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# Functionally Seaworthy: How functional alignment of integrated logistic support can deliver improved seaworthiness

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**ABSTRACT**

Integrated Logistic Support (ILS) packages for maritime mission systems have traditionally been based on a physical system centric view of the maritime system. The analyses upon which these ILS packages are built, such as Reliability Availability Maintainability (RAM) and Level-of-Repair Analysis (LORA), are generally developed by considering the equipment items that make up the system and their physical architecture. This approach tends to drive the sustainment of a maritime system towards achieving the desired availability of the individual equipment items that make up the system.

The maritime mission system, however, delivers its operational effect through the functions it performs. These functions are often implemented by multiple systems, which can lead to a purely system-centric based ILS package being poorly adapted to support the efficient delivery of the operational effect. Furthermore, taking a functional view of sustainment, allows the better linkage between the operational effect of the maritime mission system, and its ongoing support.

This paper aims to demonstrate, by means of example, how applying functional thinking, and developing the ILS package on the basis of a functionally-aligned RAM and LORA analysis of the maritime mission system, can realise efficiency gains in the allocation of sustainment resources. It will also discuss how this approach can result in an increased likelihood of efficiently achieving the operational effect, whilst at the same time satisfying the seaworthiness goals of the Royal Australian Navy (RAN).

## INTRODUCTION

The Royal Australian Navy (RAN) has the mission "to fight and to win in the maritime environment." [1] The tenets to achieve this mission are described in the capstone document Australian Maritime Doctrine [1], which describes the underlying strategic and operational concepts required to achieve the necessary sea power to successfully achieve this mission. Execution of these strategic and operational concepts is enabled by an effective support system, within which logistics, both afloat and ashore, is a key element. It is aspects of the initial development of the logistics support, that is to say, the Reliability Availability Maintainability (RAM) program, along with the System Safety Program, that are the focus of this paper.

## NOTE ON TERMINOLOGY

This paper employs systems engineering concepts in the description of a warship, where terminology is in accordance with that used in the Systems Engineering Body of Knowledge (SEBoK) [2] and the INCOSE Systems Engineering Handbook [3].

A **system** is a "*combination of interacting elements organized to achieve one or more stated purposes". [2]*

The warship mission system is a **system of systems**, made up of systems such as the propulsion system, auxiliary systems, combat system, weapons systems etc. Each of these systems may be further broken down to subsystems.

A **function** *"is a characteristic task, action or activity that must be performed to achieve a desired outcome*." [3]

**Safety** is "*freedom from conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment*", whilst **system safety** is "*The application of engineering and management principles, criteria, and techniques to achieve acceptable risk within the constraints of operational effectiveness and suitability, time, and cost throughout all phases of the system life-cycle.*" [4]

**Reliability** is defined as *"the probability that an item will perform its intended function for a specified interval under stated conditions.*" [5], and **availability** is "*a measure of the degree to which an item is in an operable and committable state at the start of the mission, when the mission is called for at an unknown (random) time.*" [5].

**Maintainability** is defined as:

> "*The relative ease and economy of time and resources with which an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair. Also, the probability that an item can be retained in, or restored to, a specified condition when maintenance is performed by personnel having specified skill levels, using prescribed procedures and resources, at each prescribed level of maintenance and repair.*" [5]

## SEA POWER AND SEAWORTHINESS

Sea power has particular characteristics that differ from air power and land power, and these characteristics make sea power a valuable contribution towards the overall strategic capability of the Australian Defence Force. Within the context of the logistical support, some of these particular characteristics of sea power may be highlighted, notably:

- Readiness: warships can be ready to rapidly deploy and conduct operational tasks; and
- Resilience: a warship has the ability to remain operational in the face of damage and defects. [1],

The highlighted characteristics of sea power are highly reliant upon both the warship mission system, via the system design for reliability and availability (frequently by the incorporation of redundancy), and the support systems, including the maintenance and spares logistics.

The RAN's Australian Maritime Operations [6] further expands on this, by the introduction of the concept of seaworthiness. Seaworthiness is defined as "A judgment of mission system(s) to be supported in becoming and thence remaining seaworthy utilising the services of the support system". [6] The concepts of seaworthiness are that mission systems need to be designed and maintained to achieve their operating intent, with a risk-based management system applied to eliminate or reduce risks to the seaworthiness outcome.

Seaworthiness is implemented within the RAN under the Defence Seaworthiness Management System (DSwMS). This system guides the achievement of the seaworthiness outcome, which is to:

> *"ensure that the operation of a maritime mission system, in accordance with its Capability Manager's operating and support intent and enabled by its support system:*
>
> 1. *maximises the likelihood of achieving the specified operational effect for the defined tasking, where*
> 2. *efforts have been made to eliminate or minimise so far as is reasonably practicable (SFARP) hazards/risks to personnel, the public and the environment.* [7]

The key concept introduced by the DSwMS is the closer integration of hazard and risk management of a maritime mission system with targeting the achievement of the maritime mission system operational effect. This requires the confluence of two different streams of specialist systems engineering activities: System Safety (which is focused on the elimination, or minimisation SFARP, of risks to safety of personnel, the public and environment), and Logistic Support Analysis, which is in place to develop the Support System that is necessary to ensure a Mission System can achieve its operational effect.

Historically, the System Safety and Logistic Support engineering activities have been developed in parallel but separately, with the point of interface between the two programs at the subsystem and equipment level, using bottom-up analysis techniques. Whilst this can result in a practical and robust outcome, the independent commencement of the two strands of analysis means that when these are integrated to assess the seaworthiness outcome, there may well be misalignments in approach above the subsystem or equipment level. This could be rectified by the overlay of a top-down analysis approach, as is demonstrated by the example later in this paper.

Furthermore, the engineering analysis that supports both of these activities is generally performed on a physical architecture basis of the system; that is to say, the system is represented through the physical configuration items within subsystems, and the analysis is performed by assessing the reliability, availability, maintainability and safety of the systems on the basis of each of these subsystems and configuration items. Functional representations of the system are more often restricted to specific analysis of support of the design of particular system elements, such as the hardware architecture and software aspects of control, monitoring and combat systems.

The operational effect of a maritime mission system is frequently achieved by functions that extend across the boundaries of multiple physical configuration items or are part of multiple subsystems. For some functions, which reside within a single subsystem, and where that subsystem has a closely defined purpose, there may be a high degree of correlation between a physical and functional representation of the subsystem. An example of this would be in the case of propulsion, which is a clearly defined function (to propel the ship), and this function is provided (for a conventional ship) from a single system (the propulsion system) Accordingly the functional architecture and the physical architecture closely correspond (i.e. via the drive-line).

However, for other functions of a warship, these representations may be more divergent, with the functional model crossing the physical system boundaries. An example of such would be a warship with an integrated electric propulsion system, where the propulsion function crosses system boundaries to the electrical generation system.

Functions-based systems engineering (FBSE) employs functional models to develop a functional architecture.[3] For design purposes, the functional architecture is used to inform the physical architecture of the system. However, in the context of system safety engineering and logistic support analysis, where there will typically have been an element of design and definition of the physical architecture already in place, a functional architecture may be mapped to the physical architecture. Such mapping will reveal where functions cross physical system boundaries, and are dependent on these other systems to achieve the operational effect.

## WHY APPLY FUNCTIONS-BASED TECHNIQUES?

As stated above, the aim of DSwMS is to ensure that maritime mission systems maximise the likelihood of achieving their operating intent, whilst eliminating or minimising SFARP risk. This implies that similar metrics should be used for assessing the operational performance (informed by the reliability, availability and maintainability of the system) and the safety of the systems.

### Method of functional analysis of aircraft systems

Civil aircraft and systems are frequently developed in the context of the requirement to certify these systems to the airworthiness regulations of the Federal Aviation Administration (FAA) in the United States, and the European Union Aviation Safety Agency (EASA). There are multiple recommended design practices that have been created to guide the development of aircraft systems and demonstrate compliance with the airworthiness regulations, amongst which is Aerospace Recommended Practice ARP4754A *Guidelines for the Development of Civil Aircraft and Systems*. [8] This recommended practice is:

> "*directed toward systems that support aircraft-level functions and have failure modes with the potential to affect the safety of the aircraft. Typically, these systems involve significant interactions with other systems in a larger integrated environment. Frequently, significant elements of these systems are developed by separate individuals, groups or organizations. These systems require added design discipline and*

*development structure to ensure that safety and operational requirements can be fully realized and substantiated*."

The guidance, which explicitly links safety with operational guidance, forms an ideal basis from which to adapt for application to maritime mission systems.

The ARP4754A process focuses on the development phase of systems, from the functional definition to the architectural definition and into the physical design and implementation phases. It is based around an approach of analysing the top-level functions of an aircraft, via a Functional Hazard Analysis, and determining the consequences of top-level functional failures. Based upon the severity of the consequence of these functional failures, a Functional Development Assurance Level (FDAL) is assigned to each function. The FDAL represents the level of assurance that is required for the development, implementation and verification of the function, to ensure that there can be confidence that the function performs as intended, and that the potential for development errors in the function are minimised. As a top-level function is decomposed into subsidiary functions, and eventually mapped to the physical architecture and design of a system, the development assurance levels are allocated to these lower levels on a formal basis, to assign Item Development Assurance Levels (IDAL) to particular physical systems and system components. The intent is to use a formalised and structured process to design systems that can be used to achieve the required level of assurance without undue reliance on any single system.

**Application to maritime systems**

Whilst the approach of ARP4754A could, in theory, be applied to the development of maritime mission systems in its entirety, there are certain objections to this. These include that application of these processes wholesale to maritime projects would be a step change increase in the complexity of engineering assurance processes, with resultant impacts on cost. Secondly, in the Australian context, many maritime mission systems are not *de novo* developments, but rather evolutions of an existing system, whereby there is an existing physical design in place, and the design cannot be solely informed by the functional design. However, the ARP4754A may be adapted for application to the maritime environment, in support of achieving the seaworthiness objective.

**APPROACH**

As noted above, the ARP4754A commences with a Functional Hazard Analysis. The top-level functions of the mission system are analysed to determine the impact of their failure upon the mission system, and based upon the assessed criticality to safety, a FDAL is allocated against the function. Such an approach is focused towards safety and must be extended to address all aspects of seaworthiness.

To apply the approach to guide the development of safety and ILS deliverables during the design phases of a maritime mission system for a seaworthiness objective, the following approach is proposed:

1. Identify the principal functions of the maritime mission system under consideration. This functional identification should be based upon the desired operational effect goals from the Operating and Support Intent for the mission system.
2. Assess the consequences of a failure of these functions using the risk categories of safety (in accordance with the Defence Safety Manual [9] and ANP2200 Navy Safety Systems Manual [10]), environment (per ANP3201 Navy Environment Risk

Management and Compliance [11]) and Seaworthiness (in accordance with ANP3001 Navy Governance Application [12]). The ratings for assessment of consequence in each category are reproduced in

3. Table 1 to
4. Table 3.
5. Assign Development Assurance Targets (DAT) to each top-level function, based upon the assigned severities in each category. The DAT, equivalent to the FDAL of ARP4654A, would correspond to critical failure rates and reliability, availability and maintainability targets.
6. Develop a functional breakdown is developed through devolving the top-level function into supporting sub-functions. The functional breakdown should be developed to the extent that the contributory functions to the top-level function can be mapped to a grouping of single physical subsystems or configuration items. This will be an iterative process through the design development of the mission system.
7. Allocate the targets downwards through the functional breakdown, following the formal processes described in ARP4754A, whereby there is a requirement for independence and redundancy of supporting the functions in order to relax the target.
8. As the breakdown reaches the physical subsystem level, specific targets for the physical system design may be allocated following the process in Step 5, such that the conventionally applied methods for analysis of safety, reliability, availability and maintainability may be followed.

*Table 1: Safety Consequence descriptors [10]*

| Rating | Consequence Description |
|---|---|
| Catastrophic | Multiple fatalities or 10 or more injuries/illnesses categorised as critical. |
| Critical | Single fatality and/or permanent total disability or 10 or more injuries or illnesses categorised as major. |
| Major | Serious injury or illness requiring immediate admission to hospital as an inpatient and/or permanent partial disability or 10 or more injuries/illnesses categorised as moderate. |
| Moderate | Injury or illness causing no permanent disability, which requires non-emergency medical attention by a registered health practitioner or 10 or more injuries or illnesses categorised as minor. |
| Minor | Minor injury or illness that is treatable in the workplace (first aid) or by a registered health practitioner, with no follow up treatment required. |

*Table 2: Environmental Consequence Descriptors [11]*

| Rating | Consequence Description |
|---|---|
| Catastrophic<br><br>*Widespread serious permanent effect* | Incident is reportable to the regulator, serious permanent/persistent and irreversible damage is caused, significant public interest and media coverage and/or impacts not contained to Defence estate or area subject to the Defence activity which resulted in the incident. |
| Critical<br><br>*Wider spread, moderate to long-term effect* | Incident is reportable to the regulator and notable damage is caused to an area or asset from which it will take more than 10 years to recover with long-term evidence of the incident resulting.<br>OR<br>Incident is reportable to the regulator and public concern raised. |
| Major<br><br>*Localised, short-term to moderate effect* | Moderate but repairable damage that will take up to 10 years to recover. OR<br>Incident is reportable to the regulator. |
| Moderate<br><br>*Localised short-term effect* | Minor damage to the environment or heritage asset or area that is immediately contained on-site. It will take less than two years for the resource or asset to fully recover or it will only require minor repair.<br>OR<br>Disturbance to scarce or sensitive environmental or heritage resources. |
| Minor<br>*No impact or no lasting effect* | Negligible damage that is contained on-site. AND<br>The damage is fully recoverable with no permanent effects, taking less than six months to fully recover. |

*Table 3: Technical Seaworthiness Consequence Descriptors [12]*

| Rating | Consequence Description |
|---|---|
| Catastrophic<br>ERM Cat 1 | Loss of maritime system. |
| Critical<br>ERM Cat 2 | Loss of functional capabilities or ability to operate/control a maritime system such that continued safe operation is in jeopardy. Large reduction in safety margins that may result in loss of system. |
| Major<br>ERM Cat 3 | Reduction in functional capabilities or ability to operate or control the platform/materiel asset, or slight reduction in safety margins. |
| Moderate<br>ERM Cat NA | Slight reduction in functional capabilities, including the ability to operate or control the platform/materiel asset, or a reduction in safety margins. |
| Minor<br>ERN Cat NA | Loss of a system or function that does not affect the capability or safety of the maritime system. |

The advantages of this approach are that:

1. The top-level functions are consistent between the desired operational effect, the system safety program and the ILS program. Therefore it is more straightforward to reconcile the two aspects of the seaworthiness objective (i.e. safety and operational performance).
2. In linking the platform's operational effect goals/functions to the structure used to analyse supportability, the effect of changes in sustainment strategies and activities on the platform's ability to deliver those functions can be readily shown.
3. Targets for the performance of each function are allocated from a top-down analysis so that there is consistency in their allocation to their contributory functions, based upon the potential for single points of failure to contribute to a reduction in safety or operational performance.
4. The process is agnostic of the system boundaries and allows the dependencies of a function upon other systems and subsystems to be incorporated into the analysis and subsequent development of requirements.
5. It enables consideration of the influence of other physical systems towards the elimination or minimisation of risks to safety SFARP, which is particularly important where the risk minimisation is reliant upon control systems or on independent layers of protection.
6. By using the top-level operational effect goals/functions of the platform to drive the analysis of the ILS and safety programs, progressive assurance of the seaworthiness outcome can be built from the earliest phases of an acquisition program.

**EXAMPLE**

**Step 1: Identify Top-Level Functions**

Consider a maritime mission system such as a notional minehunter ship. Three top-level functions of the ship would include:

- Locating mines;
- Classifying mines; and
- Prosecuting mines,

Such a ship may incorporate a number of physical systems that contribute towards these top-level functions, such as:

- A sonar system including a towed body which generates sonar signals for detecting mines;
- Remotely-operated Mine Detection Vehicle (MDV) for remote classification and prosecution of a detected mine;
- An auxiliary propulsion system for station keeping as well as reduced acoustic signature during mine hunting operations;
- A Clearance Diver Team, to manually prosecute mines;
- A degaussing system to reduce the magnetic signature of the ship; and

- An electro-optical system for remote identification of mines on the surface using video, thermal imaging and laser range-finding.

Each of these physical systems directly contribute towards the top-level functions. However, there are a number of other physical systems that support these systems, and thereby contribute to the operation effect of the top level functions, including, but not limited to:

- Electrical generation and distribution systems, which provide electric power to these systems;
- Davit and crane systems, that are used to deploy and retrieve the MDV;
- Winch systems, for deployment and retrieval of towed bodies;
- Support systems for the Clearance Diver Team, such as RHIBs (and their davit system), air compression systems, etc.;
- Internal communications systems, which pass target data between subsystems to facilitate data fusion; and
- Navigation systems, to determine position for the purpose of maintaining station and safe separation from the mine target.

**Step 2: Risk Assessment**

Taking the prosecution of the mine as the top-level function to analyse, it may be assessed for the consequences of a failure or loss of the function, resulting in an inability to prosecute a mine. The results of a notional risk assessment process are summarised in Table 4.

*Table 4: Risk Assessment of Failure of Mine Prosecution Function*

| Category | Failure Condition | Consequence Rating |
|---|---|---|
| Safety | Failure of the overall ability to prosecute and dispose of mines may place this or other vessels in danger of exposure to a mine explosion, resulting multiple fatalities. | Catastrophic |
| Environment | Failure of the ability to prosecute a mine would result in the mine remaining in the marine environment, which would have negligible impact. | Minor |
| Technical Seaworthiness | Loss of the ability to prosecute a mine using the mine disposal system would result in the loss of a primary functional capability of the mission system. | Critical |

**Step 3: Allocate Development Assurance Targets**

In the scheme, a DAT would be assigned to each top-level function. Whilst there is at present a gap in Navy (and indeed, wider Defence) practice at this time in respect of determining the appropriate targets to use, and how these correspond to the risk matrix consequence rating categories, for the purpose of this example the relationship given in Table 5 shall be used.

*Table 5: Development Assurance Targets*

| Consequence Rating | Development Assurance Target |
|---|---|
| Catastrophic | 1 |
| Critical | 2 |
| Major | 3 |
| Moderate | 4 |
| Minor | 5 |

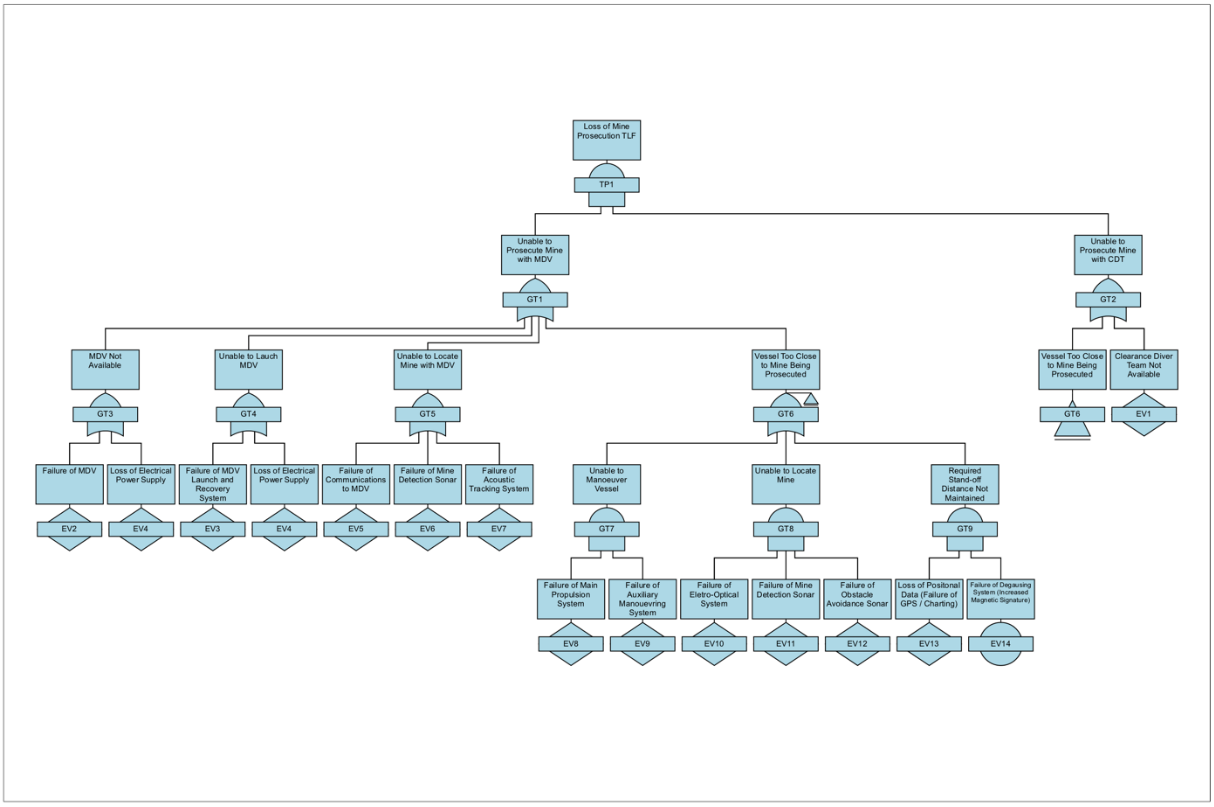
Under this scheme, the DAT for the mine prosecution function is:

- Safety: DAT 1;
- Environment: DAT 5; and
- Technical Seaworthiness: DAT 2.

**Step 4: Functional Breakdown**

Taking the prosecution of the mine as the top-level function to investigate, we would draw on the functional modelling techniques to decompose the function into the supporting functions down to the level that these can be mapped to the physical configuration. An example of such a system decomposition, using a Fault Tree technique to map the relationship from the top-level function to the physical systems supporting the function, is shown in Figure 1.

*Figure 1: Example of the Functional Decomposition from the Top-level Function*



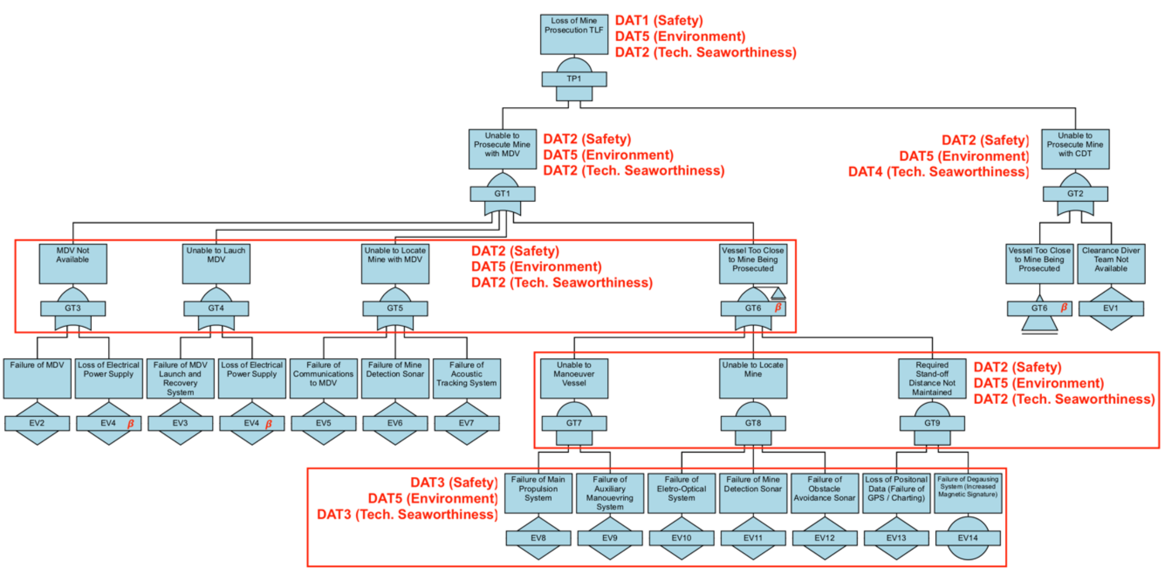
### Step 5: Allocate DAT to Lower Level Functions

Following a process generally similar to that outlined in Section 5.2 of ARP4754A [8], DAT are then allocated to lower levels of the functional breakdown. Key aspects of the ARP5754A process for allocation of DAL, that need to be kept in mind for the allocation of DAT to these lower levels of the functional breakdown are:

- If the system architecture is not considered (i.e. the relationships between different system elements in contributing towards the top-level function), then all lower-level functions inherit the DAT of the top-level function.
- Where two or more lower-level (child) functions contribute to a higher-level (parent) function via an OR gate (i.e. failure of any of the child functions results in failure of the parent function) then the child functions inherit the DAT of the parent function.
- Where two or more child functions contribute to a parent function via an AND gate and the independence of these child functions can be demonstrated (i.e. the failure of the parent function requires failure of more than one of the independent child functions) then:
    - the DAT of the child functions may be reduced by one level from the DAT of the parent function; or
    - One of the child functions inherits the DAT of the parent function, and the DAT of the other child functions may be reduced two levels from that of the parent function.

An example of such an allocation of DAT using this scheme is shown in Figure 2.

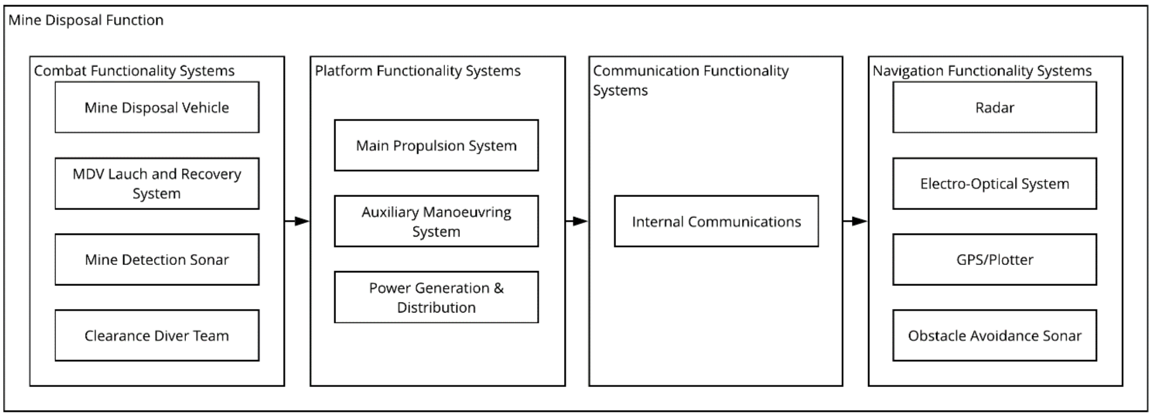
*Figure 2: Example of the DAT Allocation*



**Step 6: Conduct Safety and RAM Analysis on these Functions**

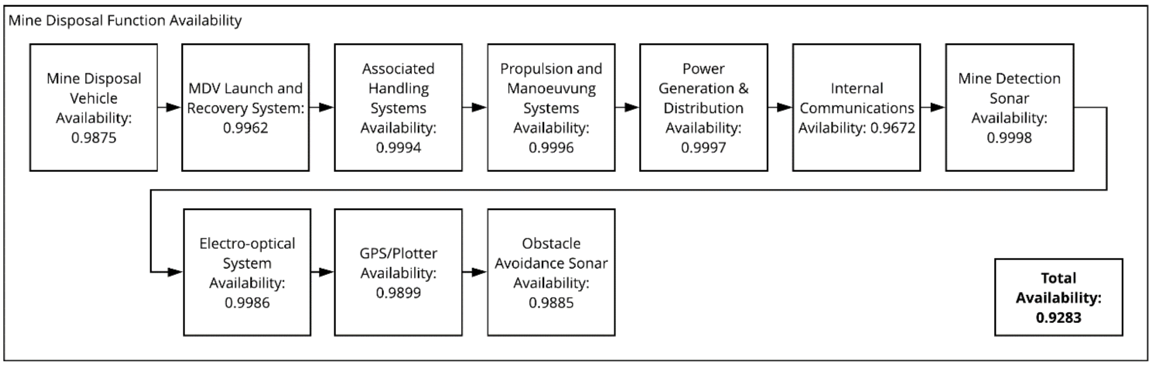
In order to achieve the benefit towards demonstrating a robust seaworthiness outcome, the bottom-up, physical system-oriented system safety and RAM analyses should be aggregated together on the basis of these functional breakdowns. To extend the example, for the mine detection function a functional block diagram of the contributory physical systems in the breakdown of Figure 1 may be developed; this is shown in Figure 3.

*Figure 3: Functional Block Diagram*




Then, using the outcomes of the bottom-up derived availability analyses of the physical subsystems that contribute to the overall function, an availability for the top-level function may be derived, shown via the availability block diagram in Figure 4.

*Figure 4: Availability Block Diagram*




The reliability and maintainability of the function may be calculated likewise in a similar manner. The risk to safety or the environment may be calculated similarly, if quantitative risk analysis techniques are being used, however more commonly semi-quantitative arguments as to the level of risk associated with a function would be developed using the overall functional decomposition structure. In particular, the structured breakdown of the top-level function would indicate where risk mitigations may be best applied (i.e. to what contributory system) to reduce the overall level of risk SFARP.

The strength of the technique would be realised when conducting the subsequent logistic support analyses, such as the Level of Repair Analysis (LORA). With this overall structure in place, there is a framework to enable changes in the LORA to significantly impact on the overall mission availability and safety (by the availability, or otherwise, of physical risk mitigations that substitute, isolate or control by engineering, the safety risk), such that this can be optimised to best achieve the seaworthiness objective.

**CONCLUSION**

The approach proposed herein draws upon existing functional analysis and modelling techniques from systems engineering to more closely integrate aspects of the system safety and logistic analysis activities, in order to better address the objectives of the Defence Seaworthiness Management System. The proposed approach is, at present, conceptual, due to certain gaps in the existing RAN practices; in particular with respect to setting targets for reliability, availability and maintainability that are tied to the consequence levels associated with the loss or impairment of the top-level functions.

Whilst the proposed approach as described in this paper is focused on the development of a maritime-mission system, the outcomes of this approach would benefit the development and operation of the support system throughout the mission system's life cycle. Furthermore, it is adaptable to in-service mission systems, albeit without the potential benefits that may accrue from influencing the system design (i.e. by improving the reliability or availability of a contributory system through design modification). However, there are sufficient potential benefits to the improvement of the likelihood of achieving the desired operational effect, whilst better meeting the seaworthiness goals, that, in the opinion of the authors, that have value in further applied study of the application of these concepts to confirm that these benefits can be realised.

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