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Research paper

Measuring Severity of Downtime Influence Factors to Naval Ship Operational Availability: A Delphi Study

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Abstract

Rapid development of shipbuilding and ship repair industry in recent years has been increasingly transforming the way organizations apply the long term strategic thinking of “cradle to grave” maintenance approach in order to maximize their growth in a dynamic marine industry. With increased ship complexity, size and revolutionary design, organizations strive to balance ideal maintenance philosophies against on-going efforts of cost reduction whilst maintaining high availability of vessels. Despite aspiration and efforts to improve the ship availability, the Royal Malaysian Navy [RMN] vessels which are currently maintained under the In Service Support [ISS] Contracts are hardly tackling the human and equipment related aspects due to limited knowledge and available data on ship Downtime Influence Factors [DIFs]. The current research carried out an explorative study across various engineering disciplines to generate RMN ship maintenance DIFs and their severity measures via a 3-Stage Modified Delphi approach. 30 Experts experienced in daily implementation of naval ship maintenance contracts were involved. In the first stage, Focus Group Discussions [FGDs] amongst Experts were conducted to produce the DIFs, followed by questionnaire distribution to measure the severity of the DIFs in the second stage. In the third stage, the Severe DIFs were confirmed and ranked based on a Risk Assessment method. The study revealed 50 DIFs to RMN ship availability and deduced the top 15 Severe DIFs pinpointing the key problem areas to prioritize efforts in improving RMN ship availability.

***Keywords**: Naval vessels; navy ship maintenance; operational availability; Downtime Influence Factors [DIFs]; Delphi method.*

1. Introduction

In contrast to merchant vessels, navy ships which naturally possess different functions, complex design characteristics [1] and concept of operations, are equipped with a vastly different range of equipment and systems onboard to suit its battle and combat management capabilities. A modern naval vessel or warship/ submarine would consist of in excess of 100 integrated systems that are linked structurally, mechanically, electrically, hydraulically, pneumatically and electronically [2]; thus warships/submarines may be viewed as a system of systems [3]. All of these systems need power and cooling, and many need to communicate with each other in order to achieve full operational capability [2]. Consequently, the naval ship operational availability turns into a complex problem [4]. Improving any asset’s operational availability undoubtedly further complicates the problem due to a long list of interconnected contributing factors [5], where ambiguities and uncertainties involving human and equipment factors appear with unclear significance and unknown weightage.

Following [6] and [7], availability is defined as the probability that the ship is available and capable of performing the intended function at any random point in time. Availability which is also commonly known as ‘Uptime’ can be formulated as *one minus Downtime* [8] or known as *Unavailability*, with the resulting mathematically implication that the more the unavailability or ‘Downtime’, the lesser the availability yielded. Ship operational availability is also described as the number of days the warships are available for operational tasking in a year [9].

To date, no literature attempted to consolidate human and equipment related factors in the ships study, which is probably due to complexity or absence of the ‘combined factors’ from other field of studies. The most recent and closest research to navy ships availability was conducted by [4] who in regards of Italian navy highlighted that navy ships operational availability requires a more innovative and comprehensive approach in design as well as support. It was emphasized that operational availability is the key process for design of warships supportability and support systems as well as measurement, improvement and optimization of the ships and support systems during In-Service phase. The In-Service phase of a naval vessel will typically constitute 70% of the vessel’s through-life cost [3] over its life cycle, therefore it is a significant area of research for efforts in optimization.

As opposed to the current trend of ‘availability-based contract’ in UK [10] and Australia [11], implementation of the In Service Support [ISS] Contracts in Malaysia remains based on ‘execution upon receipt of order only’ philosophy or commonly known as per-order basis. Decision on the maintenance services, training and procurement of spares including scheduling of works rely on Royal Malaysian Navy [RMN] directives, resulting in contractors having limited chance in achieving targeted availability figures. As such, since the contract itself is not designed for optimization efforts, improvement efforts on increasing ship operational availability rests mostly with RMN as the customer. Despite continuous improvement efforts and the implementation of three separate In Service Support contracts on RMN ships, each over a period of three years, the RMN aspires to improve the operational availability these vessels. Due to limited research on Downtime Influence Factors [DIFs] on ships, improvement efforts could not be allocated precisely in tackling issues involving combined “human and equipment” aspects impacting ship availability. Therefore, the purpose of this study is to generate RMN ship maintenance DIFs and their severity measures via eliciting expert opinions.

Other researchers have similarly used expert opinions to study maintenance downtime distribution which reflects availability of systems [12]. The author argues that expert opinions are necessary due to the fact that in many cases, the historical data or equipment downtime are limited and in poor quality therefore making them inappropriate for use in modeling. The application of expert opinion has been found in various studies covering a wide spectrum of discipline such as chemical, nuclear, health, aerospace and banking industries [13]. Considering some highlights revealed by [14] where Delphi method is best suited for researches of an institution backed with no previous history or a very complex phenomenon truly requires experts, the current research employed 3-Stage Mixed Method Modified Delphi approach to generate and measure the severity of DIFs to RMN ships operational availability.

2. Literature review

2.1. Navy Ship Availability

In general, there have been several previous studies on availability of equipment and systems from various disciplines, most of which were done on a component or equipment basis. In a way that most of the studies were carried out similar to the ‘factorization method’ [15]; divide problems, tasks and functions into sub problems, subtasks and sub functions and solve individually. Mostly, past researchers focused on a selected area of study only such as spares assessment and conclude the study by creating a link to the end but refrain from consolidating all solutions for a complete solution which is absolutely the most difficult objective while implying that any proven improvement would result in an obvious improvement to the ship availability indirectly. Whilst the solutions for the sub problems, subtasks and sub functions have to be combined to arrive at one common solution once they achieved, [15] reiterated that selection of the most technically and economically favourable combinations of principles from a large field of theoretically possible combinations is also a problem.

However, examining availability of a complex asset made up of several systems and equipment which run in series and parallel is far more complicated than studying on single component or equipment basis. For complex systems, arriving at a list of critical component may become more cumbersome due to potential time-varying load profile or internal components redundancies [16]. As a result, very limited studies on availability of complex assets or sophisticated systems have been conducted. Nevertheless, several researchers have studied a selected portion of the system [17], availability prediction [18], conceptual and optimization models [4, 19, 20], improvement of availability by improving scheduling [4, 21] and avoiding scheduling conflicts [22-24], promotion of a “design for availability” approach [25, 26] and even provision of various methods in calculating the availabilities [4].

Many navies around the globe face the same challenges of achieving high asset availability, albeit the situation is aggravated due to the complex nature of warships [27]. Modern navies such as Italian and French Navy [4], United States Navy [28], Royal Malaysian Navy [29] and Korean Navy [30], have specified targeted operational availability targets, but it is interesting to note that availability is still a problem even in the United States Navy [28] even lately. Any effort resulting in an increase of ship operational availability is commendable [31]. A Ship is a reliable performer when it has a lower annual downtime [32] therefore availability of the naval warship is a mark of its reliability. In fact, one of the measure of reliability of repairable systems is availability [33]. To present an indicative value of the losses due to downtime, [32] described that for a ship valued at $500M and a 30 year target service life, the navy loses approximately $50K/day if the ship is not able to operate.

The most recent and interesting study of naval ship availability was performed by [4] entitled *Operational Availability [Ao] of Warships – A complex problem from concept to in service phase*. The author attempted to initiate more studies on naval ship availability by introducing to the world that warships are complex and availability studies on warships would require encapsulation of all factors from concept to In-Service phase. It was highlighted that there is a need of a new design approach based on Operational Availability [Ao] of warships and associated support system in order to achieve best balance between Ao and Life Cycle Cost [LCC] along the whole operative life. Figure 1 displayed an example of Life Cycle Cost [LCC] Tree disclosed by the author.

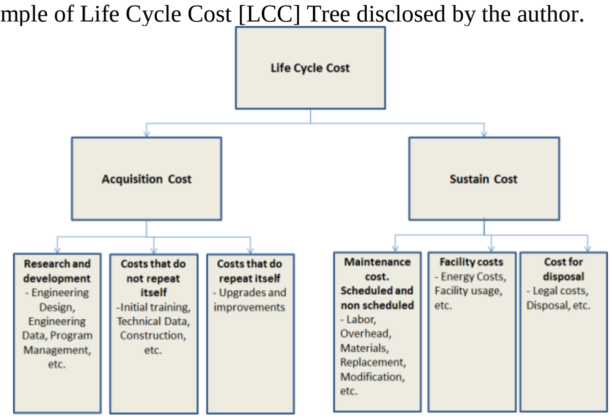

Fig. 1: The Life Cycle Cost [LCC] Tree [34]

Availability is also a measure of maintenance performance [35]. Maintenance productivity aims at minimizing the maintenance cost dealing with the measurement of overall maintenance results, maintenance and maximizing the overall maintenance performance. Control of maintenance productivity [MP] ensures that the budgeted levels of maintenance efforts are being sustained and that required plant output is achieved [36]. Maintenance productivity deals with both maintenance effectiveness and efficiency [35], therefore availability is also closely related to both. The sole objective of the maintainability engineer is to reduce downtime [37], therefore to increase uptime or maximizing availability.

Due to issues of achieving high availability targets as expected by some customers, nowadays providers of complex engineered equipment are often encouraged to offer outcome or availability-based contracts or performance-based contract [PBC], where the provider guarantees the uptime and availability of the product [16, 38-40]. This is to avoid or reduce the risks as faced by customers, such as in the process industry, whereby machine downtime in the shop floor is one of the main issues for maintenance productivity[35]. Maintenance activities are mostly non repetitive in nature, resulting in all maintenance personnel and managers facing new problems with each breakdown or downtime of plants or systems. Due to the conflicting multi-objectives issues, multi-skill levels are needed [35] and retention of these special skills is also a common problem in maintenance [5, 11, 41-43].

3. Methodology

3.1. The Delphi Study

It is well agreed among researchers that Delphi method is preferred as a research instrument for incomplete knowledge about a problem or phenomenon [44-47] or in the case of limited experts in the field are available [44, 48]. [49] emphasized that the method is appropriate for researching complex issues where larger scale quantitative hard data fail to unearth richness in tacit knowledge to help the research understand subtle expert opinion. The scientific methodology provided by the Delphi is well-suited to issues that require the insights of subject matter experts.

Whilst Delphi method is generally used with the aim of obtaining the most reliable group opinion [45], it is also useful for structuring a group communication process so that the process is effective in allowing a group of individuals, as a whole, to deal with the complex problem [50]. The method works especially well when the goal is to improve the understanding of problems, opportunities, solutions or to develop forecasts [44]. It is continuing to be a much used tool in the search for answers to normative questions [51] such as policy making [45].

With wide areas of implementation, the process of Delphi is normally the same [52]. Theoretically, the process can be continuously iterated until the consensus achieved [53]. However, while [54] suggested that a 2 or 3 iterations or stages, [55-57] and [58] pointed out that 3 iterations are often sufficient to collect needed information and reach a consensus in most cases. Further, [59] added that the responses on the final iteration usually show less spread in comparison to spreads in earlier iterations and median values are commonly taken as the best estimates for the issues.

On the implementation and enhancement of the Delphi method, various studies provided further details. Exclusively, [60] presented a framework for conducting the necessary Delphi research and how to enhance the usage of the Method including improving expert recruitment via snowballing and other methods of retention over Delphi rounds. Specifically, [61] recommended guidance and advice on sampling size for qualitative interviews based on a set of succinct “expert voice” contributions stating that saturation is central to qualitative sampling depending on the methodological and epistemological perspective. Meanwhile, [62] advised sample pool sizes and a mean of 30 though later confirmed that the best answer is simply to gather data until empirical saturation has reached since some qualitative researchers argued that as little as one expert opinion can add value to the area of research.

Among various issues based on cost, time and resources available considered in preferring the Delphi approach are outlined as follows:

i. Identification of factors affecting the downtime and therefore naval ships availability have not been itemized previously due to the complexity while identification of the most critical factors requires a Risk Analysis
ii. Limitation of current literatures relevant to availability of naval vessels encouraged the need for rich data collection hence allows the understanding of the stakeholder’s experiences as well as requirements
iii. Requirement in addressing the presence of ‘objective’ and ‘subjective’ data as it spans across equipment/system and human related issues
iv. Limitation in the number of people who have access to ISS contract, knowledgeable and experienced in dealing directly with the implementation of ISS in Malaysia
v. Requirement on end result presentation as an availability-oriented contract management model
vi. Various roles of participants/experts, nature of expertise, expert recruitment and retention over during the study

3.2. Mixed Method Modified Delphi Approach

The main component of the current research approach is the Delphi method. To strengthen the study, other methods are integrated appropriately at various stages of the Delphi study including Focus Group Discussion [FGD] and qualitative Risk Analysis method. The FGD served as initial expert validation of the DIFs identified via literature study, followed by two rounds of Delphi to re confirm the DIFs impact on ship availability and the severity of these DIFs. Figure 2 contains a diagrammatic representation of the method of identifying key variables.

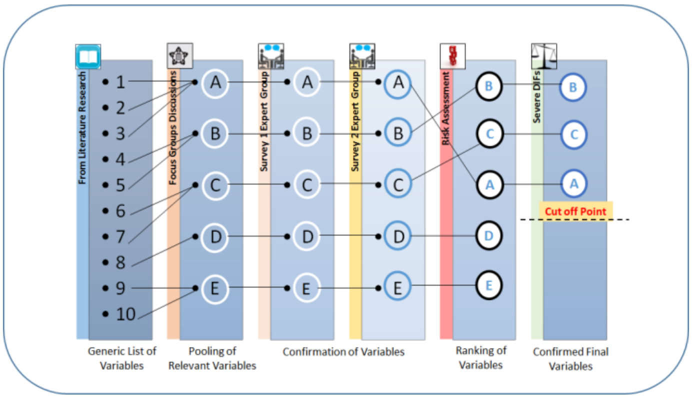

Fig. 2: Method of Identifying Key Variables

3.3. Identification of Research Variable

Identification of the current research variables commenced from a detailed literature review concerning down time elements that affect the availability of naval vessels and downtime of equipment and systems from various fields of research. All pertinent information relevant to the scope of the current ISS Contract and other data from various stakeholders relevant to the study were gathered as well. A generic list of variables namely Downtime Influence Factors [DIFs] comprised of close to 100 variables were compiled and pooled in groups as the initial reference and basis of the study.

3.4. Stage 1 – Focus Group Discussion

Addressing the first stage of the Modified Delphi approach, a Focus Group Discussion [FGD] by Expert group was designed to confirm and screen the identified variables into relevant terms with more manageable numbers. Consolidations of different interpretations, cross-referring of various definitions as well as pooling similar variables into agreed categories were carefully executed during the session. 30 Expert members who were working directly on ISS Contract and other relevant organizations with adequate working experience and/ or knowledge in the ship maintenance area from contractor and the customer’s organizations were selected to populate the variables based on their knowledge and experience. Table 1 and Table 2 listed the Expert members’ details based on years of working experience and job positions/designations.

Table 1: Working experience of the Expert members

Years	Percentage
0-5	5%
6-10	30%
11-20	30%
>20	35%

Table2: Job position/designation of the Expert members

Designation	Number
Technical Executive	6
Senior Technical Executive	9
Supervisor	1
Senior Supervisor	2
Assistant Manager	1
Manager	3
Project Manager	1
Head of Division	3
Commanding Officer Navy Ships	3
Senior Navy Engineer and Contract Manager	1
Total	**30**

3.5. Stage 2 – Delphi Round 1

The next stage was the development of questionnaire for the usage in the Mixed Method Modified Delphi study employed by the current research. The questionnaire is constructed in structured questions which consisted of closed, dichotomous questions and Likert Scales. The questions which contained the 50 DIFs produced by the FGD were brought forward to the next stage for further identification by the Expert group.

Taking advantage of the 50 DIFs identified in the FGD, each Expert member was asked to select the DIFs that have impact on ship availability via Risk Assessment method. Qualitatively, risk is proportional to the expected losses that can be induced by a certain accident and to the likelihood of an occurrence. Greater loss and greater likelihood result in an increased overall risk [63]. In engineering, the definition of risk is:

RISK = [Probability of Incident/Accident] x [Losses per Incident/Accident] [63]

According to [63], the probability and impact matrix illustrates a risk rating assignment for individual risk factors. It shows the combination of impact and probability that in turn yields a risk rank or risk priority. Risk ranking is based on a matrix whose axes are the ranks of consequences and probabilities [63]. The likelihood of occurrence and consequences of scenarios as the result of their pairing is referred to as a Risk Assessment Matrix. Typical Risk Assessment Matrices vary with organizations, however [63] concludes that the most common type of matrices contain 3x3, 4x4, 5x5, 5x4 and 6x4 likelihood and consequences categorizations.

The NASA had used Risk Assessment Matrices to avoid the problem of managers treating the values of probability and risk as absolute judgments, whilst the US Department of Defense offers the use of risk assessment matrices as a tool to prioritize risk as cited in [64]. Based on [64], both the levels of occurrence and consequences may be based on expert-opinion elicitation.

The best suited Risk Assessment Matrix for the study was as a 5x5 Matrix, with a five points Likert Scale on the impact of the DIFs onto the ship availability for the ISS Contract and five degrees of DIFs probability occur throughout the contract duration employed for the rating as summarized in Table 3 are inquired for each DIF selected.

Table 3: Rating of DIFs severity

Rating	Likert Scale of DIF Impact	Degree of Probability of DIF occurrence
5	Extreme	Almost Certain
4	High	Likely
3	Medium	Possible
2	Low	Unlikely
1	Negligible	Rare

A risk analysis is executed to ascertain the severity of each DIF using a cut-off point which is defined as product of the impact scale and its degree of occurrence. Based on the given rating, a 4x4 cut-off point is employed in defining the severity of the DIFs. Hence, a DIF has to totally value at least 16 or possesses “High” impact and “Likely” probability of occurrence to be considered as important by labeled as “Severe” and remain to be evaluated in later stages. Consequently, any results below 16 in total or combinations of “Medium” or lower impact and “Possible” or lower occurrence were considered as “Not Severe” and taken out from further evaluation. Quantitative Analysis of the standard statistical software tool SPSS was employed to summarize and analyze the collected data and results are validated in subsequent stages.

3.6. Stage 2 – Delphi Round 2

In Delphi Round 2, Expert members were required to reassess the DIF ratings in the light of the consolidated results previously obtained. New questionnaires similar to previous ones were issued for feedback. The subsequent processes of computing DIFs severity and performing risk analysis are similar to Stage 2 – Delphi Round 1.

Further computation to compare results from Delphi Round 2 and previous results from Delphi Round 1 was performed by exploiting a coefficient of variation [CV]. Parametric statistical methods such as the CV and F-test have been used in Delphi studies with samples below 50 as stated in [65] . The CV which defines ratio of standard deviation [SD] of a competency area to its corresponding means [AVG] among the Expert members was formulated as:

$$CV = \frac{SD}{AVG} \qquad [1]$$

Accordingly, an absolute difference was calculated by subtracting the CV of the current and previous stage. A small CV value would indicate that the data scatter or data variation compared to the mean is small and vice versa.

4. Results and findings

4.1. Results Stage 1 – FGD

50 groups of DIFs that impact ship availability was agreed by Expert members via FGD were generated as tabulated in Table 4.

Table 4: The 50 groups of DIFs agreed by expert group via FGD

No	DIFs for Ship Operational Availability	No	DIFs for Ship Operational Availability
1	Equipment and Systems – Hull and Design	28	Morale & Attitude of Contractor involved in Maintenance
2	Equipment and Systems – Main Propulsion		
3	Equipment and Systems – Electrical	29	Efficiency of Processes, Procedures and reporting structure include Finance
4	Equipment and Systems – Weapon Systems including guns and missiles	30	Ship Operational/sailing schedule
5	Equipment and Systems – Auxiliaries	31	Non-Commonality of Equipment issues
6	Equipment and Systems – Outfitting	32	Non Redundancy of Equipment
7	Maintenance Policy - Priority on Type of Maintenance	33	High Turnover of maintenance supervisors.
		34	High Turnover of maintainers
8	Awareness of Importance of Maintenance / Attitude – including hiding problems from becoming official.	35	Different location of ships
		36	Statutory requirements
		37	Cashflow Shortages
9	Maintenance Budget Allocation	38	Government Requirements and Policies [i.e. EEP[*2], Offset etc.],
10	Information Management		
11	Preventive Maintenance	39	Variation Order and Contract Change
12	Corrective Maintenance	40	Ageing of Equipment [Aging]
13	Predictive Maintenance	41	Force Majeure
14	Emergency Repair & Docking	42	Accidents & Hazards
15	Equipment Technology / System Complexity	43	Extraordinary Price Escalations [Spares, Consumables, Equipment]
16	Scheduling Issues	44	Pilferage, Theft & Fraud & Cheat
17	Maintenance of Special Tools, Test Equipment	45	OLM, ILM, DLM[*3] - Overlap of maintenance duties [contractual] and impact if not performed
18	Availability of Facilities	46	Contract Management across a wide range of stakeholders with conflicting interests
19	Spares Availability		
20	Obsolescence Issues	47	Impact of Parallel Contracts to Schedule, Genuinity of Spares, Professionalism of Repair Team etc.
21	Design and Design Change Issues		
22	Knowledge Management incl Training, Knowledge and Skills	48	Supporting of the Vessel outside of home ports [e.g. issue on mob, availability of materials etc.]
23	Availability of OEM[*1] Expert Support		
24	Availability of Local vendor support	49	Exogenous factors [i.e. company profit margin, administrative costs, peripheral costs, support cost]
25	Complexity and efficiency of existing contract		

26	Capability of Customer performing Maintenance	50	Exogenous factors - Contract Concept [Total Maintenance Package against segregated orders without interrelationships] and based on recommendations

Abbreviations: [*1] OEM: Original Equipment Manufacturer, [*2]EEP Economic Enhancement Programme, [*3] OLM [Operational Level Maintenance], ILM [Intermediate Level Maintenance], DLM [Depot Level Maintenance] [29]

While the FGD served as expert validation of the generic DIFs identified by literature study, no further consensus concerning the 50 agreed DIFs was yielded. The 1st Stage of Delphi was therefore designed to build the consensus among the 30 Expert members regarding the importance of each DIF towards the ship availability.

4.2. Results Stage 2 – Delphi Round 1

Consensus among the expert group members regarding the importance of each of the 50 DIF was achieved. Based on the Risk Analysis, a DIF with a total value or median of 16 was defined as "Severe" and considered as important. Table 5 displayed the Severe DIFs ranking from most severe [Rank 1] to least severe [Rank 15].

Table 5: Severe DIFs to ship availability

Severe DIF	Count	Mean	Median	Mode	Rank
Corrective Maintenance	30	24.20	25.00	25.00	1
Spares Availability	30	22.90	25.00	25.00	2
Impact of Parallel Contracts to Schedule, Genuinity of Spares, Professionalism of Repair Team etc.	30	21.70	25.00	25.00	3
Cashflow Shortages	30	21.57	25.00	25.00	4
Knowledge Management incl. Training, Knowledge, Skills and System	30	19.63	20.00	20.00	5
Equipment and Systems - Main Propulsion	30	18.83	20.00	20.00	6
Maintenance Policy - Priority on Type of Maintenance	30	18.00	20.00	20.00	7
Availability of OEM Expert Support	30	17.43	16.00	16.00	8
Maintenance Budget Allocation	30	17.23	16.00	16.00	9
Awareness of Importance of Maintenance / Attitude – including hiding problems from becoming official.	30	16.97	16.00	16.00	10
Availability of Facilities	30	16.70	16.00	16.00	11
Availability of Local vendor support	30	16.70	16.00	16.00	12
Complexity and efficiency of existing contract	30	16.20	16.00	16.00	13
Scheduling Issues	30	16.03	16.00	16.00	14
Equipment and Systems - Auxiliaries	30	15.33	16.00	16.00	15

4.3. Results Stage 3 – Delphi Round 2

After re-assessment of the DIFs severity in Delphi Round 2, the agreement level among the Expert members had improved based on the CV values. Table 6 summarizes the absolute difference between results of Delphi Round 1 and Round 2.

Table 6: Absolute difference of Delphi Round 1 and Round 2

Severe DIFs	CV		CV R1-CV R2
	R1	R2	
Corrective Maintenance	0.09	0.06	0.03
Spares Availability	0.19	0.16	0.03
Impact of Parallel Contracts to Schedule, Genuinity of Spares, Professionalism of Repair Team etc.	0.23	0.17	0.06
Cashflow Shortages	0.24	0.15	0.09
Knowledge Management incl. Training, Knowledge, Skills and System	0.09	0.08	0.01
Equipment and Systems - Main Propulsion	0.20	0.06	0.14
Maintenance Policy - Priority on Type of Maintenance	0.22	0.15	0.07
Availability of OEM Expert Support	0.17	0.17	-
Maintenance Budget Allocation	0.13	0.13	-
Awareness of Importance of Maintenance / Attitude – including hiding problems from becoming official.	0.14	0.13	0.01
Availability of Facilities	0.15	0.14	0.01
Availability of Local vendor support	0.21	0.20	0.01
Complexity and efficiency of existing contract	0.19	0.13	0.06
Scheduling Issues	0.18	0.12	0.06
Equipment and Systems - Auxiliaries	0.27	0.19	0.08

In summary,

- Mean of [CV R1 – CV R2] = 0.04
- Median of [CV R1 – CV R2] = 0.03
- Max of [CV R1 – CV R2] = 0.14
- Min of [CV R1 – CV R2] = 0.00

Whilst [66] marked that values of [CV R1 – CV R2] below 0.2 are considered as minor, [65] added that henceforth the stopping rule is applied for the Delphi study. Noting such highlights, it is deduced that stability of each Severe DIF was reached at Round 2 and no further Delphi rounds were required.

However, whilst the consensus amongst Experts had increased the ranking of the Severe DIFs remains unchanged as displayed in Table 7.

Table 7: Validation result of Severe DIFs via Delphi Round 2

Severe DIF	Count	Mean	Median	Mode	Rank
Corrective Maintenance	30	24.50	25.00	25.00	1
Spares Availability	30	23.40	25.00	25.00	2
Impact of Parallel Contracts to Schedule, Genuinity of Spares, Professionalism of Repair Team etc.	30	22.80	25.00	25.00	3
Cashflow Shortages	30	22.63	25.00	25.00	4
Knowledge Management incl. Training, Knowledge, Skills and System	30	20.20	20.00	20.00	5
Equipment and Systems - Main Propulsion	30	20.03	20.00	20.00	6
Maintenance Policy - Priority on Type of Maintenance	30	19.13	20.00	20.00	7

Availability of OEM Expert Support	30	17.43	16.00	16.00	8
Maintenance Budget Allocation	30	17.37	16.00	16.00	9
Awareness of Importance of Maintenance / Attitude – including hiding problems from becoming official.	30	17.23	16.00	16.00	10
Availability of Facilities	30	17.10	16.00	16.00	11
Availability of Local vendor support	30	17.00	16.00	16.00	12
Complexity and efficiency of existing contract	30	16.97	16.00	16.00	13
Scheduling Issues	30	16.83	16.00	16.00	14
Equipment and Systems - Auxiliaries	30	16.33	16.00	16.00	15

Figure 3 illustrates the rating of the Severe DIFs by Expert group members. The key observation is that whilst the vast majority of experts have assessed the Severe DIFs with a rating of 16 and above, there were a few outliners. The researcher requested the expert to provide justification for the rating. The key factor in assigning a significant different rating was due to having been exposed to a lesser extent to the DIF due to limited ISS contract experience and limited working experience.

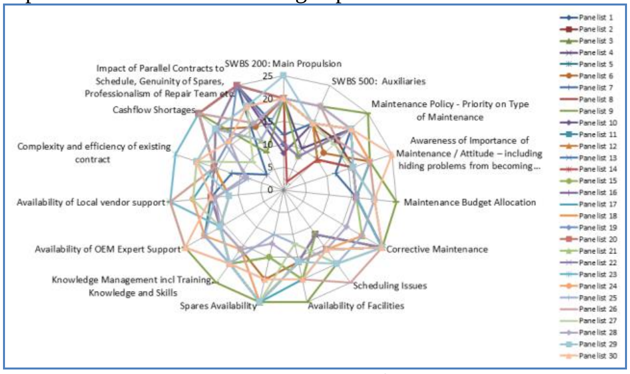

Fig. 3: Final Assessment of Severe DIFs

5. Conclusion

The current research has proven the reliability of Delphi method in tackling the complex problem of naval ship operational availability involving combined factors of human and equipment. Enhancing the factorization method mostly used in past researches which result in creation of individual solutions, the Mixed Method Modified Delphi study employed in the current research has led to generation of an integrated and more comprehensive solution in studying the factors affecting availability, holistically. Exploiting the enriched Delphi method, consensus amongst the experts has been reached and consolidation of DIFs in the naval ship domain has been attained.

This research is probably one of the most comprehensive study of its nature in consolidation of DIFs in the naval ship domain. The research pinpointed to 15 Severe DIFs as the key problem areas for prioritization of efforts in improving RMN ship availability. Furthermore, the acquired DIFs and Severe DIFs captured both human and equipment related issues which are commonly faced by all maintenance organizations facing continuous inter-related issues in improving their operational availability.

Equally important, the current research has set a fundamental basis of an availability-oriented contract management model as new knowledge towards improving naval ship operational availability.

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SEVERITY OF DOWNTIME INFLUENCE FACTORS IMPACTING NAVAL SHIP OPERATIONAL AVAILABILITY - A FIVE-STAGE DELPHI CONSENSUS PROCEDURE WITH SNOWBALLING TECHNIQUE

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ABSTRACT

Operational availability of naval ships, which reflects the number of days they are available for operational tasking in a year, is a complex problem. The number of days the ships are able to spend in an area of operations reveals the sustainability of the naval force in showing of presence and deterrent capability. There have been numerous literatures on calculating downtime through Mean Time between Failure (MTBF) and Mean Time to Repair (MTTR) to obtain availability value; however there have been limited literatures pinpointing to the root cause of the various downtime, called Downtime Influence Factors (DIF) for naval vessels. The limited literatures on DIFs of naval vessels are further restricted in the study of a single factor such as obsolescence or spares availability, or two or three factors at most, whilst in reality the DIFs encompasses a wide range of human and equipment related factors that most researchers have not attempted to study. The situation is further complicated by issues of equipment and component redundancies as well as possible interdependencies between each DIFs. The current research uses a five-stage sequential modified Delphi approach including risk analysis and snowballing technique to identify, validate and rank the severity of all DIFs from two sets of experts in naval ship maintenance contracts. The study revealed 15 severe DIFs involving human and equipment related factors impacting naval ship availability. The result complemented and validated the findings of previous study by the authors involving 30 experts. The results enable the navies and supporting industries to focus on pinpointed areas of concern to enable them to increase the operational availabilities of their ships in the fleet.

Keywords: naval vessels, navy ship maintenance, operational availability, downtime influence factors (DIFs), delphi method.

INTRODUCTION

Achieving targeted operational availability of equipment and systems can be an arduous task for any organization. Navies worldwide face the same challenges of achieving high asset availability, albeit the situation is aggravated due to the complex nature of warships including the variety of military roles [1]. The variety of military operations according to "across the spectrum of conflict" is illustrated in Navy Force Planning Scenarios. Operational availability of naval ships, which reflects the number of days the warships are available for operational tasking in a year as stated in GAO 2015 [2], is therefore a complex problem [3]. The number of days the ships are able to spend in an area of operations reveals the sustainability of the naval force in showing of presence and deterrent capability [2]. It is interesting to note that availability is still a problem in modern navies including the United States Navy even lately [4].

Given the complexity of the naval vessel itself as an asset due to advanced ship designs[3] and the various intricate maintenance contracts under which the vessels belong to[5], the race to maximize their operational availability or uptime is hampered by the simple fact that there exists a long list of possible contributing factors creating downtime. There have been several availability calculations through Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) [6, 7] However, there has been limited literatures pinpointing to the root cause of the various downtime. These factors are called Downtime Influence Factors (DIFs)as described in Alshafiq *et al.* [8]. Most studies are limited to a single factor such as obsolescence or spares availability in Sandborn [9] and Koehn *et al.* [10], or two or three factors at most. Therefore, new knowledge could be gained if DIFs are studied holistically. This research aims to simplify the complexity surrounding naval ship availability. A holistic study on combined human and equipment related Downtime Influence Factors (DIFs) enables the various stakeholder levels to achieve better understanding of factors and their severity in affecting operational availability.

Due to issues of achieving high availability targets as expected by some customers, nowadays providers of complex engineered equipment are often encouraged to offer outcome or availability-based contracts or performance-based contract (PBC), where the provider guarantees the uptime and availability of the product[5, 11-13]. As availability is also a measure of maintenance performance, the availability is guaranteed to minimize the risks faced by customers, such as in the process industry, whereby machine downtime in the shop floor is one of the main issues for maintenance productivity [14]. Maintenance activities are mostly non-repetitive in nature resulting in all maintenance personnel and managers facing new problems with each breakdown or downtime of the plant or system. Due to the conflicting multi-objectives issues, multi-skill levels are needed [14] and retention of these special skills is also a common problem in maintenance [15-19].

It is well agreed among researchers that Delphi method is preferred as a research instrument for incomplete knowledge about a problem or phenomenon [20-23] or in the case of limited experts in the field are available [20, 24]. Grisham [25] emphasized that the method is appropriate for researching complex issues where larger scale quantitative hard data fails to unearth richness in tacit knowledge to help the research understand subtle expert opinion. The scientific methodology provided by the Delphi is well suited to issues that require the insights of subject matter experts. The method works especially well when the goal is to improve the understanding of problems, opportunities, solutions or to develop forecasts [20]. On the implementation and enhancement of the Delphi method, various studies provided further details. Exclusively, Rowe and Wright[26] presented a framework for conducting the necessary Delphi research and how to enhance the use of the Method including improving expert recruitment via snowballing and other methods of retention over Delphi rounds. Specifically, Baker and Edwards [27] recommended guidance and advice on sampling size for qualitative interviews based on a set of succinct “expert voice” contributions stating that saturation is central to qualitative sampling depending on the methodological and epistemological perspective. Meanwhile, Adler and Adler[28] advised sample pool sizes and a mean of 30 though later confirmed that the best answer is simply to gather data until empirical saturation has reached since some qualitative researchers argued that as little as one expert opinion can add value to the area of research. Other researchers have similarly used expert opinions to study maintenance downtime distribution which reflects availability of systems [29]. Therefore the researcher has selected a 5-Stage Sequential Modified Delphi Approach with Snowballing Technique for this study.

MAIN RESULTS

Delphi studies are mainly concerned with eliciting expert opinions in fields where little or no literature is available [30]. Lavrakas [31] states that some non-probability samples are useful, as long as they are not used to make inference to a larger population. Qualitative research “samples” some members from a population of interest so as to gather information from or about them [32]. The sample does not need to comply to quantitative research as the results will not be analysed in view of inferential statistics but with the view to better understand the problem areas based on expert opinions in the field

The population of interest is described in this study as experienced, knowledgeable Malaysian Naval In-Service Support (ISS) Experts that have direct involvement in the Patrol Vessel (PV) ISS Contract. The total number of experts complying with these criteria is 46. Subsequently, the researcher applied judgemental sampling based on the accessibility of these experts. The final sample size for Stages 1-3 was 30 Experts from the total population of 46. For Stages 4 and 5, Snowballing Technique as described next is applied to identify 5 Top Management Experts. The total number of interviewed experts throughout the 5-Stage sequential modified Delphi was 35.

The majority of Delphi studies involve 15-20 respondents [33]. Moreover, with a homogeneous group of experts, good results can be obtained even with a panel as small as 10-15 individuals [21].

The 5-stage sequential modified delphi approach

The steps of the 5-stage Sequential Modified Delphi approach could be summarized in Table-1.

Stage 1 - Focus group discussion

Based on AlShafiq *et al.* [8], the first stage commenced with a Focus Group Discussion (FGD) with a group of 30 Experts from contractor and customer’s organizations who were directly involved in the In-Service Support (ISS) Contract with sufficient working experience or knowledge in the ship maintenance field. The FGD was designed to confirm and screen the wide range of factors that were harvested from the literature review on factors affecting the down time or availability of naval ships as well as from other engineering fields.

The 30 Expert members identified and consolidated the variables from various interpretations and carefully pooled into 50 agreed categories called Downtime Influence Factors (DIFs) that impact ship availability.

Table-1. 5-Stage sequential modified delphi approach summary.

Research stage	Phase, Expert group	Activity and Results
Stage 1 Focus Group Discussion (FGD)	Phase 1 Expert Group 1	• Focus Group Discussion conducted • 50 DIFs pooled from various literatures across various engineering fields.
Stage 2 Delphi Round 1	Phase 1 Expert Group 1	• 30 Experts identified for survey • 50 DIFs confirmed by experts • Weightage of Severity (Probability versus Likelihood of occurrence) through Risk Analysis obtained
Stage 3 Delphi Round 2	Phase 1 Expert Group 1	• Same 30 Experts surveyed • Consensus from previous rounds achieved • Severe DIFs identified with probability of likely (4 and above) and impact (4 and above). • Snowballing to identify Top Management Experts conducted • Selection Criteria of Top Management Experts
Stage 4 Delphi Round 3	Phase 2 Expert Group 2 (Top Management)	• 5 Top Management Experts selected and surveyed. • Confirmation of 50 DIFs. • Weightage of Severity to identify 15 most severe DIFs.
Stage 5 Delphi Round 4	Phase 2 Expert Group 2 (Top Management)	• Same 5 Top Management Experts surveyed • Consensus from Top Management Experts achieved • Reconfirmation of Severe DIFs • 15 most Severe DIFs ranked

Stage 2 - Delphi Round 1

From AlShafiq *et al.* [8], Stage 2 commenced with the design and development of questionnaire. The questionnaire was constructed using structured questions which consisted of closed, dichotomous questions and Likert Scales. The questions which contained the 50 DIFs produced by the FGD were brought forward to the next stage for further identification and confirmation by the Expert group. All 30 Experts confirmed the 50 DIFs brought forward from Stage 1.

The Expert members were subsequently asked to select the DIFs that have impact on ship availability via Risk Assessment Matrix. Qualitatively, risk is proportional to the expected losses that can be induced by a certain accident and to the likelihood of an occurrence. Greater loss and greater likelihood result in an increased overall risk [34]. In engineering, the definition of risk is:

RISK = (Probability of Incident/Accident) x (Losses per Incident/Accident) [34]

The probability and impact matrix illustrates a risk rating assignment for individual risk factors. It reflects the combination of impact and probability that in turn yields a risk ranking or risk priority. Risk ranking is based on a matrix whose axes are the ranks of consequences and probabilities [34]. The likelihood of occurrence and consequences of scenarios as the result of their pairing is called a Risk Assessment Matrix [35]. Typical Risk Assessment Matrices vary with organizations, however Ludwig[34] concludes that the most common type of matrices contain 3x3, 4x4, 5x5, 5x4 and 6x4 likelihood and consequences categorizations. The best suited Risk Assessment Matrix chosen for the study was as a 5x5 Matrix, as did the US Navy on ship maintenance [36].

Consensus among the expert group members regarding the importance of each of the 50 DIF was achieved. The DIFs were ranked and the Weightage of Severity (WoS) of the various DIFs was obtained. Based on Risk Analysis, a DIF with a total value or median of 16 was defined as “Severe” and confirmed as important.

Stage 3 - Delphi Round 2

Based on Alshafiq *et al.* [8], in Delphi Round 2, Expert members were asked to re-assess the DIF ratings in the light of the consolidated results obtained previously. New questionnaires similar to previous ones were issued for feedback. The subsequent processes of computing DIFs severity and performing risk analysis were similar to Stage 2. After re-assessment of the DIFs severity in Delphi Round 2, the agreement level among the Expert members had improved based on the CV values.

The 30 Experts were asked to provide their recommendation for the Top Management Experts for the subsequent rounds of Delphi, based on Snowballing Technique. In any case ‘knowledgeable persons’ could be identified either through Literature Research or recommendation from institutions and other experts, demanding techniques of purposive and snowballing sampling [37]. Giannarou and Zervas[38] indicates that an expert endorsement or recommendation can help in identifying other experts.

The researcher here enlisted the assistance of the participating panellists to pinpoint those professionals recognised in their fields to have high levels of expertise and authority. The 30 Experts from Stages 1 to 3 were requested to list down the top management experts from either Royal Malaysian Navy or Prime ISS Contractor that have extensive experience in ISS Contract Management.

Through recommendation by the 30 Experts based on a selected Fulfilment Criteria, 7 very senior position panellists were selected after fulfilling the following selection criteria in Table-2.

Table-2. Panel members fulfilment criteria for stage 4 and 5.

Stage	Delbecq's criteria [39]	Expert criteria to be fulfilled	Fulfilment
4 to 5 4 to 5	Have pertinent information to share; Are motivated to include the Delphi task in their schedule of competing tasks;	Having extraordinary working experience or extraordinary knowledge in the ship maintenance field; and the requirements of the PV ISS Contract.	Yes, all of the panellists possess extraordinary knowledge, skills and years of experience on ship maintenance. They are also either currently engaged or had previously engaged in the implementation of the PV ISS Contract.
	Feel personally involved in the problem of concern to the decision makers;	Working in relevant organizations in the naval ship maintenance field.	Yes, they are also either currently engaged or had previously engaged in the naval ship maintenance field.
	Feel that aggregation of judgement of a respondent panel will include information, which they too value, and to which they would not otherwise have access.	Stakeholder at a reasonably senior position, with interest on the subject matter, and would like to utilize the result for future work in the field.	Yes, they are stakeholders that hold very top management positions either as the customer or the contractor.

However, from a list of 7 Top Management Experts short listed and approached, 5 agreed to participate in the study. The list of panel members and their positions for Stage 4 and 5 are as reflected in Table-3.

Table-3. List of the panel members for Stage 4 and 5.

Type of organization	Number
ISS Contractor Top Management	1
Shipyard Top Management	1
Navy Admiral (Engineering)	3
Total	5

The selected experts represented a balanced view of top management perspectives from both the contractor and customer. These experts possess extraordinary knowledge and experience in ship maintenance, project management, financial management, maintenance philosophies as well as policies and procedures, and are positioned in their respective organizations to ensure that their organizations benefit from the results of the study. All experts possessed on average 35 years of working experience in the naval ship maintenance industry. Their selection provides a fair and balanced top level view for the Delphi study. All the panel members have fulfilled the criteria requirements of Delphi.

Stage 4 - Delphi Round 3

Stage 4 commenced by providing the results of Stage 3 to the group of Contract Management Experts (Top Management) to confirm their agreement to the list of 50 variables that influence ship's downtime. All the Top Management Experts confirmed the list of 50 DIFs were valid as the DIFs had direct impact to the ship's operational availability. Similar to Stage 2, the 5 Top Management Experts were asked to conduct a Risk Assessment of the DIFs that were brought forward from Stage 3, based on ranking conducted by the 30 Experts. A new ranking list was generated.

Stage 5 - Delphi Round 4

Similar to Stage 3, Top Management Experts were asked to re-assess the DIF ratings in the light of the consolidated results obtained in Stage 4. All of the Top Experts remained with their earlier assessment in Stage 4. The result after 5 Stages are as described in Table-4.

Table-4. Results of delphi after 5 stages.

RESULTS after stage 2 and 3, Consensus reached (n=30)			Results after stage 4 & 5 (n=5)		Combined (n=35)	
List of severe DIFs	**Mean**	**Rank**	**Mean**	**Median**	**Mean**	**Rank**
Corrective Maintenance	24.5	1	25	25.0	24.57	1
Spares Availability	23.4	2	25	25.0	23.62	2
Impact of Parallel Contracts to Schedule, Genuinity of Spares, Professionalism of Repair Team etc.	22.8	3	23	25.0	22.82	3
Cashflow Shortages	22.63	4	21.2	20.0	22.42	4
Knowledge Management incl. Training, Knowledge, Skills and System	20.2	5	20	20.0	20.17	5
Equipment and Systems - Main Propulsion	20.03	6	20	20.0	20.03	6
Maintenance Policy - Priority on Type of Maintenance	19.13	7	20	20.0	19.26	7
Availability of OEM Expert Support	17.43	8	18.4	20.0	17.57	8
Maintenance Budget Allocation	17.37	9	16	16.0	17.17	9
Awareness of Importance of Maintenance/ Attitude-including hiding problems from becoming official	17.23	10	16	16.0	17.06	10
Availability of Facilities	17.1	11	16	16.0	16.94	11
Availability of Local vendor support	17	10	16	16.0	16.86	12
Complexity and efficiency of existing contract	16.97	13	16	16.0	16.83	13
Scheduling Issues	16.83	14	16	16.0	16.71	14
Equipment and Systems - Auxiliaries	16.33	15	16	16.0	16.29	15

The level of concordance or agreement between Experts was measured with the help of Kendall's coefficient of concordance in Minitab and SPSS. Out of 15 measures the Experts agreed on 12 (80% Agreement, 95% Confidence Interval, 51.91, 95.67), Kendall's Coefficient of Concordance is considered high at 0.908291 with Chi Square of 63.5804, 14 Degrees of Freedom and $p < 0.001$. The 15 most severe DIFs as evaluated with a high level of consensus by the Top Management experts can be viewed in Figure-1.

CONCLUSIONS

This study concludes with 15 severe DIFs from a range of more than 50 possible factors impacting the operational availability of naval vessels, and the severity of each DIFs. This research may be the most comprehensive study of its nature in consolidating the DIFs specifically in the naval ship domain, but also in the maintenance engineering field in general. The findings of this paper would assist organizations in prioritizing their efforts in controlling specific downtime factors which greatly impact their organizations. Further focused research on individual factors and especially on various combinations of factors may shed more light on this newly explored area of study. The acquired DIFs and Severe DIFs captured both human and equipment related issues which are commonly faced by all maintenance organizations facing continuous inter-related issues in improving their operational availability.

The authors believe that Project Managers and Contract Managers shall be able to manage their contracts better with these identification of constraints and interdependencies, which they will endeavour to implement best practices [40] . The current research has proven the reliability of Delphi method in tackling the complex problem of naval ship operational availability involving combined factors of human and equipment. The 5-stage sequential modified Delphi approach including snowballing technique has provided the necessary verification, validity, accuracy and rigorousness in studying the factors affecting availability, holistically.

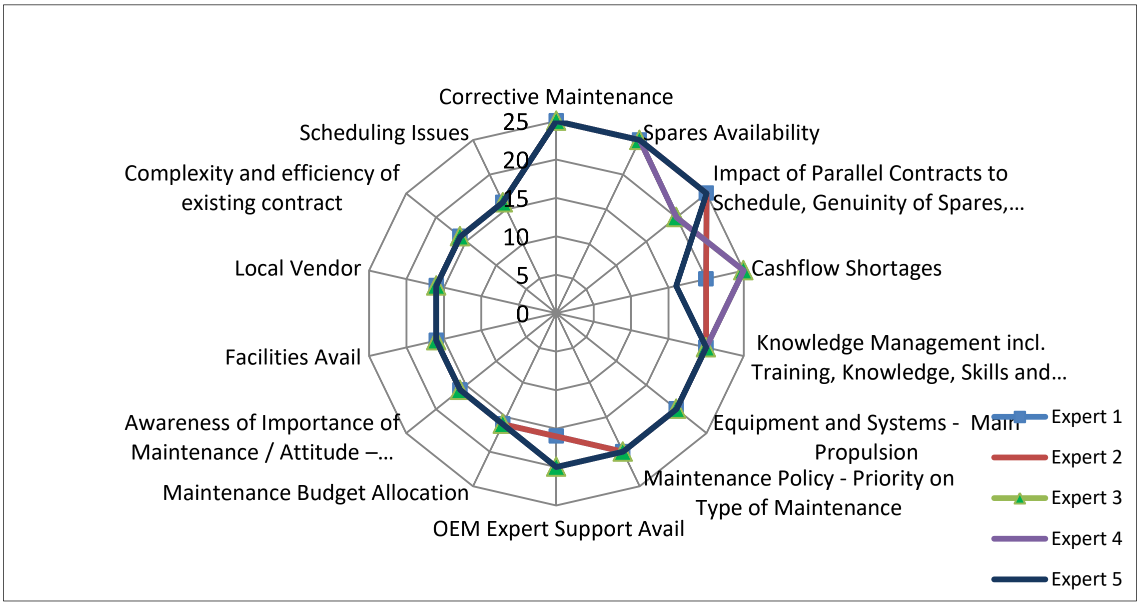

Figure-1. Radar chart of the top management identified severe DIFs.

Equally important, the current research has set a fundamental basis of an availability-oriented contract management framework/model as new knowledge towards improving naval ship operational availability. The study is a pivotal step in enabling a Severity Index (SI) to be produced in future research to assist navies to compare indexes of various types of contracts implemented globally on naval ship maintenance.

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