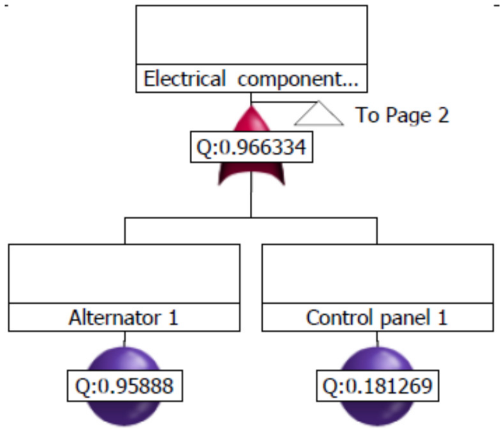
Dynamic FT structure for DG 1



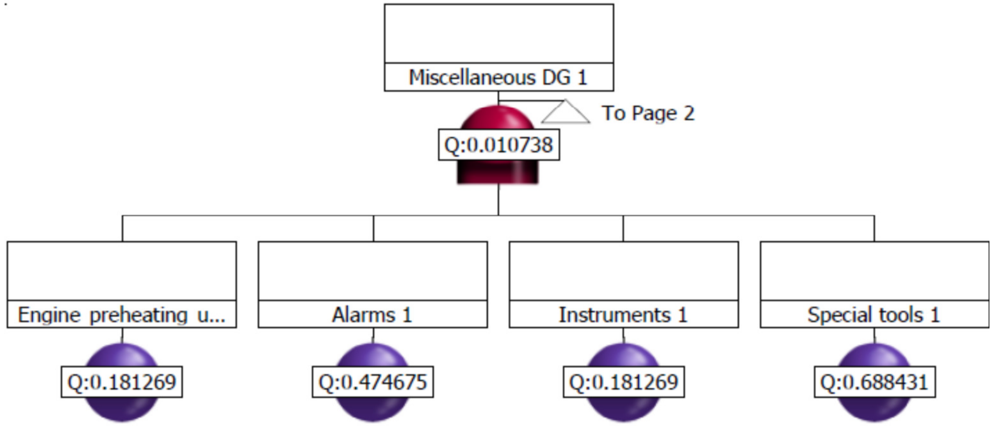
Dynamic FT structure for the main body/frame sub-system of DG 1



Dynamic FT structure for the air sub-system of DG 1

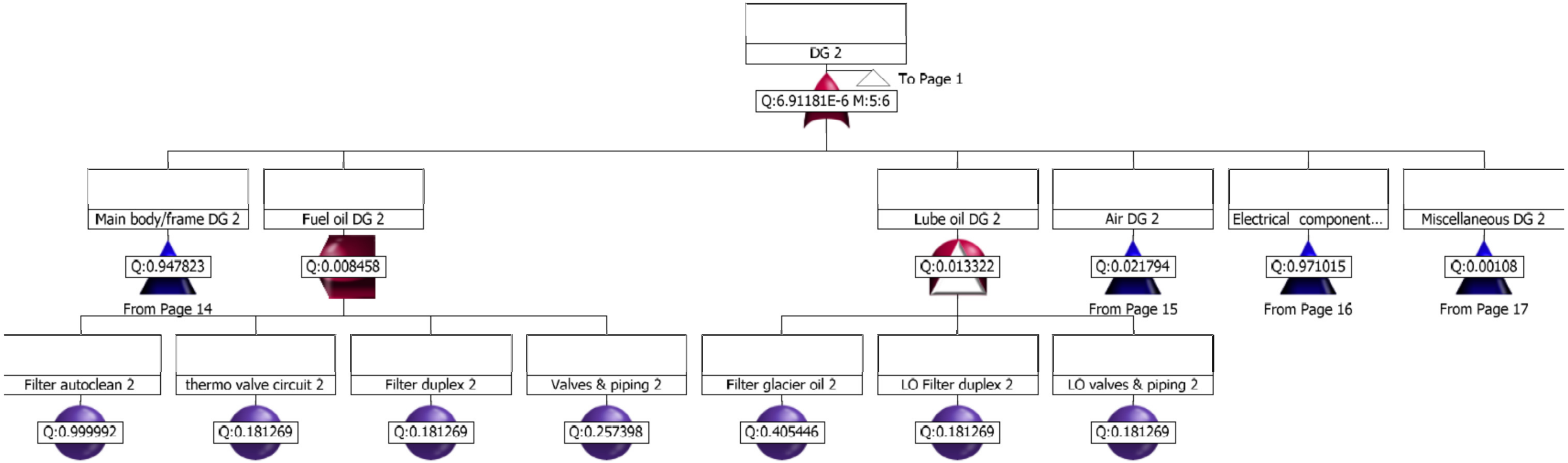


Dynamic FT structure for the electrical components sub-system of DG 1

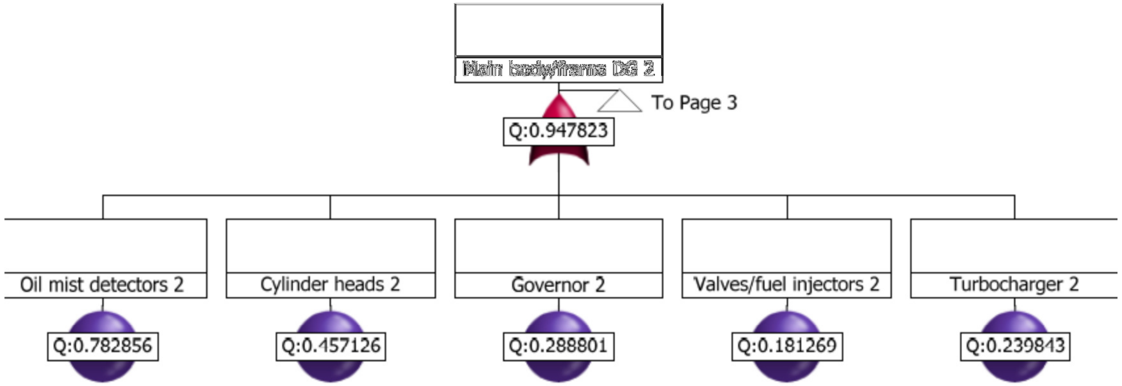


Dynamic FT structure for the miscellaneous components sub-system of DG 1

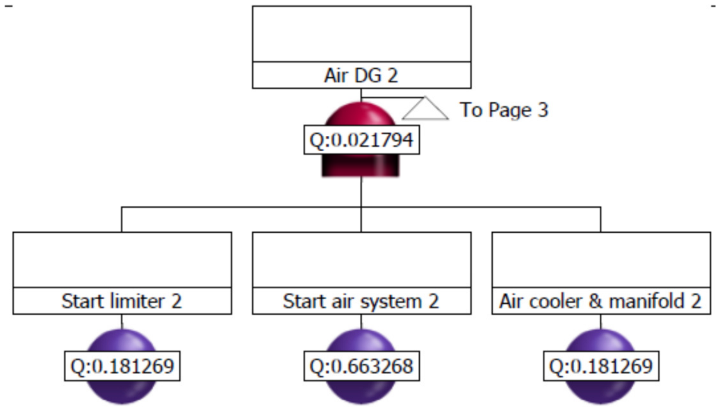
F.2 Dynamic FT structure for DG 2



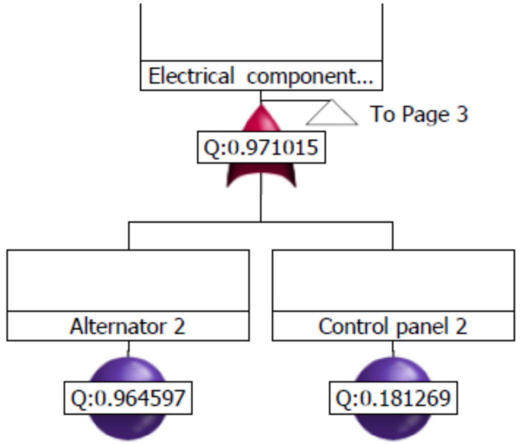
Dynamic FT structure for DG 2



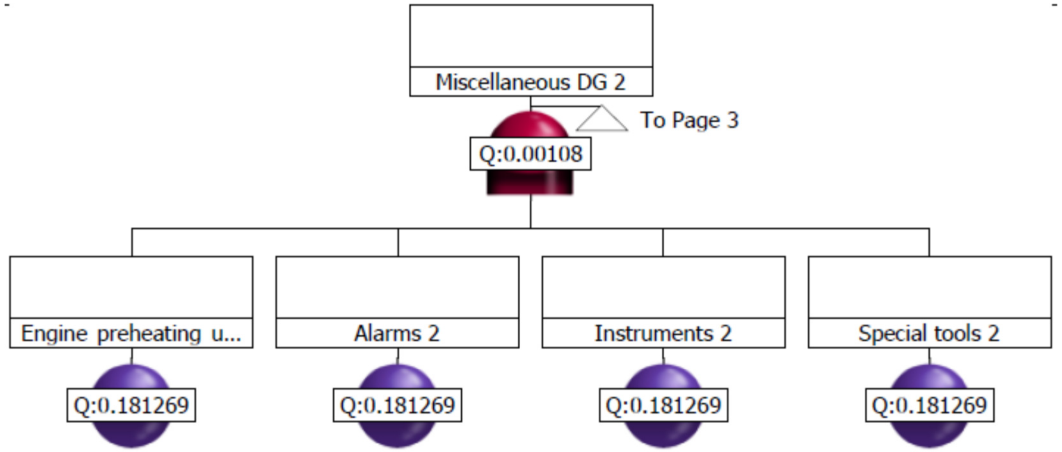
Dynamic FT structure for the main body/frame sub-system of DG 2



Dynamic FT structure for the air sub-system of DG 2

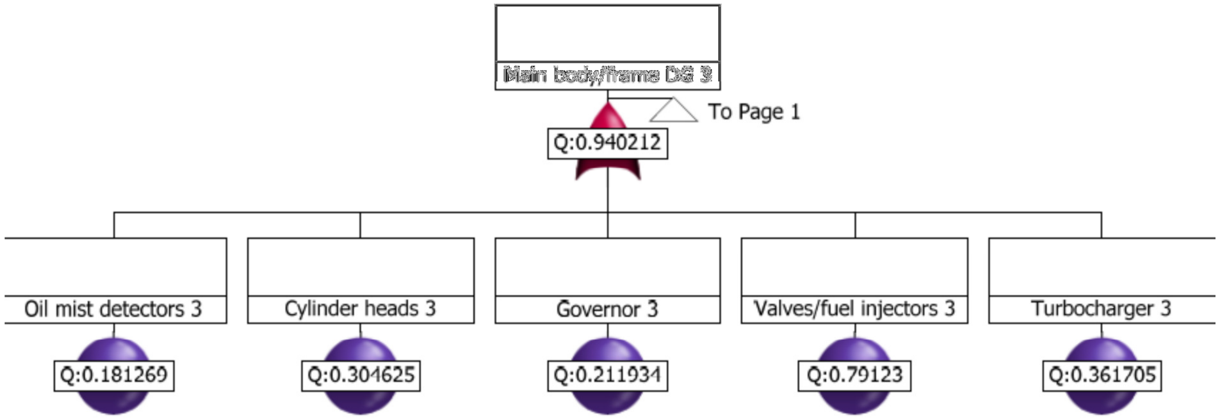


Dynamic FT structure for the electrical components sub-system of DG 2

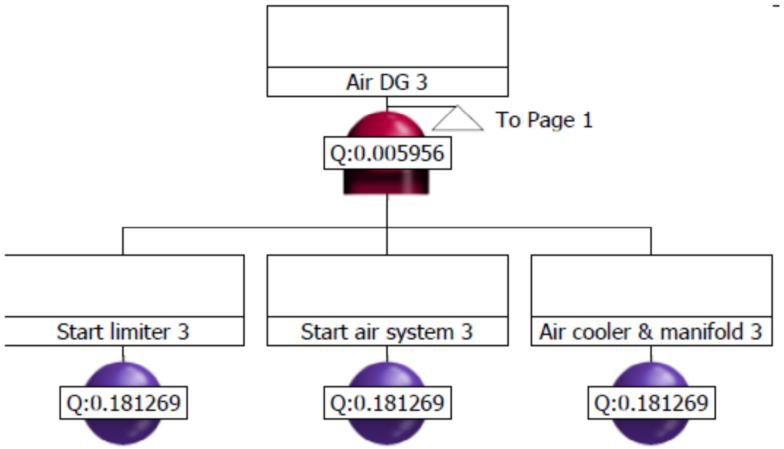


Dynamic FT structure for the miscellaneous components sub-system of DG 2

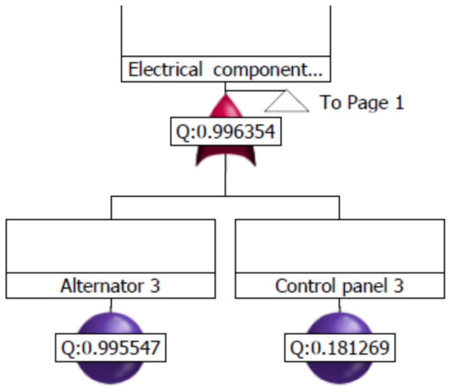
F.3 Dynamic FT structure for DG 3



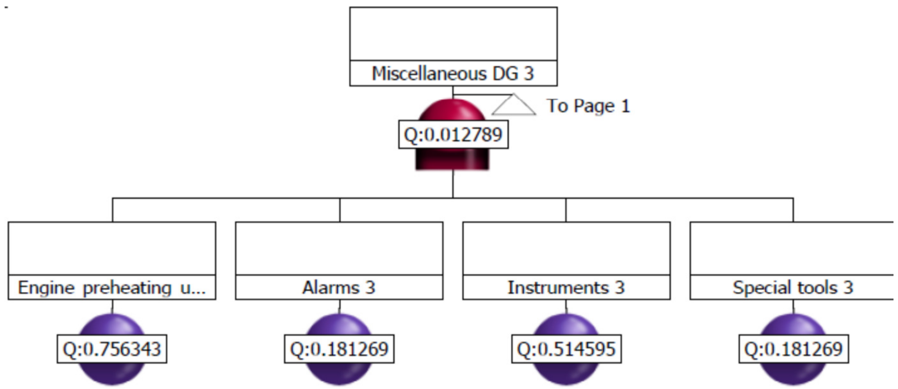
Dynamic FT structure for the main body/frame sub-system of DG 3



Dynamic FT structure for the air sub-system of DG 3

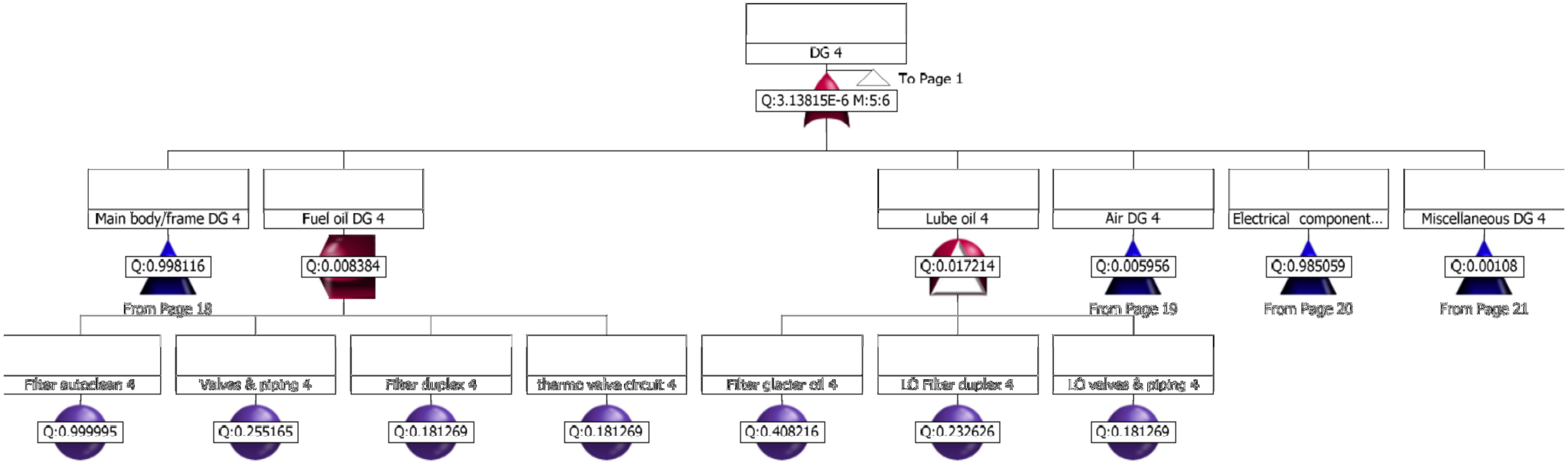


Dynamic FT structure for the electrical components sub-system of DG 3

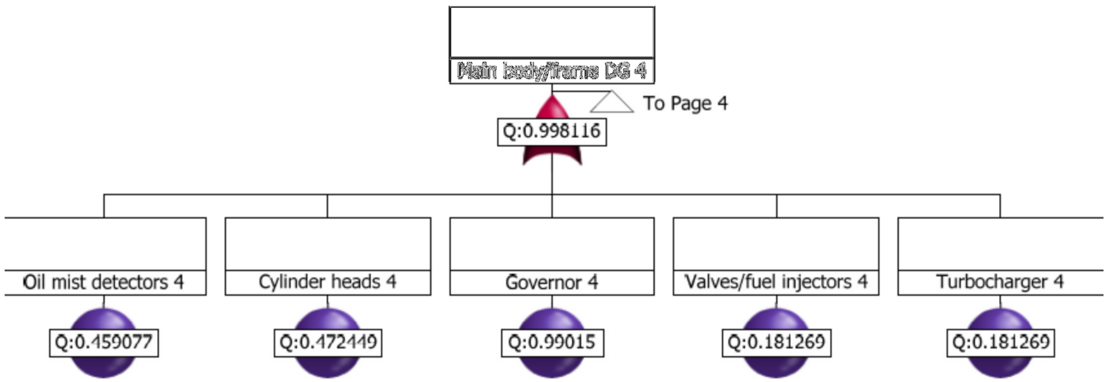


Dynamic FT structure for the miscellaneous components sub-system of DG 3

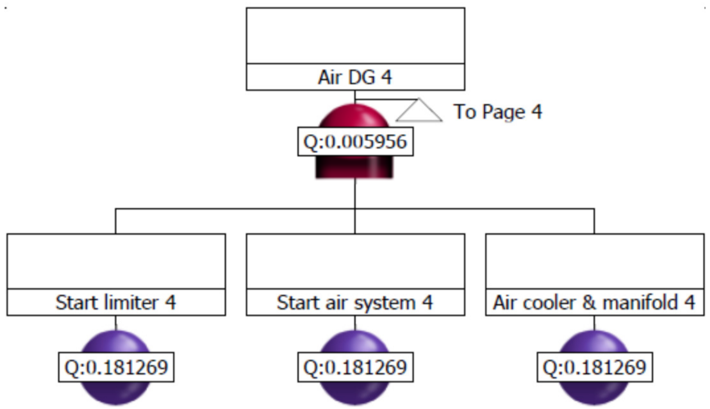
F.4 Dynamic FT structure for DG 4



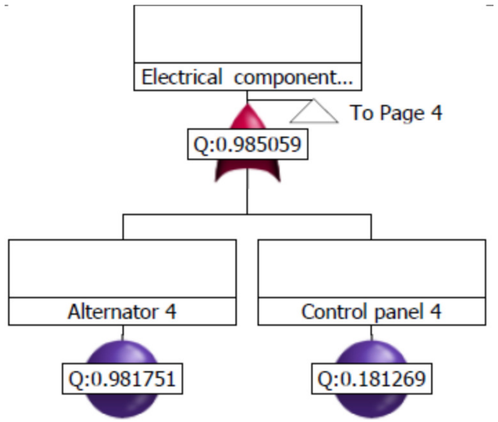
Dynamic FT structure for DG 4



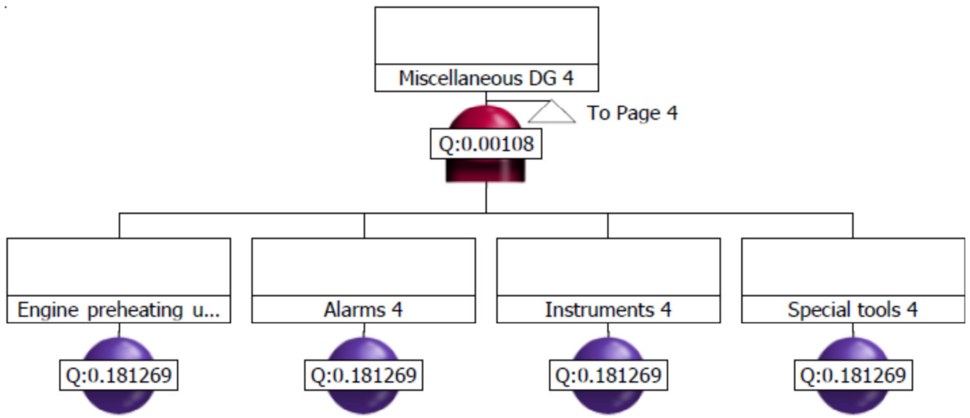
Dynamic FT structure for the main body/frame sub-system of DG 4



Dynamic FT structure for the air sub-system of DG 4

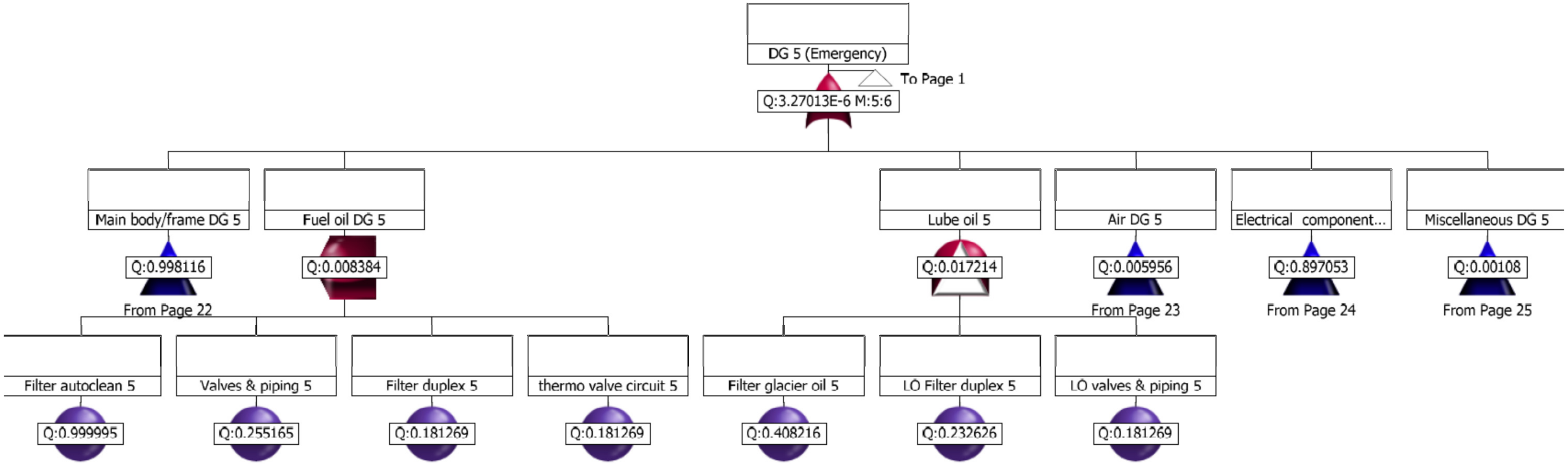


Dynamic FT structure for the electrical components sub-system of DG 4

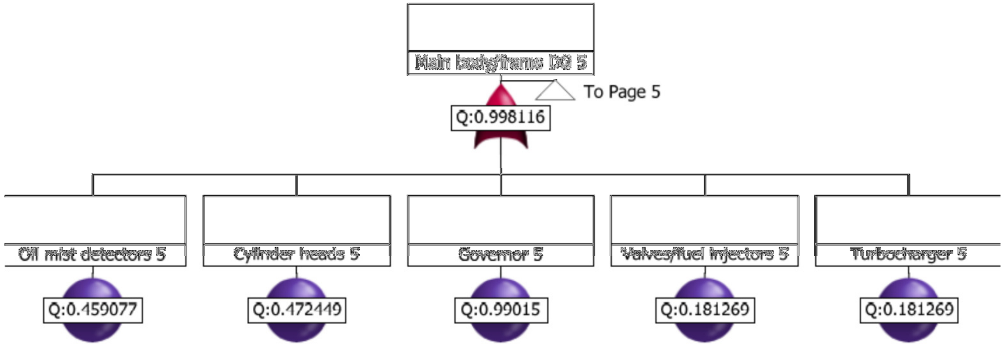


Dynamic FT structure for the miscellaneous components sub-system of DG 4

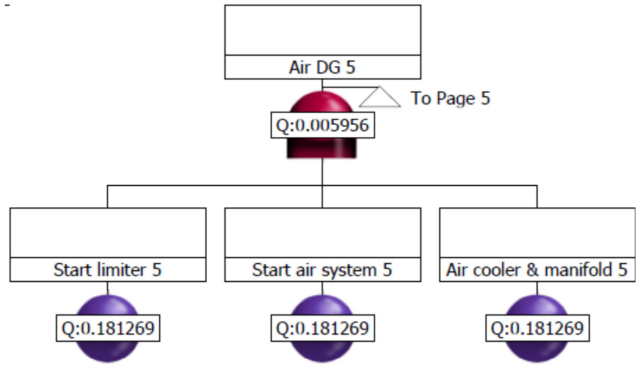
F.5 Dynamic FT structure for DG 5



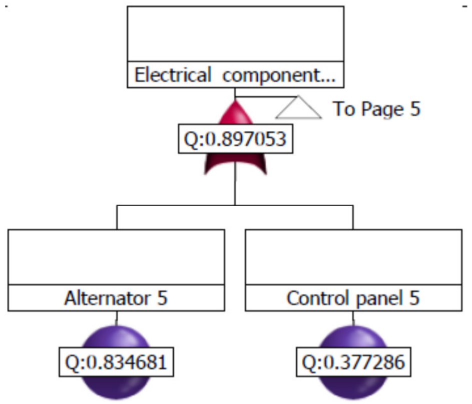
Dynamic FT structure for DG 5



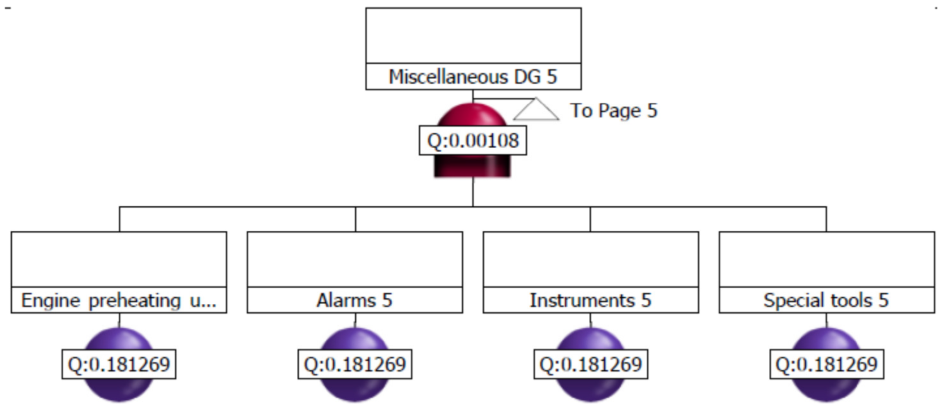
Dynamic FT structure for the main body/frame sub-system of DG 5



Dynamic FT structure for the air sub-system of DG 5

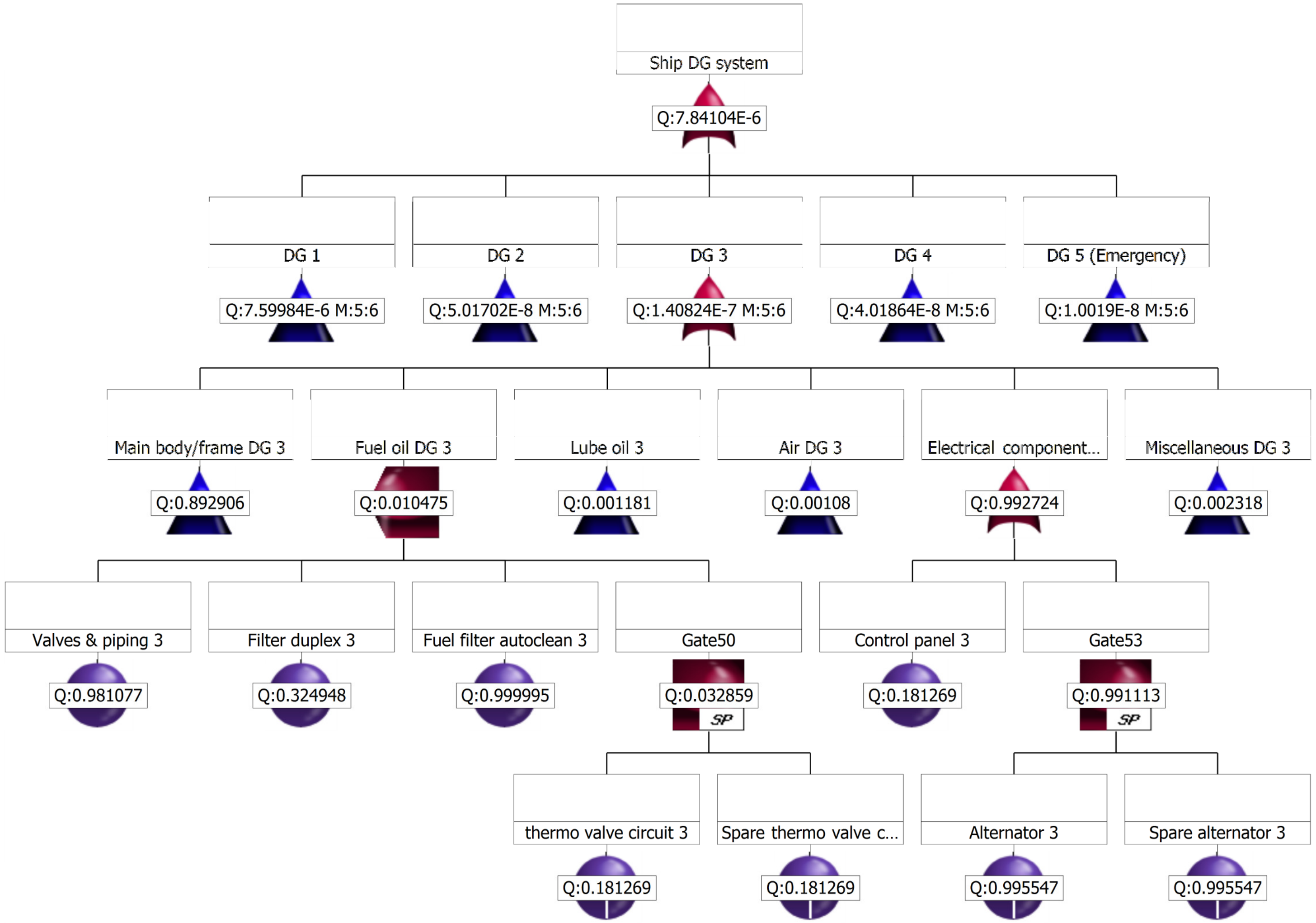


Dynamic FT structure for the electrical components sub-system of DG 5



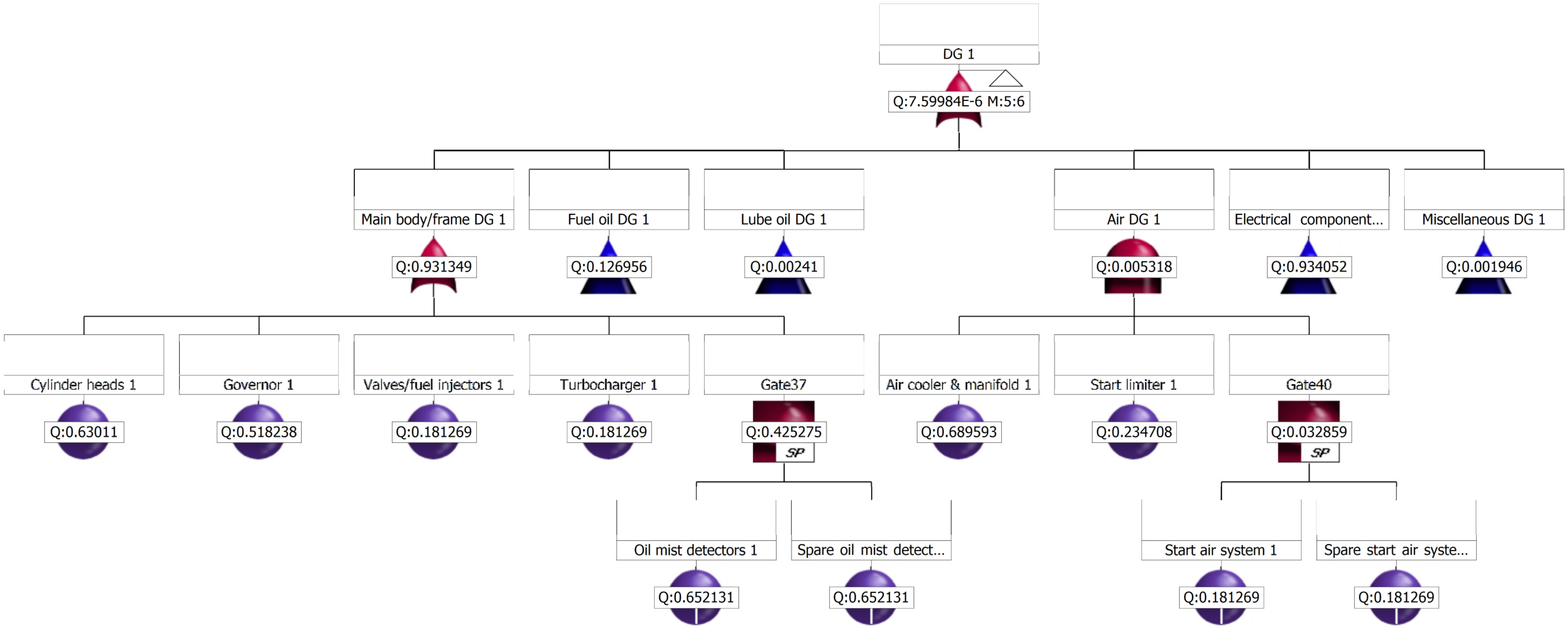
Dynamic FT structure for the miscellaneous components sub-system of DG 5

Appendix G - Dynamic Fault Tree structure of the DG system with SPARE gates

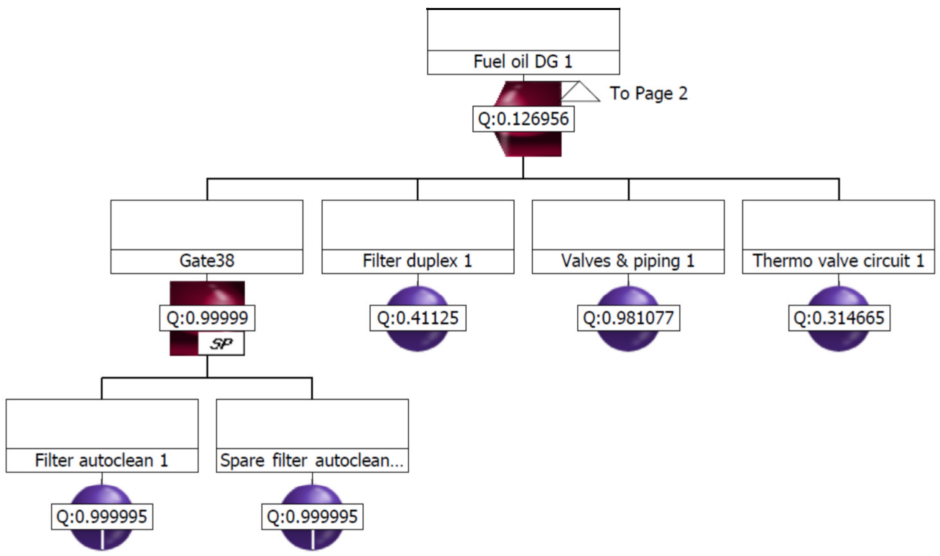


Dynamic Fault Tree structure of the DG system with SPARE gates (overall view)

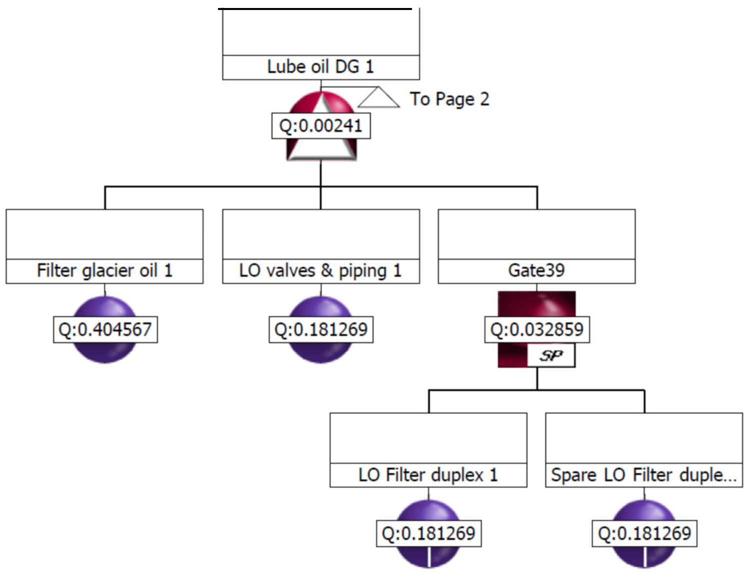
G.1 Dynamic FT structure for DG 1 with SPARE gates



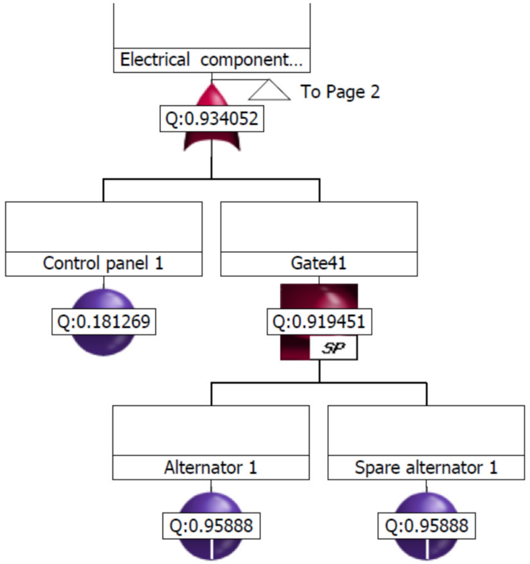
Dynamic FT structure for DG 1



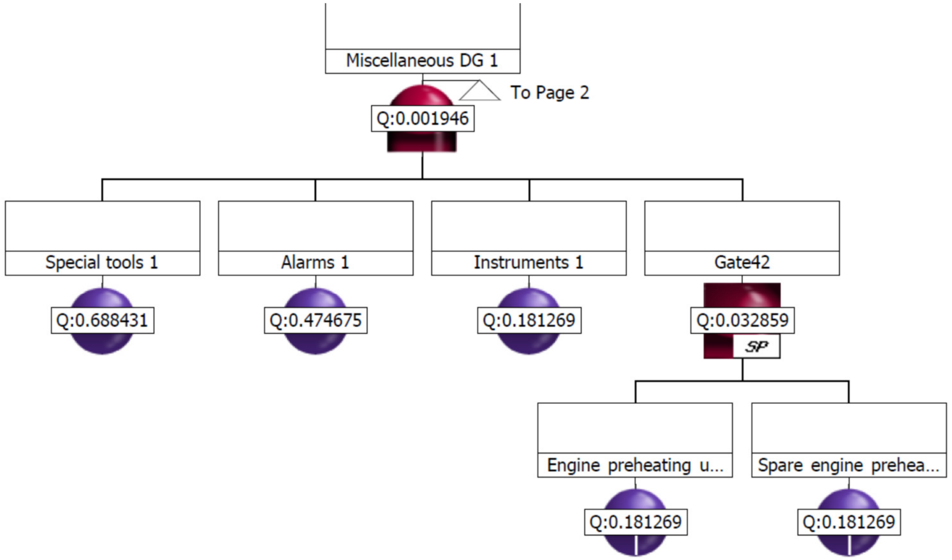
Dynamic FT structure for the fuel oil sub-system of DG 1



Dynamic FT structure for the lube oil sub-system of DG 1

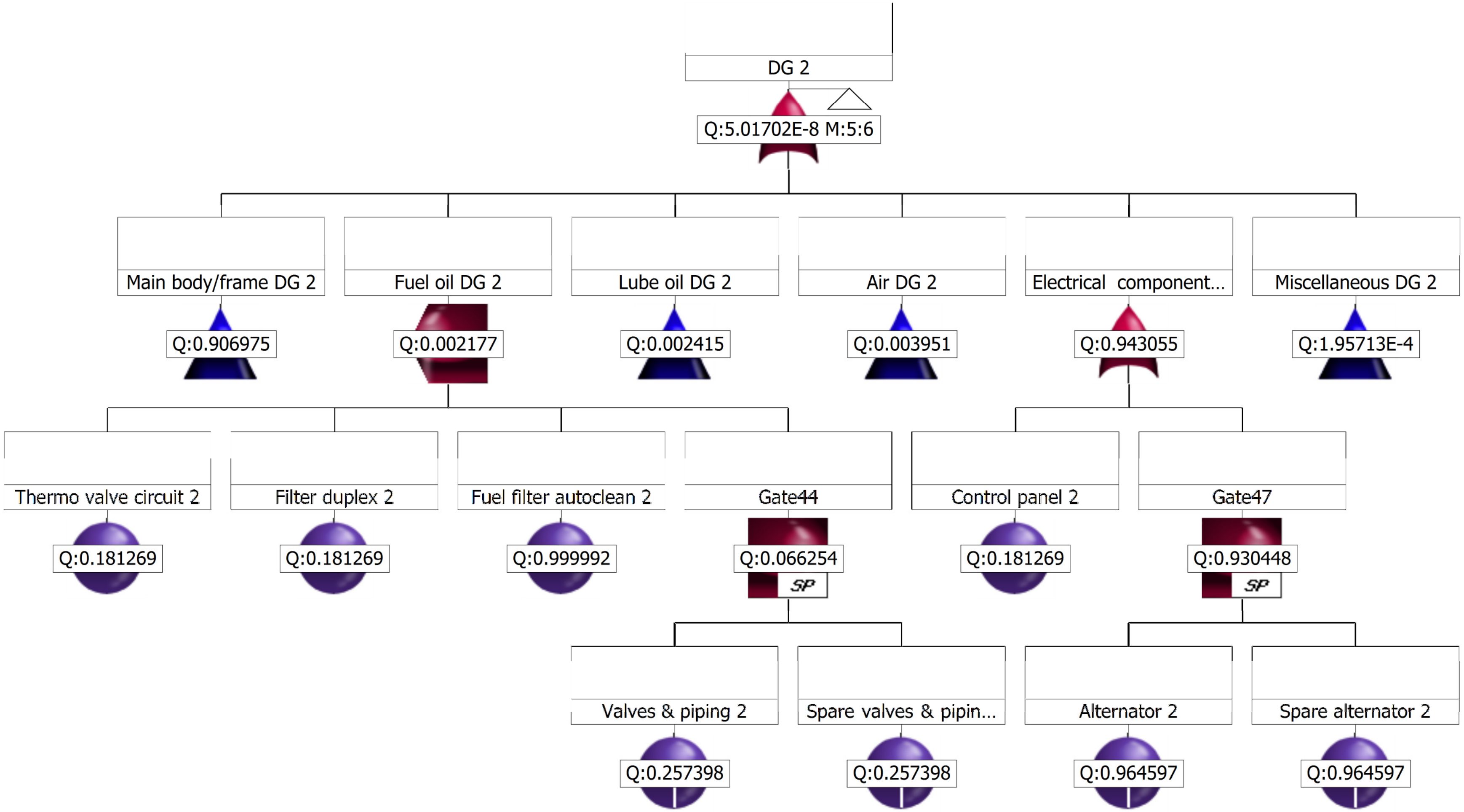


Dynamic FT structure for the electrical components sub-system of DG 1

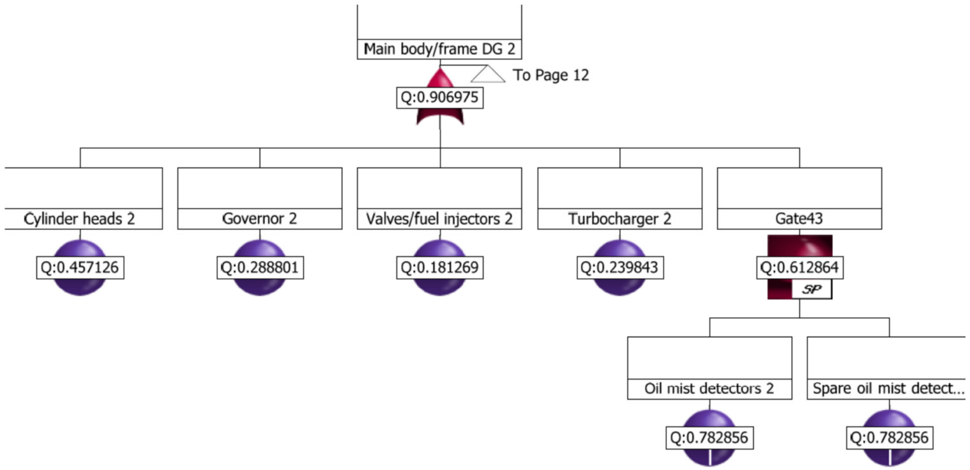


Dynamic FT structure for the miscellaneous components sub-system of DG 1

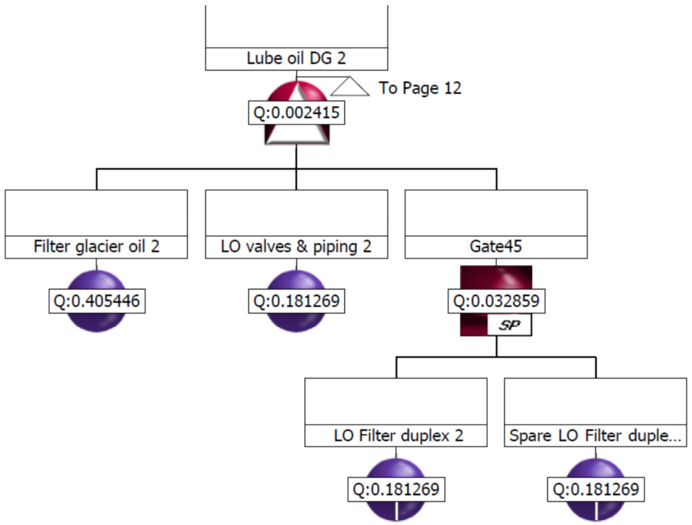
G.2 Dynamic FT structure for DG 2 with SPARE gates



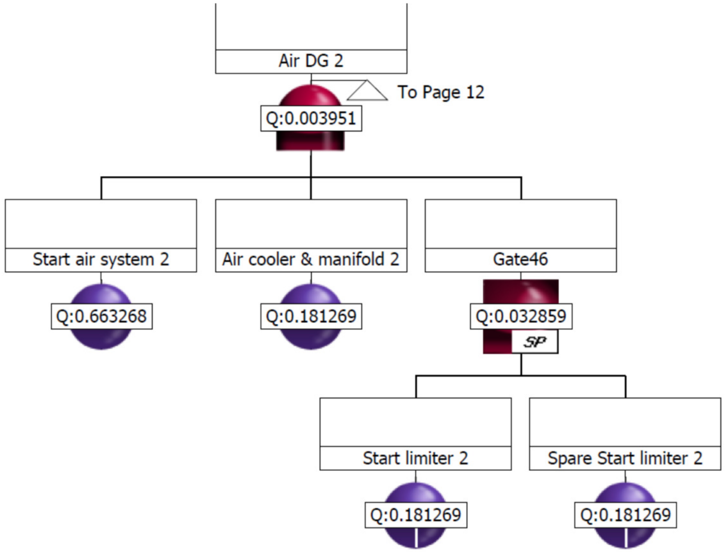
Dynamic FT structure for DG 2



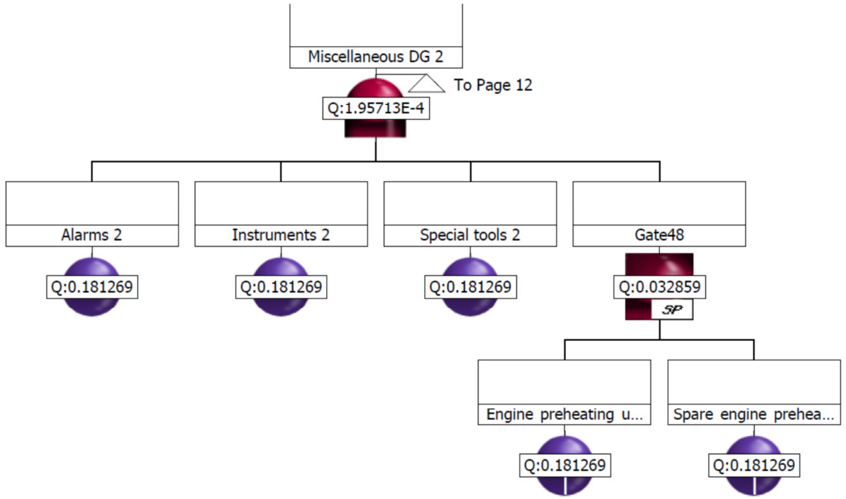
Dynamic FT structure for the main body/frame sub-system of DG 2



Dynamic FT structure for the lube oil sub-system of DG 2

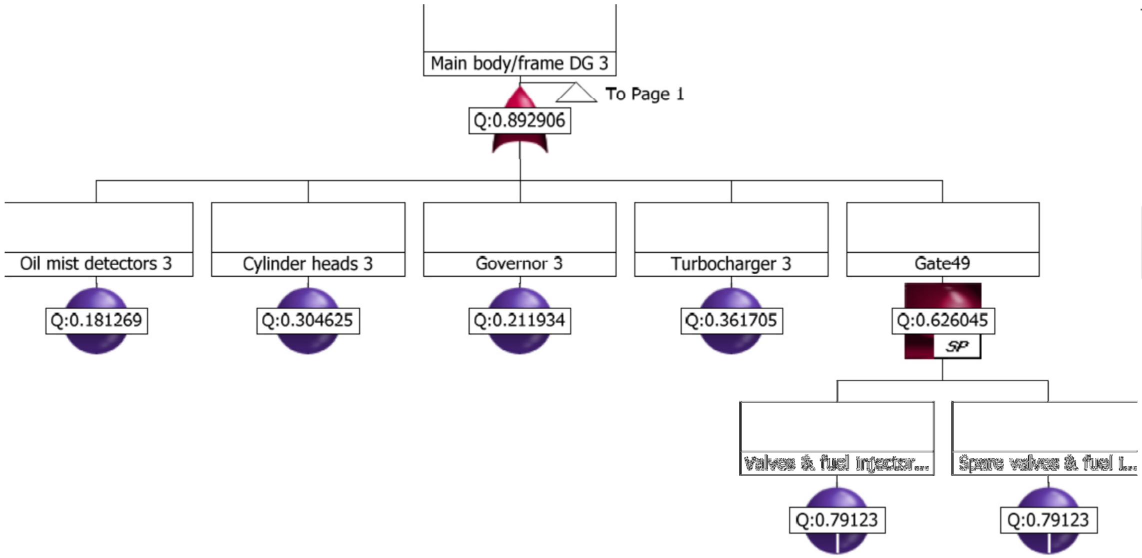


Dynamic FT structure for the air sub-system of DG 2

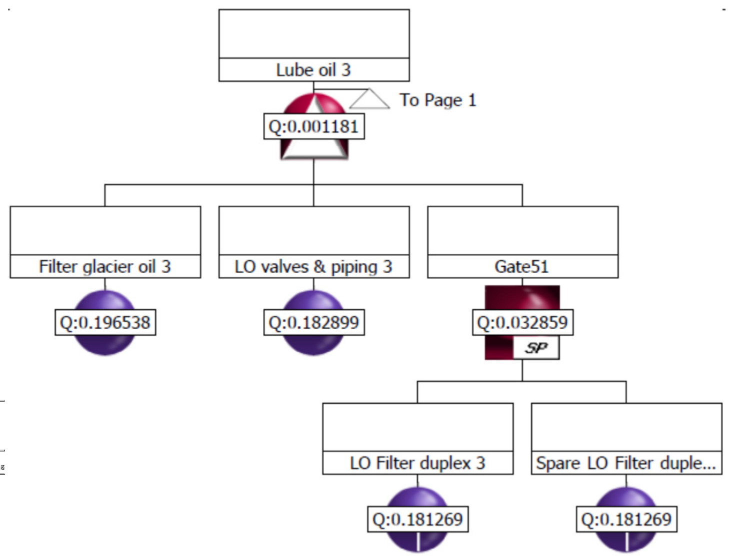


Dynamic FT structure for the miscellaneous components sub-system of DG 2

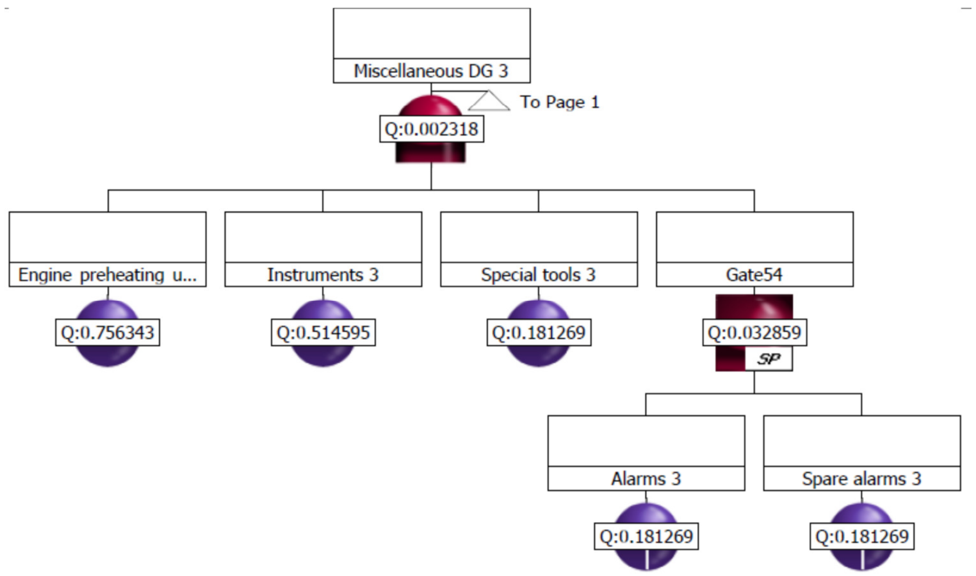
G.3 Dynamic FT structure for DG 3 with SPARE gates



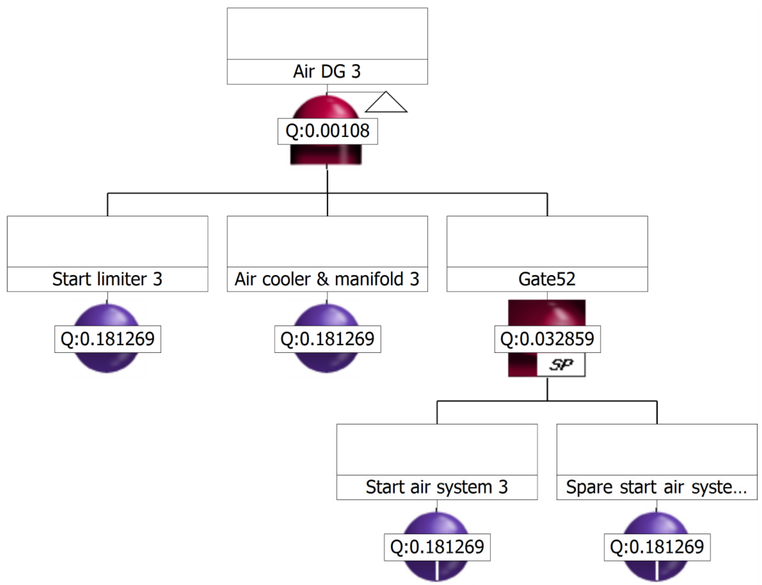
Dynamic FT structure for the main body/frame sub-system of DG 3



Dynamic FT structure for the lube oil sub-system of DG 3

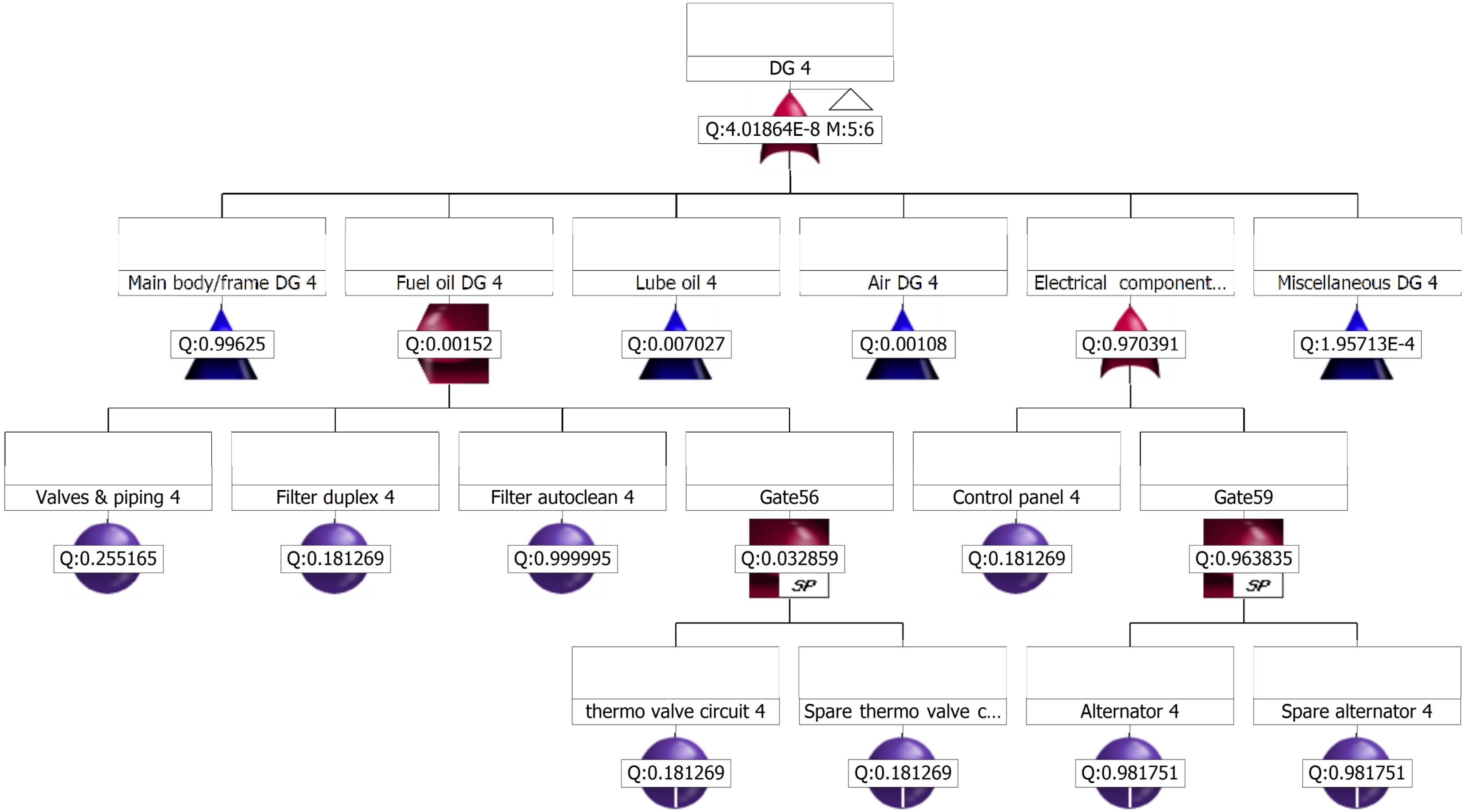


Dynamic FT structure for the miscellaneous components sub-system of DG 3

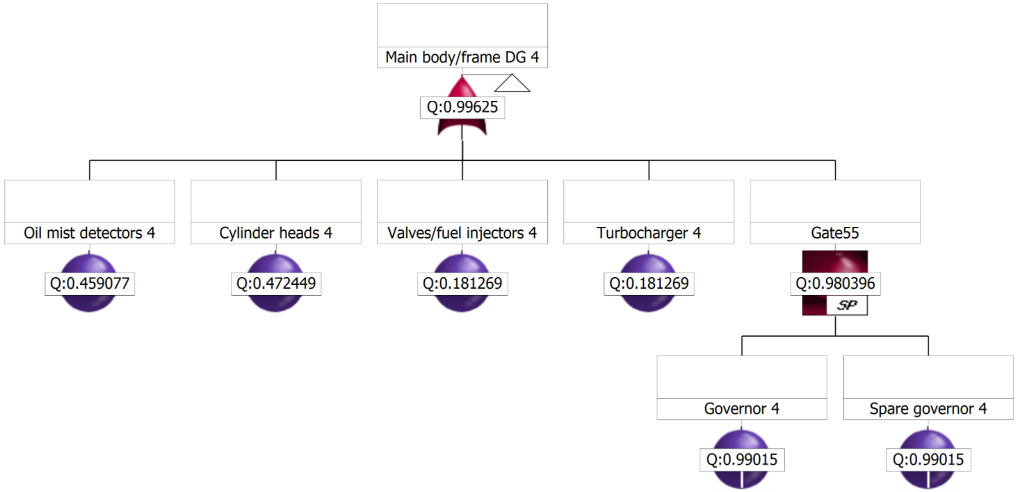


Dynamic FT structure for the air sub-system of DG 3

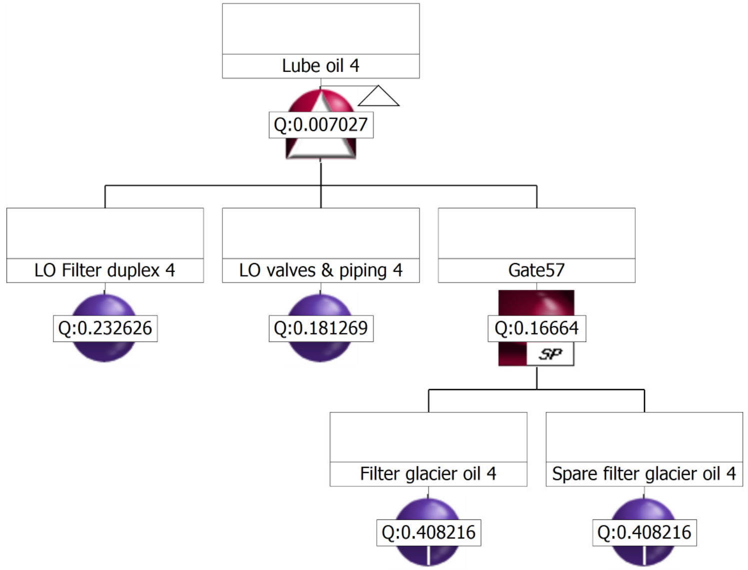
G.4 Dynamic FT structure for DG 4 with SPARE gates



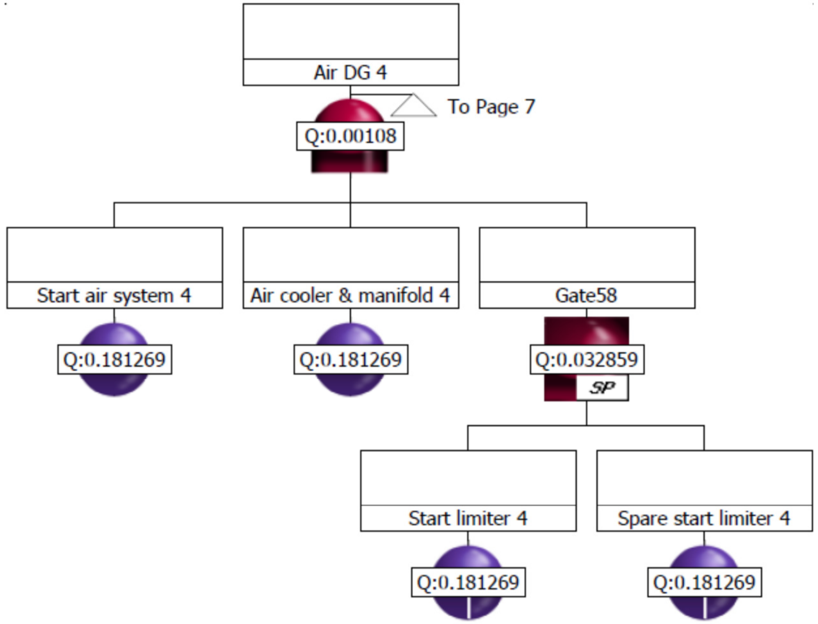
Dynamic FT structure for DG 4



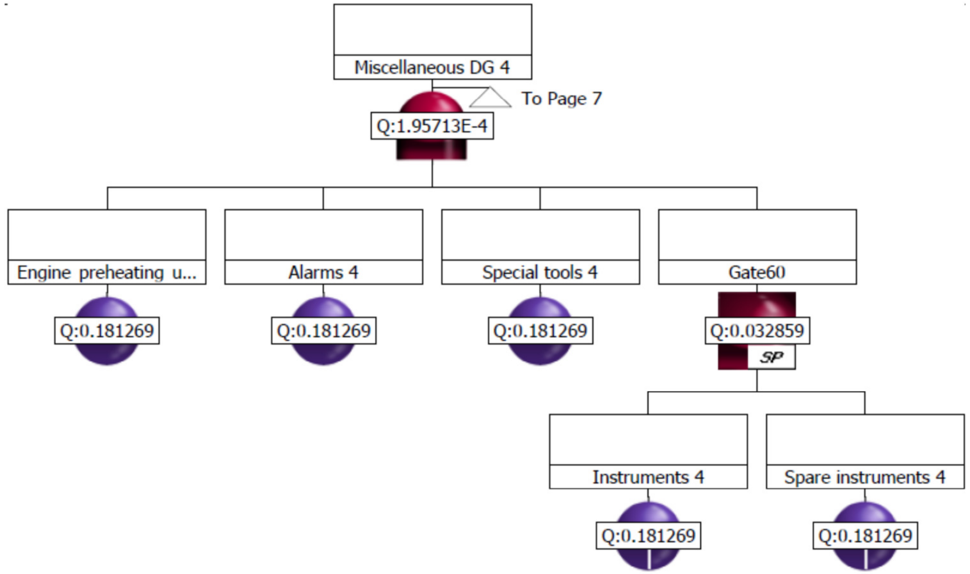
Dynamic FT structure for the main body/frame sub-system of DG 4



Dynamic FT structure for the lube oil sub-system of DG 4

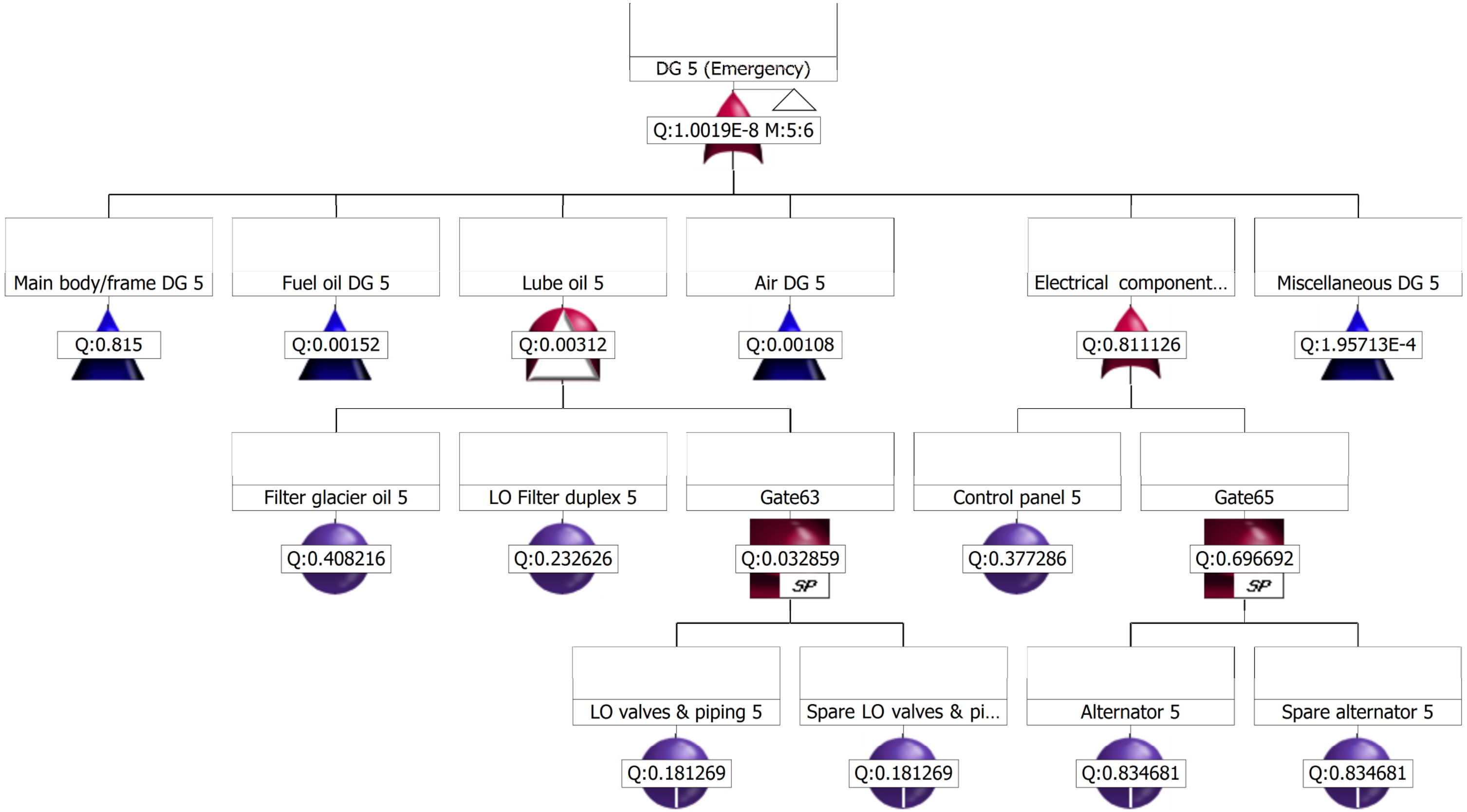


Dynamic FT structure for the main body/frame sub-system of DG 4

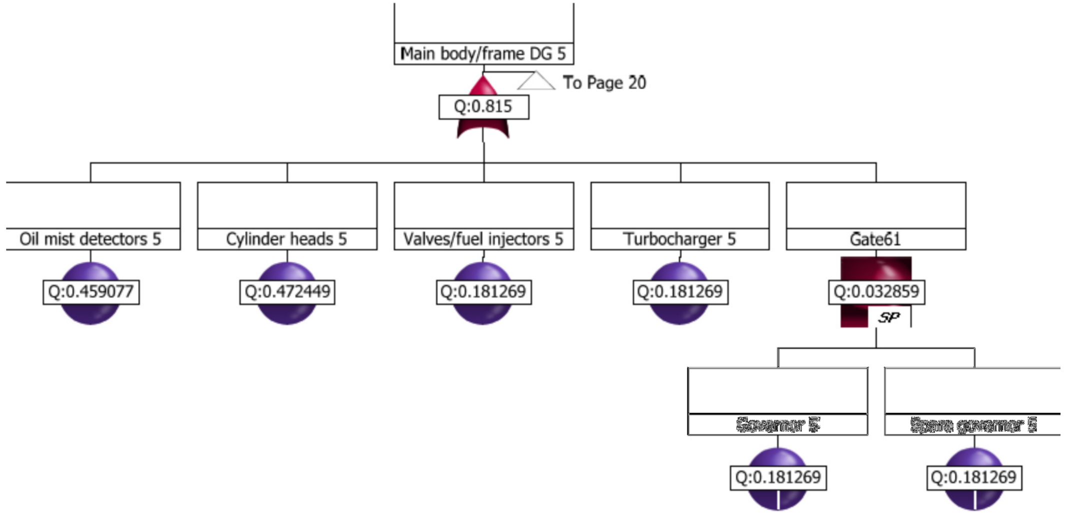


Dynamic FT structure for the lube oil sub-system of DG 4

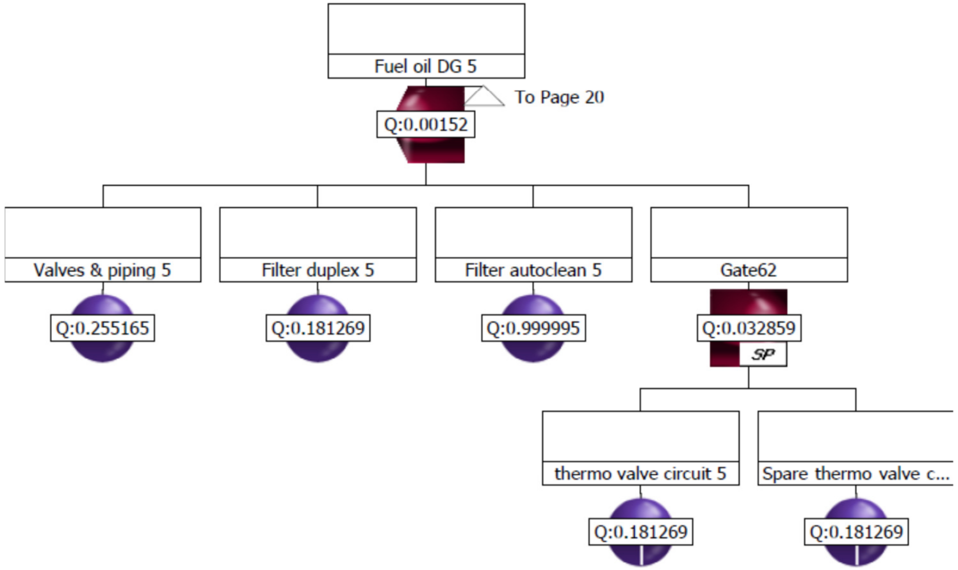
G.5 Dynamic FT structure for DG 5 with SPARE gates



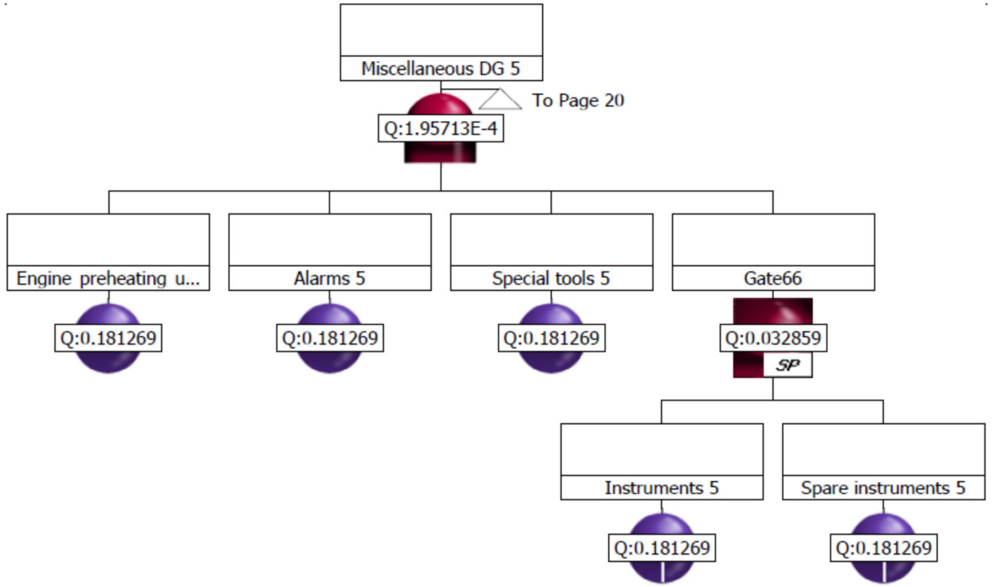
Dynamic FT structure for DG 5



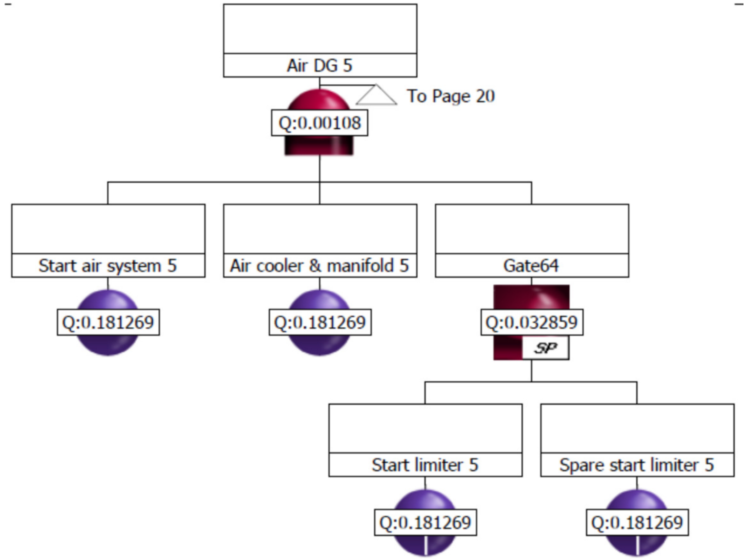
Dynamic FT structure for the main body/frame sub-system of DG 5



Dynamic FT structure for the fuel oil sub-system of DG 5



Dynamic FT structure for the miscellaneous components sub-system of DG 5



Dynamic FT structure for the air sub-system of DG 5

Appendix H - FMECA table for the overall DG system

##	Failed item	Failure event	Failure cause	Effects		Detection method	Prevention method	Severity				Frequency				Criticality				Repair time	Unavailability	Remarks
				Local	Global			S	E	A	O	S	E	A	O	S	E	A	O			
1	Oil mist detectors	blocked	No vaccum (vaccum breaks), filter chocked, faulty, valve chocked/damaged	unable to detect oil mist	stop engine, explosion	failure alarm	regular "zero setting", calibration	D	D	D	D	2	2	2	2	D2	D2	D2	D2	1hr	1.5-2 hrs	replace by spare (at least one/dg)
2	Cylinder heads 1-6	leakage, overheating	cracks, faulty exhaust valves, improper combustion	high temp alarm, smoke detection/alarm	stop engine	high pressure/temp alarms	proper monitoring of oil, exhaust & water pipes	B	B	C	C	3	3	3	3	B3	B3	C3	C3	2 hrs	3-4 hrs	proper maintenance
3	Governor	erratic function	electronic/mechanical control failure	cannot operate/malfunction load share	stop engine	frequency meter, kilowatt meter	lub oil relenish, maintain electronic circuits	A	A	C	C	3	3	3	3	A3	A3	C3	C3	2 hrs	3 hrs	
4	Valves, fuel injectors	blocked valve and/or injectors	Lack of maintenance, poor fuel quality, fuel temperature not correcct, oil leakage on valve, not proper fuel injection/combustion	Load share for relevant cylinder, insufficient oil combustion, excessive smoke	Deferential temperature of exhaust gas	High deferential temperature indicated local or at control room monitors visual inspection	Overhauling/inspection and parts replacement according to manufacturer's instructions	B	B	C	C	3	3	3	3	B3	B3	C3	C3	1/2 hr	1 hr	spare fuel injectors ready for use
5	Turbocharger	bearing failure, seizure	lack of lubrication, excessive carbon deposits, cracked blades, inlet filter ckocked, not sufficient air pressure, surging	bearing damage, turbine damage	lower output, high fuel oil consumtion	high exhaust temp, reduced efficiency, low scavenge pressure (surging)	monitorong bearings, exhaust temp, scavenge pressure & temp	A	B	C	C	3	3	3	3	A3	B3	C3	C3	6hrs	cleaning with chemicals, etc - 12-24hrs	depending on turbine condition
6	Fuel system, valves, piping	Rupture of pipe, leakage, sludges/water in the line	poor quality diesel/HFO, cat fines, sludges (MDO)	oil spillage, hot spot creation	fire in E/R, genset failure, blackout	visual, loss of power, high temp deviation	good purification, filter cleaning, fuel treatment	D	D	D	D	2	3	3	3	D2	D3	D3	D3	1/2 hr	depending on situation	
7	Fuel filter autoclean	blocked	mechanism failure	low fuel oil pressure	blackout, loss of power	differential pressure alarm	draining of water/sludges	B	B	B	B	3	3	3	3	B3	B3	B3	B3	2 hrs	2.5 hrs	autoflush mechanism in place

8	Fuel lfilter duplex	blocked	choked filter	low fuel oil pressure	blackout, loss of power	differential pressure alarm	draining of water/sludges	A	B	B	B	3	3	3	3	A3	B3	B3	B3	1 hr	1.5 hrs	manual changeover & cleaning
9	Thermostatic valve circuit	blocked	defective valve	not allowing liquid cooling	temperature control lost	temperature indication	periodical inspection	B	B	B	B	2	2	2	2	B2	B2	B2	B2	1/2 hr	1 hr	
10	L/O system valves & piping	blocked valve, burst flange connecting piping, leakage, overheating	valve defect, loose flange ,failure of gaskets or slack bolts/unions	leakage of oil and/or spray	shut down due to low pressure. Spray around, posibility for fire at high temperature surfices	visual inspection	Inspection for bolts/gaskets tightness and minor leakage. Antisplash tapes insulation for piping close to high surface temperature	C	C	C	C	2	2	2	2	C2	C2	C2	C2	1/2 hr	1 hr	depending on maintenance/repair needed
11	Filter, glacier oil	blocked	accumulation of sludge deposits	out of use	not proper cleaning	differential pressure	manual cleaning @ regular intervals	B	A	A	B	3	3	3	3	B3	A3	A3	B3	1/2 hr	1 hr	manual cleeanig of filter
12	Filter, lube oil (duplex)	blocked	choked filter	low lube oil pressure	blocked	differential pressure alarm	regular cleaning	B	A	A	B	3	3	3	3	B3	A3	A3	B3	1 hr	1.5 hrs	manual changeover & cleaning
13	Start limiter	fail to start	mechanical fault, solenoid	not opereational (on stanby position)	out of use	alarm	regular maintenance of solenoid & air system	A	A	B	B	3	3	3	3	A3	A3	B3	B3	2 hrs	3 hrs	
14	Start air system	fail to start	faulty valves or control system, low air pressure	cannot start	out of use	alarm	regular maintenance, maintain control starting air	A	A	B	B	3	3	3	3	A3	A3	B3	B3	2 hrs	3 hrs	

15	Air cooler & manifold	blocked	sea water contamination, tubes ruptured	high air temp, high exhaust temp, low power developed	higher fuel consumption (sfoc), emmissions	high temp alarm	clean cooler	A	A	B	B	3	3	3	3	A3	A3	B3	B3	3 hrs	4 hrs	
16	Alternator	cannot put on load	sparking, less cooling, airgap, insulation, bearing, alignment	high temp	system out of use	control panel indications, alarms	regular maintenance of electrical & mechanical parts	B	A	D	C	3	3	3	3	B3	A3	D3	C3	4-5 hrs	6-24 hrs	repair depending on severity of damage
17	D/G control panel	malfunctioning	high temperatures and dirtiness at electronic circuits, fan not working properly	overheating, shut down engine or failure to share load	fire on control panel	close-up visual inspection	Cleaning parts as per maker's instructions, cooling by unit's fan coolers, air filters replacement	A	A	C	C	2	2	2	2	A2	A2	C2	C2	1/2 - 1 hr	1-3 hrs	depending on specific failure cause and available spare parts
18	Engine preheating unit	cannot start, structural cracks due to thermal stress	motor pump failure, dirty jacket, no fresh water treatment	cracks, structural damage	start failure	alarm	proper water treatment	A	B	C	C	2	2	2	2	A2	B2	C2	C2	3 hrs	4 hrs	depending on jacket condition and fault (motor, jacket water, controls, etc)
19	Alarms	not operational	control failure, electrical faults	stoppage of related system	system out of use	regular tests of alarms & trips	regular tests of alarms & trips	B	A	A	B	3	3	3	3	B3	A3	A3	B3	1hr	1.5 hrs	depending on severity and number of faults
20	Instruments	unable to start	control failure (24V), electrical faults	concerned equipment out of use	automation out of use	alarms	proper maintenance	A	A	B	B	3	3	3	3	A3	A3	B3	B3	1 hr	2 hrs	depending on severity of fault
21	Special tools	broken or lost	incorrect usage	no overhaul for certain machinery eequipment	system out of use	inventory list	maintain inventory, proper use	A	A	A	B	2	2	2	2	A2	A2	A2	B2			special tools have to be ordered

Appendix I –Questionnaire used in the fuzzy set case study

Decision question: "Which maintenance approach is best to choose for the Diesel Generator (DG) system of a motor sailing cruise ship?"

A motor sailing cruise ship with a capacity of 500 passengers uses a DG system consisting of 4 DGs able to provide for the entire power needs of the vessel including propulsion, hotel needs, manoeuvrability etc. There are three types of maintenance alternatives/solutions examined in this case. These are mentioned as follows:

- Corrective (breakdown) maintenance (X_1)
- Preventive (planned) maintenance (X_2)
- Predictive (condition monitoring) maintenance (X_3)

The aim of this questionnaire is to rank all the maintenance solutions (X_1, X_2, X_3,) for all the questions provided. You are invited to fill in a table with your answers using numbers from 1-5, where **1 means very low (disagree)** and **5 very high (agree).** An indicative example is given below answering questions No. 1 and 2:

Questions	Corrective (breakdown) maintenance (X_1)	Preventive (planned) maintenance (X_2)	Predictive (condition monitoring) maintenance (X_3)
1	1	3	3
2	5	4	2

Questions

1. Which type of maintenance approach/action do you think will be more costly over a period of 5 years?

2. Which type of maintenance approach is more efficient?

3. Which type of maintenance approach do you think contributes more to the reliability of the same DG system?

4. For which type of maintenance approach do you think top management commitment is necessary more?

5. For which type of maintenance approach do you think that crew training is needed more?

6. For which type of maintenance approach do you think that company investment is needed more / should be towards to (human/technical/financial)?

7. For which type of maintenance approach do you think spare parts inventory lists are needed more?

8. Which type of maintenance approach do you think contributes less to the loss of operation income of the vessel (fewer working days)?

Questions	**Corrective (breakdown) maintenance (X_1)**	**Preventive (planned) maintenance (X_2)**	**Predictive (condition monitoring) maintenance (X_3)**
1			
2			
3			
4			
5			
6			
7			
8			