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A network science-based assessment methodology for robust modular system architectures during early conceptual design

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ABSTRACT

This article describes a methodology to assess, during the early conceptual design stage, the robustness, and modularity of engineering system architectures, which integrates concepts from network science with engineering systems. The application specifically focuses on the architecture of the power, propulsion, and cooling systems of a naval ship. The methodology incorporates a binary Design Structure Matrix as the basis for an assessment of redundancy and modularity effects on robustness, in response to the disruption of modules in the architecture. Robustness is used to drive the module selection, which supports the formulation of a robust module configuration subject to the level of redundancy in the system architecture. The case study results demonstrated that redundancy promotes robustness of the architecture and enables modularity; however, high levels of redundancy in comparison to medium level redundancy does not significantly improve robustness. The novel contribution of this article relates to the combined quantitative assessment of redundancy, modularity and robustness in a collective methodology. This methodology supports conceptual design decision making, allowing early prediction of compliance of requirements that enable cost, development time and survivability targets to be achieved.

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1. Introduction

Engineering systems is a field of research that ‘promotes the development of new approaches [. . .] to analyse, design, deploy and manage these systems’ (De Weck, Roos, and Magee 2011). The 80% lifecycle cost of a system is committed at an early conceptual stage (Duffy et al. 1993) which is the stage that the architecture of the system is essentially decided. Crawley et al. (2004) defined system architecture as ‘an abstract explanation for a system’s entities and the relationships between them’, which is designed to

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satisfy intended function, and also significantly decides the lifecycle attributes of the system. Moullec, Jankovic, and Eckert (2016) highlighted that it is ' necessary to identify early the concepts, and their underlying architectures, that are most likely to provide the best trade-offs'.

Modularity and robustness are two desired lifecycle attributes of systems, as they are strategic attributes to support business, development and operational requirements. Modularity is suggested to positively influence the lifecycle cost and the development time of such complex engineering systems. Large-scale supply chain and the various manufacturing locations surrounding the development of engineering systems are some of the reasons that have led to an increasing need for systems to be modularised, to facilitate their parallel manufacture, individual testing, the engagement of suppliers and subcontractors. Reuse, maintenance, upgrading and end of life reasons also motivate the development of modular systems (Jose and Tollenaere 2005; Meehan, Duffy, and Whitfield 2007). A modular design approach requires partitioning a system into modules. The division and integration of the modules into a functional whole depends on the modular approach adopted and is critical to ensure the success of a modular system. Literature offers a wide range of modularity design methods and metrics (Bonvoisin et al. 2016) that are motivated by different modularity drivers. Modular design methods typically attempt to maximise modularity rather than to trade-off modularity with other attributes of the systems. However, the identification of modules that have the best trade-offs amongst additional, perhaps conflicting requirements, may not entail maximising modularity.

Robustness is an essential attribute for engineering systems as it is an architectural aspect of resilience (Department of Defense 2011), thus constitutes a vital design objective when developing large-scale engineering systems. Robustness reflects on both the resilience and survivability of the complex system in the architectural level (Department of Defense 2011; Kott and Abdelzaher 2016). The USA Office of the Assistant Secretary of Defense for Homeland Defense and Global Security (2015) acknowledged that 'today's space architectures designed and deployed under conditions more reflective of nuclear war-fighting deterrence than conventional war-fighting sustainability, lack, in general, the robustness that would normally be considered mandatory in such vital war-fighting services'. Redundancy is a key design approach that promotes the robustness of systems. Modularity and redundancy are inherently conflicting concepts, as redundancy typically introduces connectivity in systems, whereas modularity intends to minimise connectivity between modules.

This article proposes a methodology to assess the impact of redundancy and modularity on the robustness in large-scale distributed engineering system architectures during the early conceptual stage of design. A robust modular methodology is developed to support the process of architecting to understand potentially conflicting requirements and take decisions in the right direction towards achieving better trade-offs.

The rest of the article is structured as follows: Section 2 discusses the literature background relating to modularity, robustness, redundancy and concludes by identifying the need for a robust modular methodology. Section 3 presents the robust modular system architecture methodology. Section 4 evaluates the methodology by applying it on a naval distributed engineering system architecture and discusses the findings. Section 5 provides conclusions and directions for future research.

2. Background literature on modularity, robustness and redundancy

Literature was used to frame the research boundaries and introduce the main research constructs: modularity, robustness and redundancy. The system architecture is defined as the unit of analysis, and the modularity, robustness and redundancy are properties of the system architecture. Table 1 presents a consolidation of definitions, methods and metrics to introduce the literature.

Hölttä-Otto et al. (2012) stated: ‘a system has a degree of modularity’, acknowledging that modularity is not a binary quantity. Thus, by clustering of components based on the degree of interactions that is maximised internally within group (modules) and minimised externally between groups (modules) (Whitfield, Smith, and Duffy 2002), a highly modular system architecture is formulated. The characterisation of the degree of modularity in a system architecture is performed using modularity metrics. Various modularity metrics exists in the literature as shown in Table 1. Guo and Gershenson (2004) proposed a normalised modularity metric. Hölttä-Otto et al. (2012) highlighted that a normalised modularity metric is an improvement because it can be used to compare the degree of modularity among different sizes of system architectures. In this article, the main criteria in deciding the modularity metric to be used in the proposed methodology was normalisation, to allow comparisons of the level of modularity amongst different system architectures.

Chen and Crilly (2016) acknowledged that there are two different types of robustness: architectural and behavioural. Architectural robustness reflects: ‘the relationship between architecture (which might be the architecture of a system, system type, state, or behaviour) and function’. By contrast, they stated for behavioural robustness, that it is ‘concerned only with the architecture it (characterised as regularities in behaviour)’. Gero and Kannengiesser (2004) established that structure drives behaviour. This is interpreted in the context of this research, as architecture (structure) drives robustness as a structural driven behavioural property of an engineering system. The definition proposed is that robustness is the ability of an instantiated system architecture to support a level of functional continuity post disruption.

Redundancy is a well-established approach to improve the robustness of engineering systems. ISO 24765 (2010) defined redundancy as: ‘the presence of auxiliary components in a system to perform the same or similar functions as other elements for the purpose of preventing or recovering from failures’. Redundancy is also defined as the presence of ‘independent alternative paths between source and demand nodes which can be used to satisfy supply requirements during disruption or failure of the main paths’ (Goulter 1987; Yazdani and Jeffrey 2012). ISO 24765 (2010) defines redundancy in relation to auxiliary components that are included whereas Goulter (1987) relates to additional connectivity between sources and demand components. Redundancy design is defined here as architectural (components and their connections) options in the instantiated system architecture that are capable of satisfying the same function.

2.1. The need for methods to analyse redundancy and modularity’s impact on robustness during the early conceptual design

Technical systems are designed to satisfy functions by exhibiting the desired behaviour that arises from their structure (Gero and Kannengiesser 2004). Redundancy and modularity

Table 1. Consolidated literature review on modularity, robustness and redundancy.

	Modularity	Robustness	Redundancy
Definition	‘“systems” property of being made up of modules. A module is a system’s element that presents a high, albeit not complete, independence of other elements’ (Miraglia 2014)	‘the maintenance of some desired system characteristics despite fluctuations in the behavior of its component parts or its environment’ (Carlson and Doyle 2002)	‘the provision of additional capacity in a system, so that system performance is maintained despite partial system failure’ (Chen and Crilly 2014)
Methods	Minimum description length theory based-methods (Yu, Yassine, and Goldberg 2007; Helmer, Yassine, and Meier 2010), Weighted and directed network-based method (Li et al. 2016), Multi-objective modular architecture method (Sanaei et al. 2017)	Decision-based (Malak, Baxter, and Hsiao 2015), System robustness (Zakarian, Knight, and Baghdasaryan 2007), Semi-analytical approach to robust design (Andersson 1996)	Design for function redundancy (Umeda et al. 1996), Resilient architecture of a cyber-physical production system method (Tomiyama and Moyen 2018)
Metrics	Module strength indicator (Whitfield, Smith, and Duffy 2002), Singular value modularity index (Hölttä-Otto and de Weck 2007), Social network centrality (Sosa, Eppinger, and Rowles 2007), Normalised modularity metric (Guo and Gershenson 2004), New modularity indices (Jung and Simpson 2017), Alternative modularity measure (Sinha, Suh, and de Weck 2018)	Sensitivity robustness metrics, Size of feasible design space robustness metrics, Functional expectancy and dispersion robustness metrics; Probability of compliance robustness metrics (Göhler, Eifler, and Howard 2016)	Clustering coefficient, Meshedness coefficient (Yazdani and Jeffrey 2012), Redundancy Distribution Index, Redundancy Magnitude Index (Elmaraghy et al. 2012)

are formulated in the structure of the system. Robustness is a behavioural property of the system that is dependent of the structure. The literature is sparse with respect to the relationship between redundancy, modularity and robustness. Hölttä, Eun Suk, and de Weck (2005) advised that high modularity penalises system performance. Mehrpouyan et al. (2014) stated that 'isolation of failures into a single module typically makes the system less robust'. Walsh, Dong, and Tumer (2019) identified that there is 'tradeoff between modularity and robustness in the design of engineering systems'.

The influence of modularity and redundancy on the robustness of a system is acknowledged in the literature (Fricke and Schulz 2005; Slagle 2007). Redundancy is accepted as a means to increase the robustness of systems. Fricke and Schulz (2005) and Ross, Rhodes, and Hastings (2008) recognised the tension between modularity and redundancy in terms of connectivity. Mehrpouyan et al. (2014) argued that 'to design a robust system and to recommend or oppose the modular physical system architecture, it is utterly important to understand the architectural properties of complex engineered systems'.

Although the potential trade-offs between redundancy, modularity and robustness are recognised, a collective quantitative methodology that analyses them together does not exist in the engineering design literature. Browning (2016) surveyed the design structure matrix (DSM) literature, including modularity metrics and methods, while Bonvoisin et al. (2016) studied modular product design literature systematically, neither review reported a robustness related modularity method. This article addresses this gap by developing a robust modular methodology to quantitatively assess the redundancy and modularity effects on the robustness of a system architecture during the early conceptual stages.

3. A robust modular system architecture assessment methodology

Section 3 presents the research solution, which is the robust modular system architecture assessment methodology illustrated in Figure 1. The methodology intents to support system architects during the early stages of conceptual design, to analyse the trade-offs between the different levels of redundancy, modularity, and robustness for system architecture. Such early assessment can better inform decisions on the most appropriate level of redundancy and modularity to achieve desired robustness in the system architecture. The methodology aids on the formulations of a robust modular configuration, establishing a modularisation of the architecture that will not jeopardise the robustness of system due to disruption of a module. The methodology is divided into four stages: input, analysis, evaluation, and selection as shown in Figure 1.

The input stage of the methodology requires inputs by the system architect. The methodology requires as inputs: the description of the system architecture in a binary DSM form, definition of system's main function, sub-functions, an initial definition of level of redundancy and a primary definition of the sets of source and sink components corresponding to sub-functions. The system architecture is modelled in a binary directional DSM. The directed network in combination with the sources and sinks represents the function viewpoint of the system architecture, whereas the edges of the network represent flows (energy, material, flow) and nodes of the components. The flow network with the definition of the source and sink components is termed the functional viewpoint as discussed in Section 3.1.1 and shown in Figure 1.

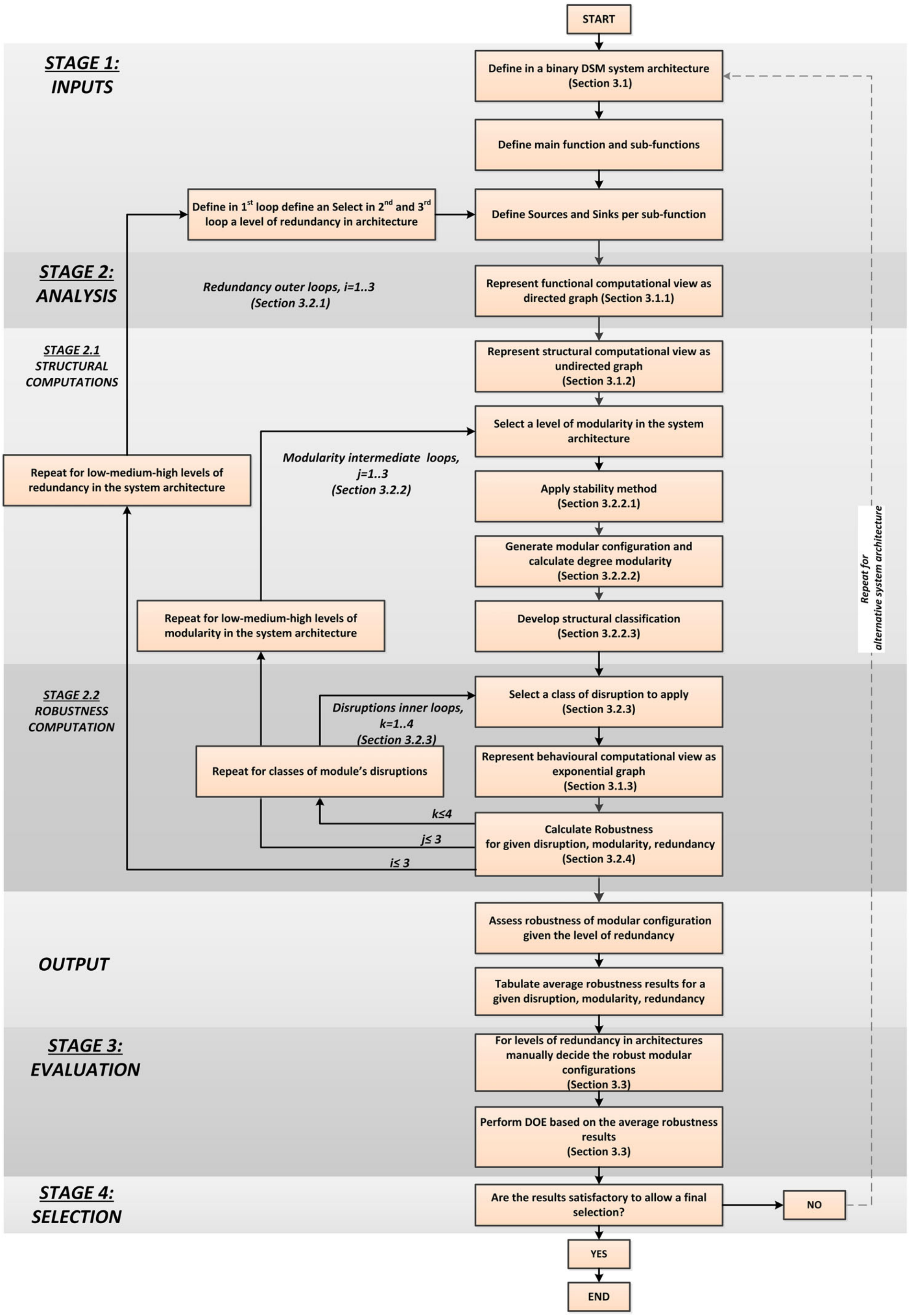

Figure 1. Robust modular system architecture assessment methodology (colour online).

The analysis stage of the methodology consists of three embedded loops: the redundancy loop, modularity loop, and disruption loop that encapsulate the structural and robustness computations. The analysis stage of the methodology is computational offering a time-efficient quantitative approach to simultaneously examine modularity and robustness. The main instrument to perform the computational analysis stage of the methodology is the establishment of the directed network through its transformation from a DSM into a mathematical adjacency matrix. The direct network is transformed into undirected network that is the basis for the structural computations in the modularity loop.

The structural computations are performed through the modularity loop and generate the classification of modules. In the structural undirected network, the edges represent tangible structural connections amongst components, and represent the structural viewpoint Section 3.1.2 as noted in Figure 1. The intermediate modularity loop uses the stability method, which is tuneable through a resolution parameter, allowing the generation of different modular configurations corresponding to different levels of modularity of the architecture.

The robustness computations utilise a disrupted exponential matrix with the known sources and sinks and are realised through the disruptive inner loop. The direct network is transformed into an exponential matrix that forms the basis to perform the robustness computation in the disruptive loop. The exponential matrix represents the behavioural viewpoint as discussed in Section 3.1.3 as noted in Figure 1, requires the definition of the source and sink to enable the robustness calculation. The disruption simulations disrupt modules that correspond at different levels of modularity that are generated through the modularity intermediate loop. This becomes a link between the structural and behavioural viewpoints of the system architecture.

The analysis stage continues iterating through three embedded loops: the redundancy loop, modularity loop, and disruption loop as per recommendations of Design of Experiments (DOE) or as the architect (user) prefers. The analysis stage is concluded by tabulating the robustness results for a given level of redundancy, modularity, and disruption. The tabulated robustness results inform the evaluation stage of the methodology.

In the evaluation stage, the formulation of a robust modular configuration of the system architecture for different levels of redundancy is reformulated based on the outcomes of the methodology. At this stage, the methodology advocates reformulating a robust modular configuration for a given a level of redundancy by combining robust modules identified for different levels of modular configuration. The robust modular reconfiguration principle is that a robust module of higher modularity is preferable if the module disruption does not penalise the robustness of the architecture.

The methodology supports the selection of robust modules generated by the stability method for different levels of modularity. Alternative modularity approaches rely on generating modular configurations by maximising the degree of modularity without reflecting on the generated module's impact on the robustness of the system architecture under their disruption. The methodology recommends that modules should be selected and gathered together to form a modular configuration on the basis that a module disruption does not compromise functional continuity, thus ensuring robustness of architecture, rather than on maximising the degree of modularity of the architecture. One of the novelties of this research is that the robustness drives the selection of modules from the set of the various modular configurations and that different levels of redundancy can be considered.

The evaluation stage of the methodology focuses on supporting a decision-making process of the choices in a trade-off between the desired levels of modularity and redundancy. The evaluation stage allows the expert (user) preferences and input to be considered.

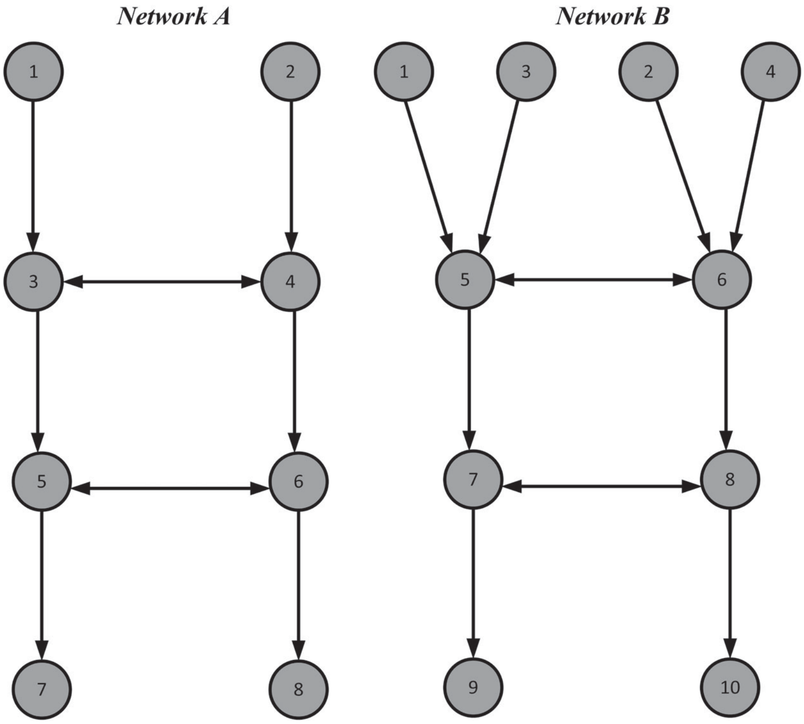

Figure 2. Network A and B examples.

The methodology explains the steps to formulate the robust modular configuration based on the analysis stage outputs. DOE is also recommended to provide a framework for the application of the methodology as it can recommend the number of iterations of the redundancy – modularity – disruptive loops of the analysis stage. In a DOE analysis modularity and redundancy are viewed as the design variables whereas robustness is considered the response variable.

The final selection stage is that the user decides if the outcome results are satisfactory. If the outcomes of the DOE and the generated robust modular configuration are not satisfactory, a completely new system architecture should be devised and reassessed. Two simple network examples are provided to support the explanation of the methodology as seen in Figure 2. These examples have similarities with the power distribution system that is discussed in Section 4 and they provide a preliminary exposition of the methodology and its constructs.

3.1. Inputs

A binary DSM (Browning 2016) was used to model the distributed system architecture and was an initial input for the methodology. Additionally, the main function and the number of sub-functions that the architecture was designed to also support are required to be identified at the beginning of the methodology. The definition of function relates with the connectivity amongst sink and source, for example in Networks A and B a level of power function is satisfied if any source is connected to any sink. The proposed methodology models the system architecture using three viewpoints: functional, structural, and behavioural.

3.1.1. Functional viewpoint

A system architecture that is conceived during early conceptual stages is represented as a schematic synthesis of functional elements and their interconnections modelled as a directed graph. Components of the system architecture correspond to functional elements and are represented as nodes, and functional flows (such as material or energy or flow) are the connections that are represented as directed edges. Figure 1 illustrates the step in the methodology, that the system architecture is represented in a functional computational view as a directed graph.

3.1.1.1. Sources and sink component identification. A preliminary input in the methodology is the definition of source and sinks components. This is required in combination with the definition of the directed network in order to define the functional view. This is in line with the notion that a functional continuity is satisfied if sufficient connectivity between sources and sinks exists after disruption. Associating sources and sinks of a directed graph with a function becomes the criterion that is assessed in the behavioural viewpoint. Figure 2 the Networks A sources are nodes 1 and 2 whereas nodes 7 and 8 are sinks and for B the sources are nodes 1, 2, 3, 4 and nodes 9 and 10 are sinks.

3.1.2. Structural viewpoint

An undirected network represents the structural connectivity among components and is generated by transforming the flow network (generated by architects through the construction of the DSM) into being undirected. This undirected network represents tangible physical connections such as cables and pipes. In the methodology, the initial input is defined to be a flow directed network that is mathematically transformed into an undirected and symmetrical structural network. In case that the flow connections do not correspond to tangible structural connections, such as the flow of information across a wireless network, then a structural network should also be included as an initial input. In analysis stage Figure 1 depicts the point that the system architecture is represented in a structural computational view (undirected network) which indicates the start of the modularity loop.

3.1.3. Behavioural viewpoint

A behavioural network is modelled as an exponential matrix, which captures direct and indirect connections with the purpose of assessing the robustness of the system architecture. The exponential matrix models the connectivity among components directly and indirectly (at any number of steps of connectivity). This means that the exponential matrix becomes the mathematical basis to assess robustness by determining if the source and sink components remain connected (in any number of steps). The sufficiency of the level of connectivity amongst source and sinks is evaluated through the redundancy threshold criterion (RTC). In the disruption loop shown in Figure 1 denotes the stage that the system architecture is represented in a behavioural computational view through the exponential matrix, which forms the mathematical basis for the robustness computation.

3.2. Analysis stage of the methodology

The analysis stage of the methodology constitutes of two parts the structural and robustness computation and includes three embedded iterative loops: redundancy loop, modularity loop, and disruption loop as illustrated in the analysis stage of Figure 1. The following sections elaborate on the redundancy, modularity, and robustness loops of the methodology.

3.2.1. Redundancy loop

The redundancy loop of the methodology lies between the preliminary input stage and analysis stage. The redundancy level variations in the architecture are considered to reflect on the structural viewpoint of the architecture thus, is positioned on the structural computation part of the analysis stage. The redundancy in the system architecture is varied using the RTC that defines the required level of connectivity amongst source and sink components to satisfy function, and by changing the number of the main supply/source components and number of interconnections which reflect on the architectural options. Varying the level of redundancy changes the structure, in spite that comparable architectures are suggested to be developed for each iteration of the redundancy loop that only differentiates in respect to their redundant character.

3.2.1.1. Identify source and sink components corresponding to function. A set of source (supply) and sink (demand) components that relates to a functional requirement are identified as input for the methodology as shown in Figure 1. This is required for the calculation of the robustness evaluation indicator metric. The proposition is that the source components are required to maintain connectivity with sink components, to satisfy functional continuity after a disruption. With respect of the example presented in Figure 2 for Network Type A, if any of source {1,2} and sinks {7,8} are connected, it is assumed that the function is maintained at acceptable levels, and this is the same for Network Type B, for any of the source {1,2,3,4} and sinks {9,10}.

3.2.1.2. Determining the level of redundancy in the architecture. Two constructs are proposed to determine the redundancy of the architecture. The first is the RTC and the second is the functional hierarchy and architectural options diagram.

3.2.1.2.1. Redundancy threshold criterion. The RTC indicates the ratio of connectivity amongst an individual set of source and sinks components that are sufficient to satisfy a specific level of functional requirements in the system architecture. The RTC is derived based on the level of redundancy in the connectivity of the architecture and is considered as a design variable during the implementation of the methodology. The RTC acts as an evaluation criterion, assessing if the remaining connectivity among an individual set of source and sink components is sufficient to satisfy functional continuity. Thus RTC defines the sufficient level of connectivity which can support function. The RTC requires to be defined by the user and is expected to be different for different operational demands. In the methodology is suggested that the redundancy first loop treats RTC as an input (or assumption), the 2nd and 3rd redundancy loops are the loops where the level of redundancy is treated as a design variable, by alternating the level of redundancy of the system architectures.

The evaluation indicator catalogues robustness values that only exceed the pre-defined RTC. For example, if a system has triple redundancy, the RTC is defined as 0.33, and for quadruple redundancy, it is defined as 0.25. To test the various combinations of sources, all cases with a common number of sources available (*i*, say) are grouped together, and the fraction of cases that satisfies the RTC is used to calculate the robustness. By varying the RTC and recalculating the robustness evaluation indicator metric, the effects of redundancy on the robustness of the system can be determined.

The RTC is controlled by the architect, as is considered as a design variable, within the methodology. For Network Type A, (the RTC was defined as 100% amongst the individual set of source and sinks, meaning that source {1} should remain connected 100% with sink {7} or source {2} should remain connected 100% with sink {8}). For Network Type B, the RTC was defined as 50% amongst the set of source and sinks meaning that for the set of source {1, 2} connected with sinks {9} is required only 50% connectivity to achieve the satisfactory function, respectively RTC is 50% connectivity is required amongst the sources {3, 4} to sink {10} to satisfy function.

3.2.1.2.2. Functional hierarchy and architectural options. A second construct proposed in this article is the functional hierarchy and architectural options diagram. This captures the high level of redundancy that entails the design of additional architectural options to satisfy sub-functions. In complex system architecture, there is often a hierarchy of functions that can be satisfied through various architectural options. This is illustrated in Figure 3 that architectural options are characterised as 'AND', 'OR'. Architectural options are viewed as a segment of the architecture that individually can satisfy a sub-function. If more than one architectural option is designed to satisfy the same sub-function that constitute as an architecture option ('OR') designed for redundancy in the architecture.

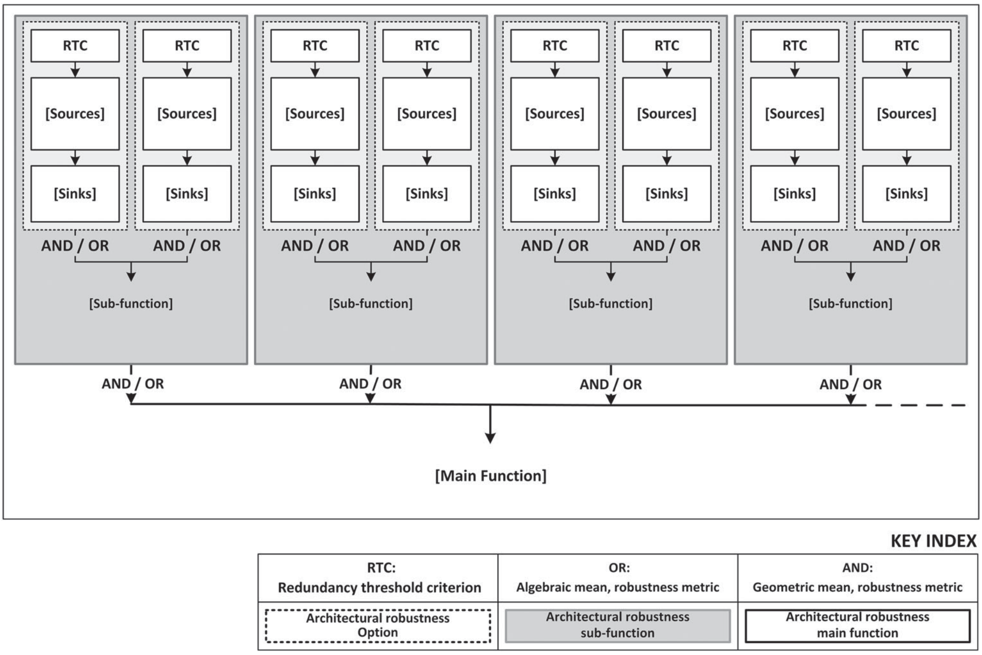

Figure 3. Functional hierarchy, architectural options, and RTC.

Figure 3 reflects on the functional hierarchy and architectural options illustrating how they are designed in the structure of the system. This hierarchy of main functions and its sub-functions, and the definitions of 'AND', 'OR' shown in Figure 3 should be defined by the users. The functional hierarchy and architectural option representation can be varied through the redundancy loops to investigate how the different functional hierarchy, architectural options, and RTC affect the robustness of the architecture.

'OR' reflects on the additional architectural optional designed for redundancy, The RTC reflects in designing for redundancy in relation to additional connectivity, whereas architectural options reflect redundancy in relation to an additional set of source and sink components.

Network A has two architectural options: option 1 is the set of source and sink {source: 1, sink: 7} and architectural option 2 is {source: 2, sink: 8}. Network A has four options: {source:1, sink:9}, {source:2, sink:9}, {source:3, sink:10}, {source:4, sink:10}.

3.2.2. Modularity loop

The methodology allows the identification of potential modules, which is flexible and tuneable, allowing for different levels of modularity. The stability method was used due to the inclusion of a resolution parameter, which allows the consideration of modularity as a design variable. This allows the degree of modularity to be varied through the manipulation of this parameter. The modularity loop as indicated in Figure 1 is part of the structural computations of the analysis stage.

3.2.2.1. Stability method. The stability method formulates a quality function that captures the persistence of clusters in time (Fortunato 2010). A cluster is persistent about a random walk (a walk in a network is a series of edges, not necessarily distinct) after t time steps if the probability that the walker escapes the cluster before t steps is low. The probability is computed via the clustered auto-covariance matrix R_t, which, for a partition of the network in c clusters, is defined in Equation (1):

$$R_t = H^T(\Pi M^t - \pi^T\pi)H, \tag{1}$$

where H is an $n \times c$ membership matrix where element H_{ij} equals one, if node i is in cluster j and is zero otherwise; M is the transition matrix of the random walk; Π the diagonal matrix whose elements are the stationary probabilities of the random walk:

$$\Pi_{ii} = \frac{k_i}{2m}, \tag{2}$$

with k_i: the degree of node i; π is the vector whose entries are the diagonal elements of Π.

Thus, the quantity $(R_t)_{ij}$ expresses the probability for the walk to start in cluster i and end up in cluster j after t steps, minus the stationary probability that two independent random walkers are in i and j.

In this way, the persistence of a cluster i is related to the diagonal element $(R_t)_{ii}$.

The stability of the clustering is defined by:

$$r(t; H) = \min_{0\le s\le t} \sum_{i=1}^{c} R_{s_{ii}} = \min_{0\le s\le t} \operatorname{trace}[Rs]. \tag{3}$$

For a given t, the aim is to maximise the stability. For $t = 0$, the most stable partition is that in which all vertices are their own cluster while for $t = 1$, maximising stability is equivalent to maximising Newman–Girvan modularity. Time can be considered as a resolution parameter, and the advantage of this method is that the resolution can be tuned by treating time as a continuous variable (Fortunato 2010).

Martelot and Hankin (2013) stated: 'the stability optimisation can be seen as an extension of modularity optimisation that does not alter the graph or the importance of the null factor, but instead exploits the graph by interpreting it as a Markov process'.

The specific version of algorithm used in this methodology, was the fast multi-scale detection of communities using stability optimisation as described by Martelot and Hankin (2013). This method uses a resolution parameter to tune the algorithm, in order to identify modules that are not necessarily maximising modularity but correspond to different levels of modularity. Another reason of using this method, was that it does not involve defining in advance a specific number of clusters (Fortunato 2010; Martelot and Hankin 2013).

For the examples of Figure 2, using the stability method for Network A, allowed four modules to be identified: Module 1 (1, 4 nodes); Module 2 (1, 3 nodes); Module 3 (5, 7 nodes); and Module 4 (6, nodes). For Network B also four modules were identified: Module 1 (1, 3, and 5 nodes); Module 2 (2, 4, and 6 nodes); Module 3 (7, 9 nodes); and Module 4 (8, 10 nodes).

3.2.2.2. Modularity metric.

The Newman modularity index, Q (Newman 2010) is a metric that originates from network science but has been used in a number of engineering applications (Sinha and Suh 2017). It is defined as:

$$Q = \sum_{i=1}^{k} (e_{ii} - a_i^2) \tag{4}$$

where e_{ii} represents the fraction of edges with both end nodes in the same module i (intra-module interfaces) and a_i the fraction of edges with at least one end node inside module i (inter-module interfaces). Here k is the number of modules.

Magee, Whitney, and Moses (2010) suggested a normalised Newman modularity metric to allow fair comparison among different size networks.

A parameter f is introduced:

$$f = 1 - \frac{(p-1)}{m}, \tag{5}$$

where p is the number of sub-groups and m is the total number of edges of the network. The normalised version of the Newman modularity metric is given by:

$$Q_n = \frac{\sum_{i=1}^{k} (e_{ii} - a_i^2)}{f - \sum_{i=1}^{k} (a_i^2)}, \tag{6}$$

Since normalisation of the metric allows comparisons among architectures of different sizes it is the one selected to be incorporated in the proposed methodology of this article. The metric is used to assess the level of modularity of the system architecture, and it requires as input the modular configuration and the undirected network (symmetric and binary adjacency matrix). Network A has the degree of modularity calculated as 0.67, whereas for Network B it was 0.77.

3.2.2.3. Structural classification.

The network theory concept of eccentricity was adapted to suggest a classification for modules. The node eccentricity *v* is the greatest distance between node *v* and any other node. The diameter *d* of a network is defined to be the maximal value of node eccentricity and the radius *r* is the minimum value. A central node in a network of radius *r* is one whose eccentricity is *r* and a peripheral node is any node with eccentricity equal to the diameter *d* (Estrada and Knight 2015). The concept of eccentricity was adapted to classify modules by determining the smallest and largest diameters of each module, and as shown in Table 2, modules are categorised into central, semi-peripheral and peripheral classes.

Due to the simplicity of Network A the modules were classified as central and periphery. For Network B, Module 1 (1, 3, 5 nodes) and Module 2 (2, 4, 6) were classified as central modules, whilst Module 3 (7, 9 nodes) and Module 4 (8, 10) were classified as periphery modules.

3.2.3. Disruption loop

The objective of the methodology is to modularise the architecture in a way that any single module disruption does not stop the system functionality thus does not jeopardise the robustness of the architecture. The disruption loop aid on identify how the disruption of the generated modules will affect the robustness to the architecture. In this way, the disruption loop is informed by the modularity loop, and includes the robustness computations. The disruptions are required inputs to calculate the robustness. Disruptions involved disturbances of components and connections of the system architecture. Disruptions are considered as generic (without knowledge of the cause).

In this methodology, the focus is the disruptions of modules. Disruption can relate to damage of several or all components within a module due for example to explosion, fragmentation, or fire. For example, in naval ships, from a survivability viewpoint it is expected that a single disruption event can result in the loss of a number of components and connections. If the system architecture is modularised, then a single disruption event may cause the loss of a module. Module disruption is simulated within the methodology through the removal of the nodes and edges within the exponential matrix. The probability that a disruption will occur, or the type of disruption, are not specifically investigated.

The main disruption scenario of the methodology which involves each module within the modular configuration to be consecutively disrupted is termed as Class 1. The structural classification of modules can inform other disruption scenarios such as a Class 2 scenario where only the central module within the configuration is being disrupted. Class 3 and Class 4 relate to disruptions to peripheral and semi-peripheral module disruption respectively.

Table 2. Classification of modules.

Classification of modules		
Central	Peripheral	Semi-peripheral
Modules' diameter equals the smallest diameter amongst the modules.	Modules' diameter equals the largest diameter amongst the modules.	Modules that are neither central nor peripheral

The formulation of disruption scenarios provides the basis on the classification of modules that may provide additional insight to the role of classes of modules in system architecture and their effects on the robustness of the system architecture.

The disruptions are formulated based on the generated modules from the stability method for the different levels of modularity. That means that for different modular configuration in the system architecture different disruptions are developed. The disruptions provide a basis to assess in what way different modules affect the robustness of the architecture, aiding in selecting an appropriate robust modular configuration.

In general, there are wide ranges of potential disruptions that must be considered in the design of a system. The effect of any disruption will depend on the architecture, which it is applied. The aim was to link non-specific disruptions with a modular architecture, providing a new approach to assess the generated modules.

3.2.4. Robustness evaluation for given redundancy, modularity and disruptions

The notion that a function can be satisfied if a set of source and sink components of the flow network maintain sufficient connectivity after a disruption is accepted in order to formulate the robustness evaluation indicator metric. The following paragraphs present the robustness evaluation indicator metric which is an updated version from an earlier formulation developed by Paparistodimou et al. (2019).

3.2.4.1. Measuring connectivity among sources and sinks before and after disruption.

For a system architecture that is represented by a directed network G, and has an adjacency matrix A, a new matrix S is constructed, a binary matrix that catalogues the existence of paths/walks (of any length) between nodes in the network. A mathematical way to compute S is to first compute the matrix exponential e^A. Estrada and Knight (2015) stated that an entry of the exponential matrix is nonzero if and only if there is a path in the network between nodes i and j. We then form a matrix S using the identities:

$$S_{ij} = \begin{cases} 1, & (e^A)_{ij} > 0, \\ 0, & \text{otherwise}. \end{cases} \tag{7}$$

S can be interpreted as determining the structurally driven behavioural robustness of the system architecture.

Sets of e sourcess $= \{s_1, s_2, s_3, \ldots, s_e\}$ and k sinks $t = \{t_1, t_2, t_3, \ldots, t_k\}$ are chosen in system architectures, and the number of 1s in the corresponding intersection of rows and columns of S is computed. The proportion of 1s gives a measure of the interconnectivity between the sources and sinks of the network. This can be recalculated after the network is subject to disruption (i.e. loss of nodes or edges). The measure works equally on directed and undirected networks. More precisely, the robustness R_{st} of the intact system architecture is measured using:

$$R_{s,t}(G) = \frac{\sum_{i=1}^{e} \sum_{j=1}^{k} S_{ij}(s_i, t_j)}{ek}, \tag{8}$$

A disruption (loss of nodes/edges) generates a damaged system architecture represented by a network G' with adjacency matrix A'. Robustness is recalculated by evaluating the connectivity among sources and sinks after disruption to give:

$$R_{s,t}(G') = \frac{\sum_{i=1}^{e} \sum_{j=1}^{k} S'_{ij}(s_i, t_j)}{ek}. \tag{9}$$

Equation (9) is computed for all non-empty subsets of S. Equation (9) is compared against the threshold redundancy criterion (RTC) generating the robustness evaluation indicator values, which if greater than the RTC are recorded as successful and values less than RTC are recorded as failures (zero value).

3.2.4.2. Average of a weighted combination of operational sources.

For e source components, all $2^e - 1$ combinations of operational sources are tested (excluding the case of all sources unavailable as that inevitably leads to loss of functional continuity). For ease of use, the information contained in the individual values of the robustness is condensed into a single term. This is achieved by calculating a weighted average where the robustness of operational sources R_i is weighted by a value that is proportional to the number of states with i sources operational and is represented by the reciprocal of the binomial coefficient $w_i = \frac{(e-i)!i!}{e!}$. Alternative experts' input could also be used to define the weight values(w_i).

Therefore, the weighted robustness R_w is calculated as:

$$R_w = \frac{1}{e} \sum_{i=1}^{e} w_i R_i. \tag{10}$$

3.2.4.3. Total robustness evaluation indicator metric.

Figure 3 presented in Section 3 illustrated the functional hierarchy and architectural options that are designed in the system architecture. The robustness evaluation indicator metric shown in Equation (9) is therefore, calculated for each architectural option.

At the sub-function level, the robustness is calculated in the following way: If a sub-function is designed for redundancy of architectural options (OR) then the robustness of the sub-function is calculated through an algebraic mean. If sub-function is not designed for redundancy the architectural option (AND) the robustness of the sub-function is calculated by the geometric mean.

Finally, the robustness is represented by Equation (11) below relates to a main functionality of the system as a whole. The geometric mean of the sub-function robustness values is used to generate an overall robustness measure for the whole system, since if any individual value is zero (which means the relevant sub-function has failed) then the overall robustness is then automatically equal to zero, given sub-functions are interdepended to satisfy the main function.

For a system with interdependent functions enumerated $l = 1, \ldots, q$ with corresponding robustness *R(l)* the total robustness is given by

$$R_{\text{total}} = \prod_{l=1}^{q} \sqrt[q]{R_{s,t}(l)}. \tag{11}$$

Equation (11) is applicable for sub-functions that must at the same time be in operation for the main function to be satisfied, thus interdependent functions. It is noted that a component could simultaneously be a source for a Type A sub-function (e.g. source cooling pump for cooling) and a sink for a Type B sub-function (e.g. sink cooling pump for power). By using a directed (flow) network, in combination with the robustness evaluation indicator metric that accepts the same components as sources or sinks, interdependencies among the sub-functions are able to be captured.

3.3. Evaluation stage of the methodology

The evaluation stage includes two approaches the reformulation of robust modular configuration and a high-level DOE analysis of the results. A manual process of reformulating the robust modular configuration, to allow an expert's preferences to be input is suggested. The robust modular configuration is formulated based on the outcome results of the analysis stage, following the principle that a disruption to a module should not stop the functional continuity of the architecture and that maximum modularity is favoured. The first step on the reformulation is to select the generated modules from the maximised modular configuration. However, the maximisation of the degree of modularity may generate non-robust modules. The second step is to search on substituting the non-robust modules with robust modules generated in the medium modular configuration. If a robust module is not found in the medium configuration, then the low-level configuration is investigated. If in the low-level configuration, a robust module is found, then two approaches are suggested to be employed. The first approach is to perform additional iterations through the modularity loop by manipulating the resolution parameter of the stability method in different values until a substitutable robust module is identified. The second approach is to manually intervene to update a specific non-robust module by removing one by one its components and calculating the robustness, until a suitable robust module is identified. Through these approaches, the architect can devise a final robust modular configuration for the system architecture.

Through the application of the proposed methodology on the Networks A and B of Figure 2, the following modules are identified: for Network A, Module 1 contains node 2 and 4 and Module 2 contains node 1 and 3 nodes, Module 3 groups nodes 5 and 7 and Module 4 clusters nodes 6 and 8. For Network B, the methodology proposed module 1 to contain nodes 1, 3 &,5 nodes and Module 2 to contain nodes 2,4,& 6, Module 3 to group nodes 7 and 9 and Module 4 to cluster nodes 8 and 9. The generated modules were assessed in Class 1 disruption and were found to be robust. Whilst an experienced engineer could find such robust modules in this simple power system without computational tools, this is challenging for increasingly complex systems with interconnected subsystems. The methodology provides both a verifiable means to track decisions made during early conceptual stages, and an objective and systematic approach to engineering systems design.

The second stage of evaluation is the DOE analysis. The methodology proposes the treatment of modularity and redundancy as two design variables of the system architecture and uses robustness as the response variable. The robustness results accumulated by the low, medium, and high levels of modularity and redundancy are analysed using a full factorial DOE. The main effects provide a basis to assess the relationship between redundancy, modularity, and robustness for the system architecture under examination. This offers insights to guide architects and decision makers for the system architecture formulation. The final stage of the methodology that involves the Selection is not further discussed here, as it is a qualitative process that depends on the decision making of the users.

4. Case study

The methodology was evaluated by applying it in an existing naval distributed system architecture. In this section, the case study system's functions and specification are described, representations of the technical system architecture are illustrated, and the implementation and results generated by the methodology are presented.

4.1. Data collection

The researcher had close communication with Subject Matter Experts (SME) of the technical system architecture to develop the case study. A senior power and propulsion engineer was involved in the development of the binary DSMs. A chief engineer was also involved to propose the alternative system architectures for the low and medium redundancy. The outcomes were discussed through meetings and unstructured interviews with the engineering manager central engineering and the engineering manager research & technology. Formal permission was granted to include SME quotes in this section.

4.2. Preliminary evaluation of the robustness evaluation indicator metric

Combined failure scenarios that would lead to a total loss of functionality were provided by the SME based on the technical specification. These scenarios would be expected to cause the robustness evaluation indicator metric to return a value of zero (not robust). Examples of these scenarios include a combined loss of HV Switchboard 1 and LV Switchboard 2; Steering Gear 1 and 2; and Chilled water manifold 1 and HV Switchboard 2. All possible combinations of two simultaneous component failures were assessed, and the associated robustness calculated. The results were checked against the expert's combined failure scenarios, providing a preliminary evaluation to allow the robustness evaluation indicator metric utilisation in the proposed methodology.

4.3. Inputs of methodology

4.3.1. Definition of the system architecture

The system architecture represents a naval ship that has either electric or gas turbine (GT) propulsion. Power is generated by four diesel generators, which supply HV switchboards, which in turn supply two propulsion motors mounted on the propulsion shafts, and the LV switchboards, via transformers. Each shaft can also be driven by a gas turbine via a dedicated gearbox. The gas turbine lubrication coolers rely on seawater for cooling. The Low-Pressure (LP) seawater system provides cooling for the transformers, and propulsion motors. The chilled water system only supplies weapons and other systems, thus does not influence the power and propulsion.

Figure 4 illustrates the schematic representation of the system architecture that is divided into four parts representing the four primary systems. The upper right section illustrates the power system, upper left illustrates the propulsion system, lower left illustrates the chilled water system, and the lower right section illustrates the seawater system. The power sources (generators one to four) are positioned on the upper right section of the schematic, whereas sinks such as propulsion motors one and two are positioned on

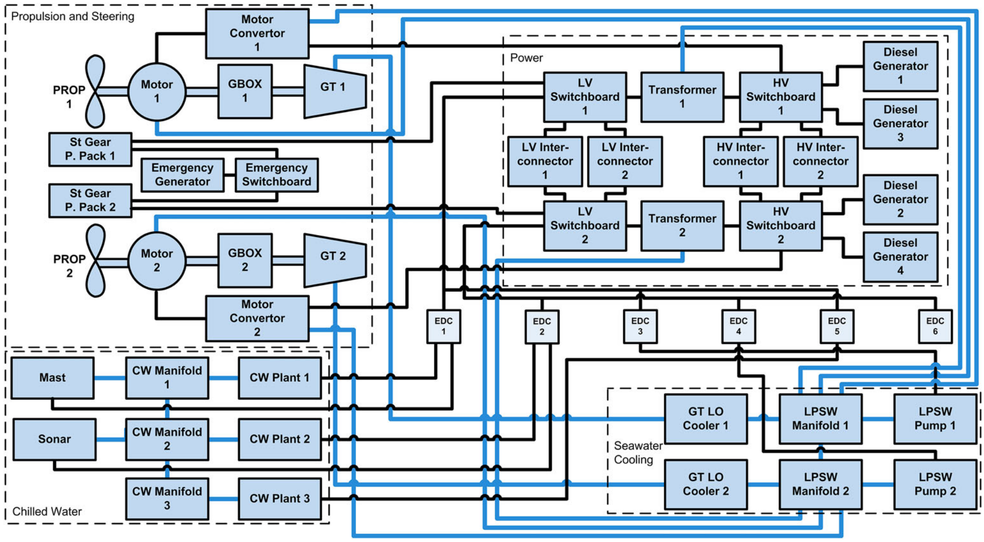

Figure 4. High redundancy technical system schematic (colour online).

the left of the schematic. The figure captures the interconnectivity amongst the different subsystems that are crucial for the system to satisfy the main function but are also critical in case of disruptions. It also encapsulates integration across functions that are not typically represented in practice, with multiple drawings used to reflect the individual subsystems for example the chilled water diagrams or electrical power distribution diagrams.

The manifolds that are critical to allow various configurations of the architecture to be instantiated are included as components. The schematic depicts the flow connections with blue and the electrical power flow connections with black colour. The system architecture represents naval distributed engineering systems (power, propulsion, chilled and seawater cooling systems) at normal cruising configuration, which requires a level of equipment and connectivity to achieve the minimum functional requirements (operational demand). After disruption, the normal cruising capability required is to be able to move and orientate the ship (propulsion and steer) and to operate fighting equipment, such as the mast or sonar. The normal cruising configuration of the system architecture has a high level of redundancy, as the functional requirements could be achieved with different alternative options of connectivity among the sources and sinks.

The system architecture should possess a high degree of robustness, as in the event of a disruption; functional continuity is required to be achievable.

4.3.2. Definition of the main functions and sub-functions

The naval ship's main function is typically described as float, move, and fight. The float function is achieved by the design of the ship and internal subdivision and is not considered in this research. The distributed systems support the other two main functions, which are move and fight. The specific sub-functions (power, propulsion, chilled water, and seawater cooling) were selected due to their direct influence on achieving the main functions of move and fight. The four sub-functions of the system architecture are examined:

generating and distributing power to electrical distribution centres (EDCs); provide energy (power or mechanical) for propulsion and steering; provide chilled water-cooling for combat systems and power and propulsion; and, provide seawater cooling for power and propulsion and other consumers. The system architecture provides additional functionalities to the naval ship but is not included within this analysis. The level of functional requirement depends on the operational scenario. For the case study, the operational scenario that was examined is the State of cruising that corresponds to a minimum level of functions.

4.3.3. Identifying the source and sink components, and determining the level of redundancy

The functional hierarchy, options, and RTC illustrated in Figure 5 are in relation to the existing system architecture characteristics that correspond to the high level of redundancy. The architectural options represent the sets of sources and sinks that were designed within the architecture to satisfy the sub-functions. The RTC was defined as the level of connectivity required amongst a set of individual source and sinks in the architecture to satisfy the corresponding function. Figure 5 shows that the RTC is 33% for the power function, as the functional requirement is satisfied if 33% connectivity is available between the power sources and sinks. In contrast, in Figure 5 for the propulsion sub-function there are 4 options, however, each option requires 100% connectivity to be considered successful. Specifically, a full connectivity amongst DG1 and DG 3 is required with PM1, a 100% connectivity of GT1 to Gearbox 1. The RTC relates to the level functional requirement (depends on the operational state) that the robustness of the architecture is assessed.

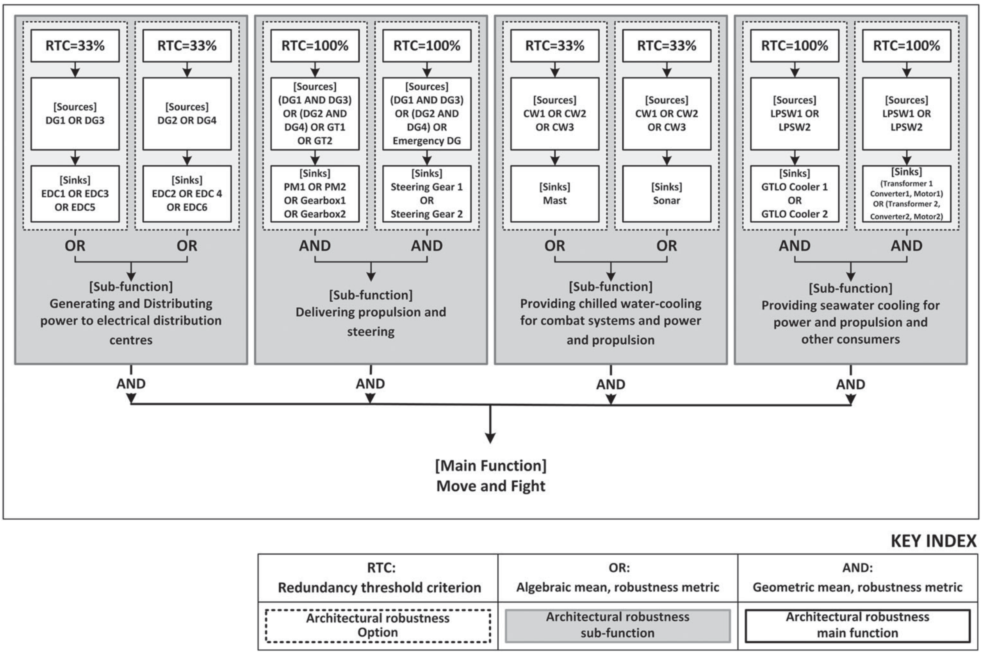

Figure 5. Functional hierarchy, architectural options and RTC for high redundancy technical system.

4.4. Analysis stage of methodology

The analysis stage of the methodology was computationally implemented using MATLAB. Figure 6 presents an abstraction of Figure 1 to provide focus on the iterative analysis loops of this stage of the methodology. Figure 6 illustrates that the disruptive loop is embedded within the modularity loop, which is embedded within the redundancy loop. That means for a single level of redundancy, iteration through the low–medium–high level of modularity is suggested, and for each level of modularity iteration through the module disruption scenarios is proposed.

Redundancy and modularity are treated as the design variables that effect robustness, that is the response variable. Redundancy is controlled through varying the additional architectural options and the RTC of the architecture. Figure 3, which defines the functional hierarchy, architectural options, RTC, sources, and sinks, requires to be redefined to vary the level of redundancy in the system architecture. The alternative system architectures with different levels of redundancy for this case study were conceived with discussions the SME. The proposed methodology recommends architects to formulate alternative options of the system architecture of different levels of redundancy for the analysis stage. In this article case study, the low level of redundancy represents an option of an architecture with

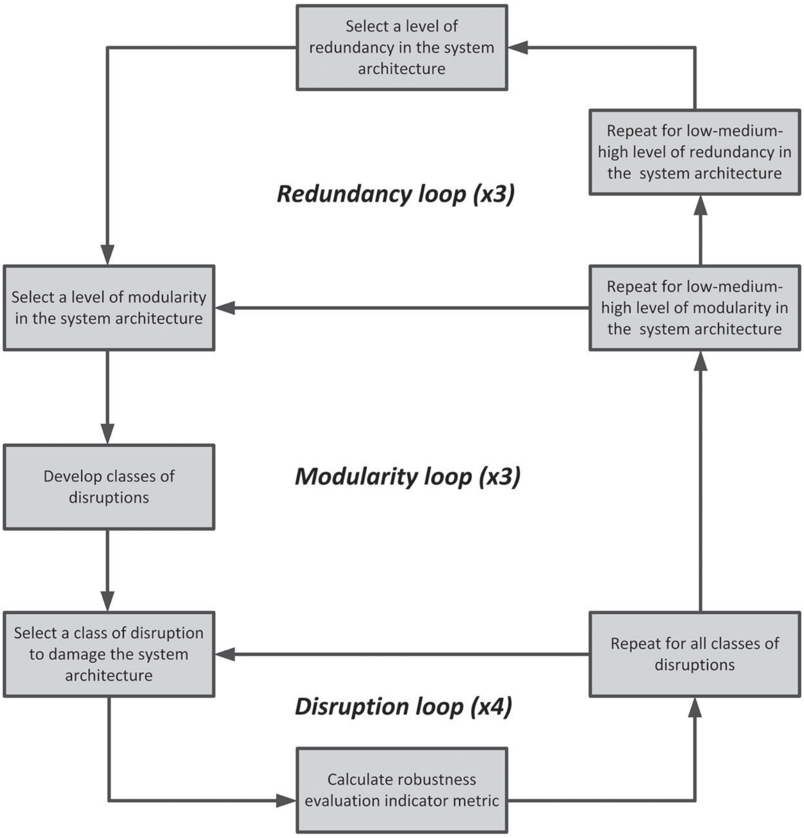

Figure 6. Redundancy-modularity-disruption loops of the analysis stage.

Table 3. Variations of the levels of redundancy in the system architecture.

DOE levels	Control factor	Level of redundancy in the system architecture	Iteration of the redundancy loops
3	High-level	Figures 4 and 5	First redundancy loop
2	Medium-level	Figures 7 and 8	Second redundancy loop
1	Low-level	Figures 9 and 10	Third redundancy loop

Table 4. Variations of the levels of modularity in the system architecture.

DOE levels	Control factor	Level of modularity	Iterations of the modularity loops
1	Low-level	Stability resolution parameter: 0.2	First modularity loop
2	Medium-level	Stability resolution parameter: 0.5	Second modularity loop
3	High-level	Stability resolution parameter: 1	Third modularity loop

almost zero redundancy (other than for propulsion), whilst the medium level of redundancy represents an option of an architecture with approximately double redundancy. The existing system architecture represents the high level of redundancy as illustrated in Figure 4.

Table 3 associates the iterations of the redundancy loop with the low–medium–high redundancy and provides a reference on the figures that are presented in following Sections 4.4.1–4.4.3.

Modularity is treated as a design variable and its levels are manipulated using the stability method. The resolution parameter of the stability method was used to control the modularity as a design variable. Through the variation of the resolution parameter, the level of modularity in the system architecture was controlled as shown in Table 4 in each iteration of the modularity loop.

In the following section, the modular configurations generated for different levels of modularity and redundancy are presented.

4.4.1. First redundancy loop

Table 5 presents the low, medium, and high modularity intermediate loop results, for the high redundancy architecture. The highlighted cells within the Tables illustrate non-robust modules whilst all other cells illustrate robust modules. Tables 5–7 encapsulate the results from all iterations of the redundancy, modularity, and disruption loops.

The high level of modularity generates a smaller number and largest in sizes modules, whereas the low level of modularity generates higher number modules of smaller size. Amongst the high and medium level of modularity a specific non-robust module was identified (EDC 1, EDC 2, CW Plant Chiller 1, CW Plant Chiller 2, CW Plant Chiller 1 – Manifold, CW Plant Chiller 2 – Manifold, Essential Consumer1 – Mast, Essential Consumer2 –Sonar). For the low level of modularity, this non-robust module is divided into two modules, whereas the one becomes robust (Module 12: EDC 1, CW Plant Chiller 1, Essential Consumer2 – Sonar) and the other remains non-robust (Module 13: EDC 2, CW Plant Chiller 2, CW Plant Chiller 1 – Manifold, CW Plant Chiller 2 – Manifold, Essential Consumer1 – Mast).

4.4.2. Second redundancy loop

The system architecture level of redundancy was varied in the second redundancy loop to represent a medium (double) level of redundancy in the architecture (Figures 7 and 8).

Table 6 presents the results of the modularity loops for system architecture of medium level of redundancy.

Table 5. Modular configurations for high redundancy technical system.

	First redundancy loop High level of redundancy in the system architecture		
Module ID	First modularity loop *Low level of modularity*	Second modularity loop *Medium level of modularity*	Third modularity loop *High level of modularity*
1	Gas Turbine 2, Gearbox 2, GT LO Cooler 2	Gas Turbine 1, Gearbox 1, GT LO Cooler 1	Gas Turbine 2, Gearbox 2, GT LO Cooler 2
2	Gas Turbine 1, Gearbox 1, GT LO Cooler 1	Gas Turbine 2, Gearbox 2, GT LO Cooler 2	Diesel Generator 2, Diesel Generator 4, Transformer 2, HV Switchboard 2, HV Switchboard Inter1, HV Switchboard Inter2, Propulsion Motor 2, Converter Regular 2, LP Sea Water Pump Manifold 2
3	Diesel Generator 1, Diesel Generator 3, HV Switchboard 1, HV Switchboard Inter1, HV Switchboard Inter2	Diesel Generator 1, Diesel Generator 3, Transformer 1, HV Switchboard 1	LV Switchboard 1, LV Switchboard Inter2, EDC 3, EDC 5, Steering Gear Hydraulic Power Pack 1, CW Plant Chiller 3, LP Sea Water Pump 1
4	Diesel Generator 2, Diesel Generator 4, Transformer 2, HV Switchboard 2	Diesel Generator 2, Diesel Generator 4, HV Switchboard 2, HV Switchboard Inter1, HV Switchboard Inter2	Gas Turbine 1, Gearbox 1, Diesel Generator 1, Diesel Generator 3, Transformer 1, HV Switchboard 1, Propulsion Motor 1, Converter Regular 1, LP Sea Water Pump Manifold 1, GT LO Cooler 1
5	Emergency Generator, Emergency Switchboard	Emergency Generator, Emergency Switchboard	EDC 1, EDC 2, CW Plant Chiller 1, CW Plant Chiller 2, CW Plant Chiller 1 – Manifold, CW Plant Chiller 2 – Manifold, CW Plant Chiller 3 – Manifold, Essential Consumer1 – Mast, Essential Consumer2 – Sonar
6	EDC 4, LP Sea Water Pump 2	EDC 1, EDC 2, CW Plant Chiller 1, CW Plant Chiller 2, CW Plant Chiller 1 – Manifold, CW Plant Chiller 2 – Manifold, Essential Consumer1 – Mast, Essential Consumer2 – Sonar	LV Switchboard 2, LV Switchboard Inter1, Emergency Generator, Emergency Switchboard, EDC 4, EDC 6, Steering Gear Hydraulic Power Pack 2, LP Sea Water Pump 2
7	LV Switchboard 1, LV Switchboard Inter2, EDC 5, Steering Gear Hydraulic Power Pack 1	LV Switchboard 1, LV Switchboard Inter2, EDC 5, Steering Gear Hydraulic Power Pack 1	
8	LV Switchboard 2, LV Switchboard Inter1, EDC 6, Steering Gear Hydraulic Power Pack 2	EDC 3, Propulsion Motor 1, Converter Regular 1, LP Sea Water Pump 1, LP Sea Water Pump Manifold 1	
9	Propulsion Motor 1, Converter Regular 1, LP Sea Water Pump Manifold 1	Transformer 2, Propulsion Motor 2, Converter Regular 2, LP Sea Water Pump Manifold 2	
10	Propulsion Motor 2, Converter Regular 2, LP Sea Water Pump Manifold 2	LV Switchboard 2, LV Switchboard Inter1, EDC 6, Steering Gear Hydraulic Power Pack 2	
11	EDC 1, CW Plant Chiller 1, Essential Consumer2 – Sonar	CW Plant Chiller 3, CW Plant Chiller 3 – Manifold	
12	CW Plant Chiller 3, CW Plant Chiller 3 – Manifold	EDC 4, LP Sea Water Pump 2	

(*continued*)

Table 5. Continued.

	First redundancy loop High level of redundancy in the system architecture		
Module ID	First modularity loop *Low level of modularity*	Second modularity loop *Medium level of modularity*	Third modularity loop *High level of modularity*
13	EDC 2, CW Plant Chiller 2, CW Plant Chiller 1 – Manifold, CW Plant Chiller 2 – Manifold, Essential Consumer1 – Mast		
14	EDC 3, LP Sea Water Pump 1		
15	Transformer 1		
Modularity metric	0.72	0.75	0.8
	Classification of modules (Modules ID)		
central modules	[3]	[6]	[4]
peripheral modules	[5,6,9,10,12,14]	[5,11,12]	[1]
semi peripheral modules	[1,2,4,7,8,11,13,15]	[1,2,3,4,7,8,9,10]	[2,3,5,6]

Table 6. Modular configurations for medium redundancy technical system.

	Second redundancy loop Medium level of redundancy in the system architecture		
Module ID	First modularity loop *Low level of modularity*	Second modularity loop *Medium level of modularity*	Third modularity loop *High level of modularity*
1	Gas Turbine 2, Gearbox 2, GT LO Cooler 2	Gas Turbine 2, Gearbox 2, GT LO Cooler 2	Gas Turbine 1, Gearbox 1, GT LO Cooler 1
2	Gas Turbine 1, Gearbox 1, GT LO Cooler 1	Gas Turbine 1, Gearbox 1, GT LO Cooler 1	Diesel Generator 1, Transformer 1, HV Switchboard 1, HV Switchboard Inter1, Propulsion Motor 1, Converter Regular 1, LP Sea Water Pump Manifold 1
3	Diesel Generator 1, Transformer 1, HV Switchboard 1	Diesel Generator 2, Transformer 2, HV Switchboard 2, HV Switchboard Inter1	LV Switchboard 1, LV Switchboard Inter1, Emergency Generator, Emergency Switchboard, EDC 3, EDC 5, Steering Gear Hydraulic Power Pack 1, LP Sea Water Pump 1
4	Diesel Generator 2, HV Switchboard 2, HV Switchboard Inter1	Diesel Generator 1, Transformer 1, HV Switchboard 1	EDC 1, EDC 2, CW Plant Chiller 1, CW Plant Chiller 2, CW Plant Chiller 1 – Manifold, CW Plant Chiller 2 – Manifold, Essential Consumer1 – Mast, Essential Consumer2 –Sonar
5	EDC 3, LP Sea Water Pump 1	LV Switchboard 1, LV Switchboard Inter1, EDC 5, Steering Gear Hydraulic Power Pack 1	Gas Turbine 2, Gearbox 2, Diesel Generator 2, Transformer 2, HV Switchboard 2, Propulsion Motor 2, Converter Regular 2, LP Sea Water Pump Manifold 2, GT LO Cooler 2
6	Transformer 2, LV Switchboard 2	Emergency Generator, Emergency Switchboard, EDC 6, Steering Gear Hydraulic Power Pack 2	LV Switchboard 2, EDC 4, EDC 6, Steering Gear Hydraulic Power Pack 2, LP Sea Water Pump 2
7	LV Switchboard 1, EDC 5	EDC 1, EDC 2, CW Plant Chiller 1, CW Plant Chiller 2, CW Plant Chiller 1 – Manifold, CW Plant Chiller 2 – Manifold, Essential Consumer1 – Mast, Essential Consumer2 – Sonar	
8	Propulsion Motor 2, Converter Regular 2, LP Sea Water Pump Manifold 2	Propulsion Motor 1, Converter Regular 1, LP Sea Water Pump Manifold 1	
9	Propulsion Motor 1, Converter Regular 1, LP Sea Water Pump Manifold 1	Propulsion Motor 2, Converter Regular 2, LP Sea Water Pump Manifold 2	
10	LV Switchboard Inter1, Steering Gear Hydraulic Power Pack 1	EDC 3, LP Sea Water Pump 1	

11	Emergency Generator, Emergency Switchboard, EDC 6, Steering Gear Hydraulic Power Pack 2	LV Switchboard 2, EDC 4, LP Sea Water Pump 2	
12	EDC 1, CW Plant Chiller 1, Essential Consumer2 – Sonar		
13	EDC 2, CW Plant Chiller 2, CW Plant Chiller 1 – Manifold, CW Plant Chiller 2 – Manifold, Essential Consumer1 – Mast		
14	EDC 4, LP Sea Water Pump 2		
Modularity metric	0.71	0.78	0.84
	Classification of modules (Modules ID)		
central modules	[11]	[7]	[5]
peripheral modules	[5,6,7,8, 9,10,14]	[8,9,10]	[1]
semi peripheral modules	[1,2,3,4, 12,13]	[1,2,3,4,5,6,11]	[2,3,4,6]

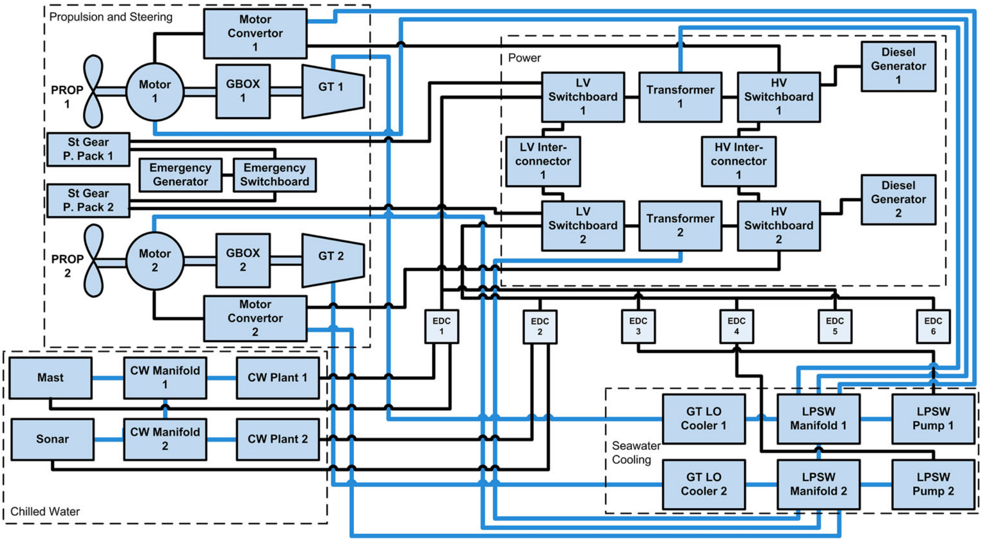

Figure 7. Medium redundancy technical system schematic (colour online).

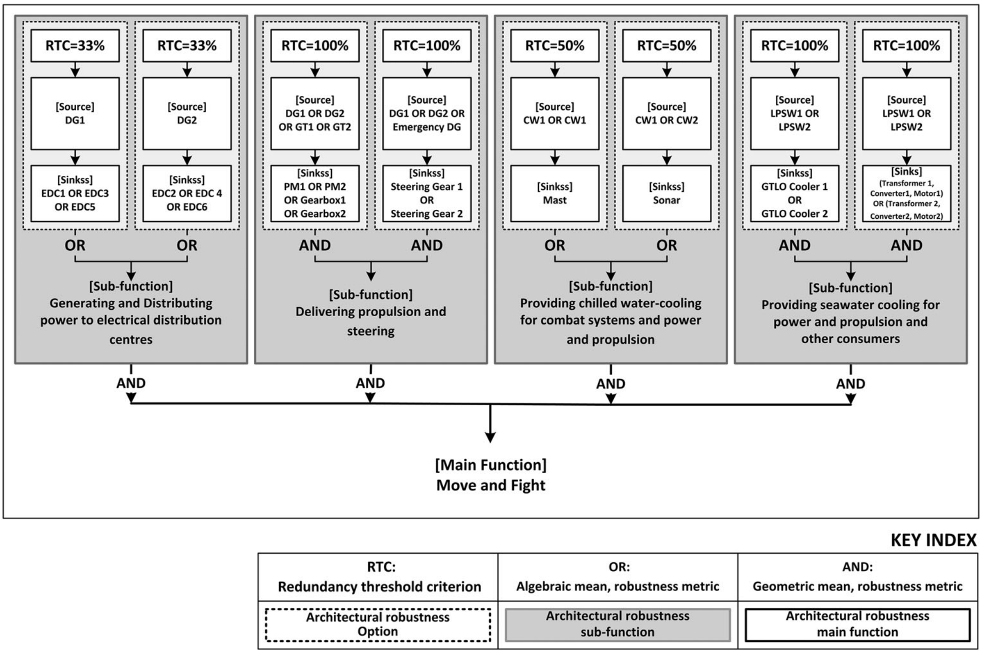

Figure 8. Functional hierarchy, architectural options, and RTC for medium redundancy technical system.

The results generated for the medium redundancy share similarities with the results generated for the high level of redundancy. This suggests that iterating through the various levels of redundancy and modularity for the same system architecture can help architects identify common robust modules. This could allow potential standardisation and commonality design initiatives to be implemented. Identifying standard and common robust modules can help to develop library robust modules that can be used at the beginning of the design.

4.4.3. Third redundancy loop

The system architecture level of redundancy is manipulated in the third redundancy loop to reflect to a system architecture with a low level of redundancy (Figures 9 and 10). This

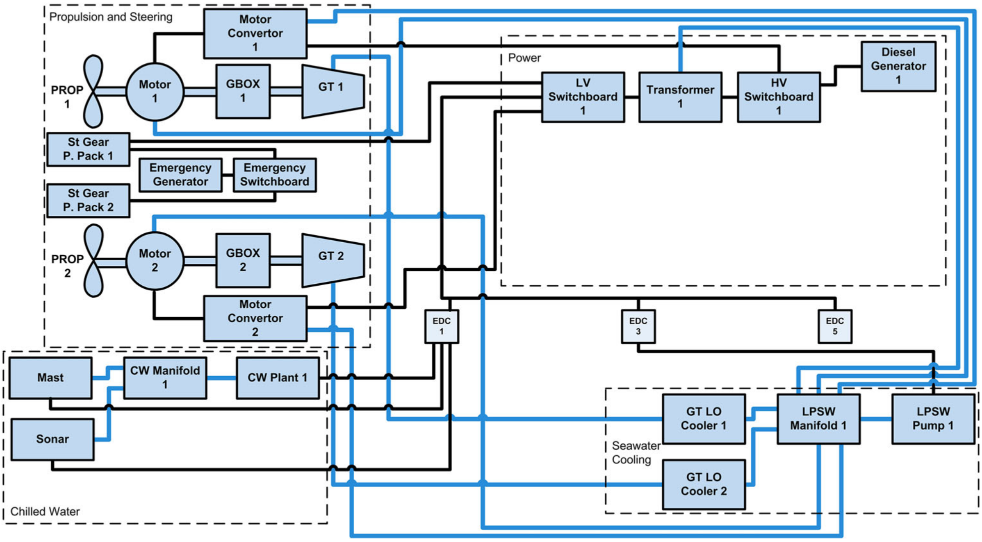

Figure 9. Low redundancy technical system schematic (colour online).

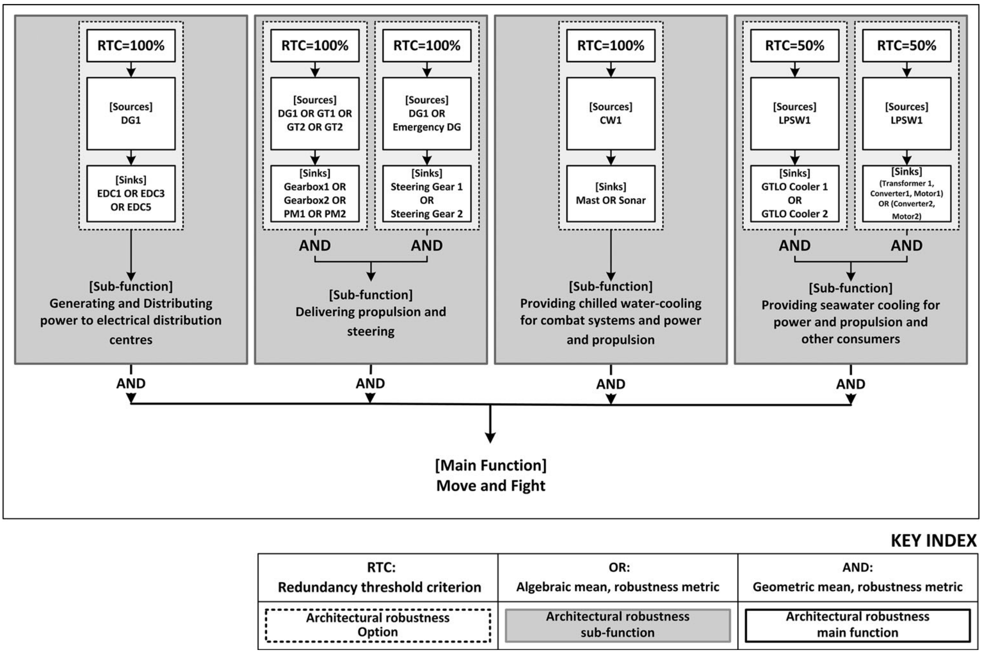

Figure 10. Functional hierarchy, architectural options and RTC for low redundancy technical system.

Table 7. Modular configurations for low redundancy technical system.

	Third redundancy loop		
	Low level of redundancy in the system architecture		
Module ID	First modularity loop *Low level of modularity*	Second modularity loop *Medium level of modularity*	Third modularity loop *High level of modularity*
1	Gas Turbine 2, Gearbox 2, GT LO Cooler 2	Gas Turbine 1, Gearbox 1, GT LO Cooler 1	Gas Turbine 2, Gearbox 2, GT LO Cooler 2
2	Gas Turbine 1, Gearbox 1, GT LO Cooler 1	Gas Turbine 2, Gearbox 2, Propulsion Motor 1	Transformer 1, Transformer 2, LV Switchboard 1, LV Switchboard Inter2, Emergency Generator
3	Diesel Generator 1, Transformer 1, HV Switchboard 1	Diesel Generator 1, Diesel Generator 2, Diesel Generator 3	Gas Turbine 1, Gearbox 1, LV Switchboard 2, HV Switchboard Inter1, HV Switchboard Inter2, LV Switchboard Inter1, EDC 5, EDC 6
4	LV Switchboard 1	Transformer 1, Transformer 2, LV Switchboard 1, LV Switchboard Inter2, Emergency Generator	HV Switchboard 1, Emergency Switchboard, EDC 1, EDC 2, EDC 3
5	Emergency Generator, Emergency Switchboard, Steering Gear Hydraulic Power Pack 2	HV Switchboard Inter1, LV Switchboard Inter1, EDC 5	Diesel Generator 1, Diesel Generator 2, Diesel Generator 3, Diesel Generator 4, HV Switchboard 2, EDC 4
6	EDC 3, LP Sea Water Pump 1	LV Switchboard 2, HV Switchboard Inter2	
7	EDC 5, Steering Gear Hydraulic Power Pack 1	HV Switchboard 1, Emergency Switchboard, EDC 1, EDC 2, EDC 3	
8	Propulsion Motor 2, Converter Regular 2	Diesel Generator 4, HV Switchboard 2, EDC 4	
9	Propulsion Motor 1, Converter Regular 1		
10	EDC 1, CW Plant Chiller 1		
11	CW Plant Chiller 1 – Manifold, Essential Consumer1 – Mast, Essential Consumer2 – Sonar		
12	EDC 5		
Modularity metric	0.71	0.85	0.9
		Classification of modules (Modules ID)	
central modules	[1,2,3,5, 11]	[4]	[5]
periphery modules	[6,7,8,9,10]	[5,6]	[1]
semi periphery modules	[4,12]	[1,2,3,7,8]	[2,3,4]

is achieved by minimising the level of connectivity and number of the source components in the system architecture. The low redundancy system architecture is able to achieve the main function defined as move and fight, however, in a naval engineering context, would not satisfy vulnerability design requirements. Hence, this is not a realistic architecture in the naval context, and is used as an ideal architecture, for comparison and analysis purposes.

Table 7 presents the modular configurations for the given low redundancy system architecture. This lowest redundancy architecture has the highest degree of modularity; compare against the medium and high-level architectures (low-level redundancy calculates maximum 0.9 degree of modularity, medium level redundancy calculates maximum 0.84 degree of modularity, high-level redundancy calculates maximum 0.8 degree of modularity). However, the potential to generate robust modularisation was lowest as shown in Table 7, whereas most of the modules generated were non-robust (highlighted cells).

4.5. *Output: robustness results for given level of redundancy and modularity*

Table 8 presents the accumulate robustness results post a single module disruption for the different levels of redundancy and modularity.

Table 8 indicates that the highest robustness results (0.757) were for a high level of redundancy combined with a lowest level of modularity, which is an expected outcome. A surprised result is that for low level of redundancy and modularity and for high level of redundancy and modularity, the same level of robustness is calculated (0.467). The medium level of redundancy and modularity calculates an average robustness 0.7, which is 0.55 less than the best robustness results. The calculated robustness values are functioning as quantitative evaluation indicators to compare amongst different types of system architecture, and their meaningfulness relates to such comparison purposes.

4.6. *Evaluation stage of the methodology*

Following the recommendations of the evaluation stage of the proposed methodology (Section 3.3), the robust modular configurations for the various levels of redundancy were devised. Moreover, the DOE analysis was performed based on the average robustness results presented in Table 8, to gain an overview of the effects of the different levels of modularity and redundancy to robustness

4.6.1. *Robust modular configurations*

Table 9 presents the robust modular configuration devised following the steps explained in the evaluation stage of the proposed methodology as discussed in Section 3.3.

The robust modular configuration ensures that in case of a module disruption the system continues functioning. The low redundancy architecture was not illustrated as it is not an appropriate solution to allow robust modularisation. Figures 11 and 12 illustrate the robust module configuration, given that there is medium and high redundancy that corresponds to the findings presented in Table 9. There were seven robust modules identified for the medium redundancy architecture as seen in Figure 11, and seven modules for the high redundancy architecture as seen in Figure 12. The different colours illustrate the modules.

Table 8. Robustness results.

	Design variables		Response variable
RUNS	Level of redundancy	Level of modularity	Level of robustness
Run 1	Low	Low	0.467
Run 2	Low	Medium	0.361
Run 3	Low	High	0.192
Run 4	Medium	Low	0.745
Run 5	Medium	Medium	0.702
Run 6	Medium	High	0.544
Run 7	High	Low	0.757
Run 8	High	Medium	0.730
Run 9	High	High	0.467

The robust modular configuration for both the medium and high redundancy ensures a high level (not maximum) of modularity in the system architecture by enabling the partition into modules without a penalisation of the robustness. The robust modular configurations were discussed with the SMEs who advised that they considered the modules to be logical in the context of a naval design given that typically at least a minimum level of double redundancy exists across the systems (in specific subsystems the level of redundancy could be either triple or quadruple). The SME commented:

> The module suggestions are interesting and provide a start point for consideration. There is sound logic in their formulation but transforming into a ship of course requires a bit more consideration, generally of constraints. For example, the orange modules have a diesel generator and propulsion motor. It may not be possible to provide enough longitudinal separation for the diesel generators given the constraints on motor location within the ship perhaps leading to the need to split each of these modules into two. This does not devalue the results in any way as they give a good starting point for the design which has already been shown to display the characteristics required.

The methodology provides an early formulation of robust modular configuration that shows compliance with the design requirements of robustness, modularity, and redundancy. Spatial constraints were not considered, and it was expected that revisions of the proposed robust modular configuration would be required. Establishing a foundation for a robust modular configuration provided a compass for architects to direct the design towards the desired requirements.

The SME noted 'High level of modularity is not necessarily better than medium level of modularity when all considerations of build ability, installation, setting to work etc. are considered. Obviously, the benefits of modularity will need to be assessed for each possible configuration.' The desirable level of modularity is subject to other aspects and trade-offs that architects are expected to take into consideration. This was the reason that the methodology was constructed using a tuneable method to identify modules that correspond to different levels of modularity.

In relation to redundancy, the SME commented

> The observation that increasing redundancy for a similar level of modularity does not necessarily increase robustness is to be expected as some of the larger modules start to contain redundant systems, for example two generators in a single module. The results for all modules in Table 9 therefore seem logical.

Redundancy at a component level requires investigation to ensure that it contributes to improving robustness. In response to disruption, the existence of redundant components

Table 9. Robust modular configurations for medium and high redundancy technical systems.

MODULE ID	Medium level of redundancy in the architecture	High level of redundancy in the architecture
1	Gas Turbine 1, Gearbox 1, GT LO Cooler 1	Gas Turbine 2, Gearbox 2, GT LO Cooler 2
2	Diesel Generator 1, Transformer 1, HV Switchboard 1, HV Switchboard Inter1, Propulsion Motor 1, Converter Regular 1, LP Sea Water Pump Manifold 1	Diesel Generator 2, Diesel Generator 4, Transformer 2, HV Switchboard 2, HV Switchboard Inter1, HV Switchboard Inter2, Propulsion Motor 2, Converter Regular 2, LP Sea Water Pump Manifold 2
3	LV Switchboard 1, LV Switchboard Inter1, Emergency Generator, Emergency Switchboard, EDC 3, EDC 5, Steering Gear Hydraulic Power Pack 1, LP Sea Water Pump 1	LV Switchboard 1, LV Switchboard Inter2, EDC 3, EDC 5, Steering Gear Hydraulic Power Pack 1, CW Plant Chiller 3, CW Plant Chiller 3 – Manifold, LP Sea Water Pump 1
4	EDC 1, CW Plant Chiller 1, Essential Consumer1 – Mast, CW Plant Chiller 1 – Manifold	Gas Turbine 1, Gearbox 1, Diesel Generator 1, Diesel Generator 3, Transformer 1, HV Switchboard 1, Propulsion Motor 1, Converter Regular 1, LP Sea Water Pump Manifold 1, GT LO Cooler 1
5	EDC 2, CW Plant Chiller 2, CW Plant Chiller 2 – Manifold, Essential Consumer2 – Sonar	EDC 1, CW Plant Chiller 1, CW Plant Chiller 1 – Manifold, Essential Consumer1 – Mast
6	Gas Turbine 2, Gearbox 2, Diesel Generator 2, Transformer 2, HV Switchboard 2, Propulsion Motor 2, Converter Regular 2, LP Sea Water Pump Manifold 2, GT LO Cooler 2	EDC 2, CW Plant Chiller 2, CW Plant Chiller 2 – Manifold, Essential Consumer2 –Sonar
7	LV Switchboard 2, EDC 4, EDC 6, Steering Gear Hydraulic Power Pack 2, LP Sea Water Pump 2	LV Switchboard 2, LV Switchboard Inter1, Emergency Generator, Emergency Switchboard, EDC 4, EDC 6, Steering Gear Hydraulic Power Pack 2, LP Sea Water Pump 2
Modularity metric	0.78	0.76
Robustness metric	0.70	0.64

does not ensure the robustness of the architecture. It was, however, acknowledged that such redundancy was included for reliability and availability reasons rather for than surviving an extensive disruption relating for example to damage within all components of a module.

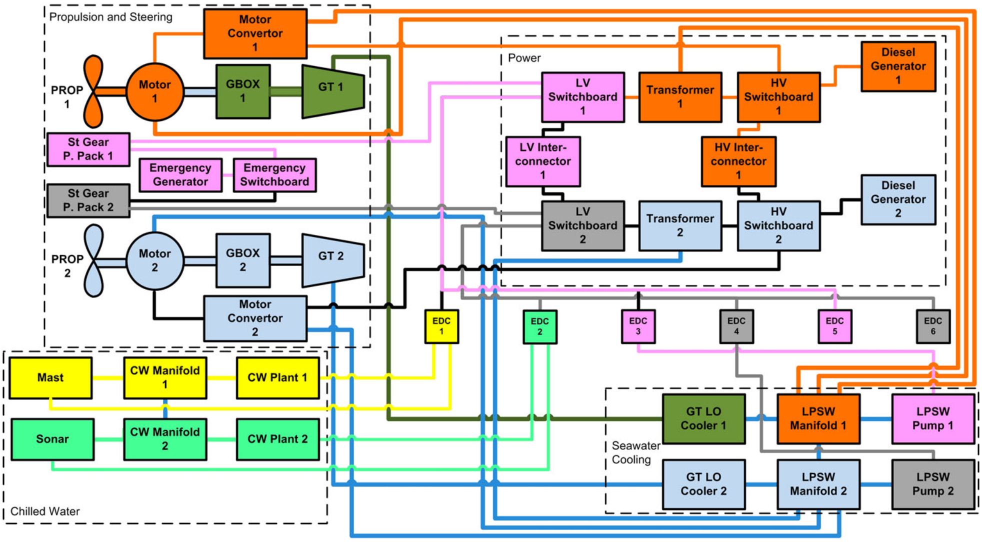

Figure 11. Robust modular configuration for medium redundancy technical system (colour online).

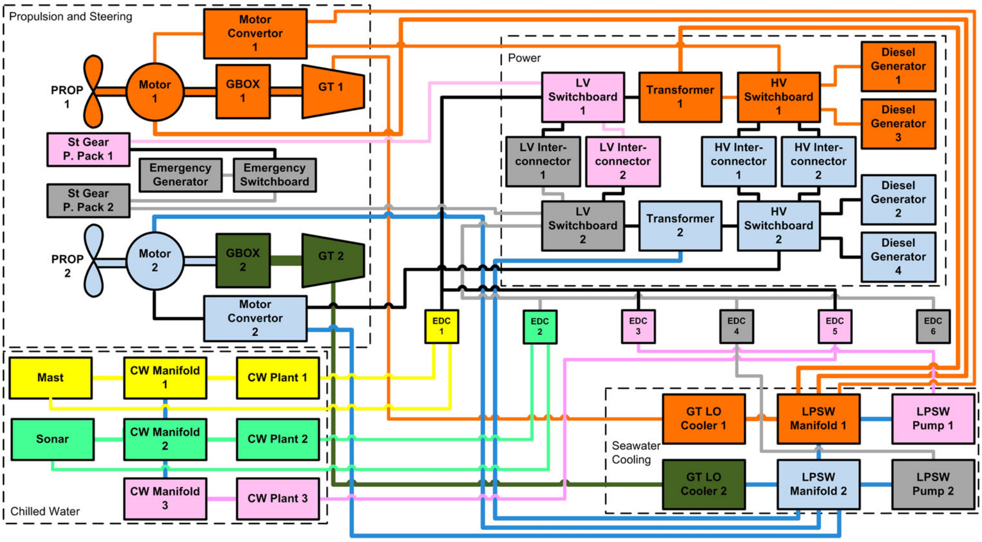

Figure 12. Robust modular configuration for high redundancy technical system (colour online).

With respect to the methodology, the SME provided the following observations:

> Being able to understand the trade-offs between redundancy, robustness and modularity has got to be a good thing! I think this helps make sense of conflicting requirements. It is always easier to develop a design when you have some start points even if they are not perfect.

The robust modular configurations were systematically generated through the application of the proposed methodology, and can offer a foundation for the design, that has demonstrated early compliance with the design requirements of redundancy, modularity and robustness. Grouping components into robust modules could help the system architect to develop the foundation for robust modular system architecture at the early design stages within the system development process where critical decisions are taken, and before detail engineering design and production take place. The methodology could be used to support architects and decision makers to take decisions at the right trajectory during the conceptual stages that can lead to significant improvements associating with cost, development time, and operational capability.

4.6.2. *DOE analysis: redundancy and modularity effects on robustness*

Figure 13 illustrates the results of the DOE analysis on redundancy and modularity effects on robustness which were calculated using the results of Table 8.

Figure 13 indicates that an increase in the modularity level, negatively affects robustness. This preliminary observation was expected, as disrupting a module of highest modularity would lead on the loss of a bigger size module that contains a higher number of components in the architecture. Medium redundancy compared to low redundancy, significantly improves robustness. However, high redundancy compared to medium redundancy does not continue to improve robustness of the architecture, subject to a module disruption, at the same extent. This observation is subject to the type of system architecture under examination, the type of disruption the robustness is calculated against and the type of redundancy. This observation is noteworthy because increasing redundancy has cost implications; it increases the spatial and power requirements; increases weight; and has a higher susceptibility for accidents and errors when relying on additional components and connections to satisfy function. From an engineering system perspective, a desired solution is to achieve robustness with increased modularity and reduced redundancy.

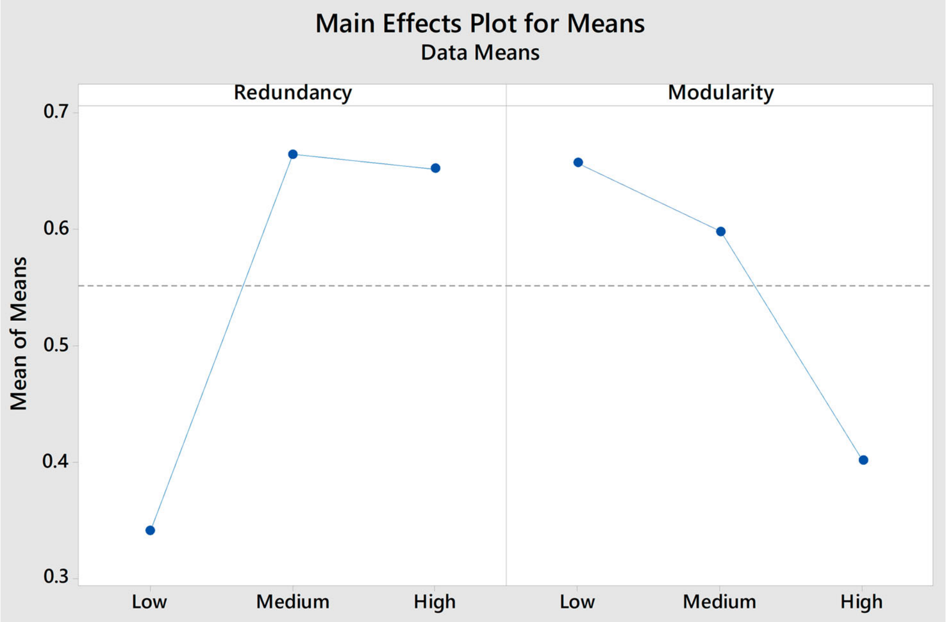

Figure 13. Redundancy and modularity main effects on robustness (colour online).

The decision on the level of modularity and redundancy is suggested as situation dependent on the system architecture under examination and the specific desired requirements relating with redundancy, modularity, and robustness. The proposed methodology is suggested to be applied in particular instances of system architectures, and the evaluation stage depends on the specific design requirements established concerning redundancy, modularity, and robustness.

With respect to the naval distributed system architecture, increasing from low to medium redundancy significantly increased the robustness. The high redundancy (redundancy of source components and connections) was not found to considerably improve the robustness of the system architecture under a module's disruption. The increase in the level of modularity leads to an increase in the size of modules. If a disruption were to happen to a large-sized module, a higher number of components (which includes the adjacently redundant component) would be simultaneously lost, meaning that the redundant component will not offer additional contribution to the robustness of the architecture.

Reflecting on the results in Tables 5–7 is also observed that for the low redundancy architecture the highest modularity is generated. This general finding confirms that increasing redundancy can lead also to reducing the potential to modularise the system architecture. The findings of the application of the methodology the naval technical system promoted the notion that a medium redundancy and a medium level of modularity could be an acceptable trade-off for satisfying a level of robustness of the system architecture. This is suggested considering the desired trade-offs which rely on the level of modularity, the considerations for redundancy and the situation depended on nature of the problem.

4.7. Reflections on the classification of modules

The proposed classification of modules was a construct proposed to investigate the architectural role of modules in the system architecture. The network theory concept of diameter was adapted to suggest the classification of modules. Diameter in network theory is used as an analogy with the survivability concept of damage extent. This analogy suggested an approximation between damage extent and diameter that allows correlation between the network and the instantiated system architecture. The damage extent in the survivability context is the physical length between components that are vulnerable to impairment by a disruption.

Based on the results of this article's technical case study, inferences on the association of the classes of modules were made. Peripheral modules were deduced to have an association with the survivability damage extent. Central modules were deduced to have an association with system functionality. For semi-peripheral modules, their association with functionality or survivability was less pronounced.

A high diameter implies a higher length amongst nodes in the network, which was assumed to relate with increased separation amongst components in the system and a higher damage extent, increasing the possibility of impairment following disruption. Based on this analogy, it was suggested that the peripheral module, which has the maximum diameter and therefore the maximum damage extent, was consequently the most likely type of module to be affected by disruption.

Accepting that peripheral modules have a high possibility to be disrupted, this suggests that a higher level of modularity could be preferable for specific periphery modules, given that concentration of components into highly coherent peripheral modules is preferable.

The central modules in the technical system case studies were observed to hold a high proportion of system functionality. These imply that the largest sized central modules could endanger the robustness of the architecture under high level of modularity as developing large size modules and given these are central, their disruption may lose a high proportion of the functionality of the system.

Semi-periphery modules are suggested to have a reduced association with survivability damage length (peripheral) and system functionality (central) and therefore offer opportunities for further manipulation, and updates. For example, in the case studies the non-robust module that was required to be updated to reformulate the robust modular configuration was a semi-periphery module.

It is expected that a different analogy would be appropriate for different system architectures which will generate different results; thus the findings are not suggested for generalisation. This discussion suggests the development of different rules and recommendations to formulate the new robust modular configuration. If architects find analogies and associations between classes of modules with other requirements and design requirements, then new principles could be developed for selecting modules. For example, another principle could be that the semi-periphery robust module of the maximum modular configuration is most preferable.

The purpose of classifying modules was to offer an additional means to expand the investigation, by supporting architects in reflecting on the architectural role and behaviour of the different classes of modules.

5. Conclusion

This article reports the development of a methodology to support in the early conceptual design of a robust modular system architecture given the level of redundancy. The methodology supports an investigation of the level of redundancy and modularity, allowing a high-level trade-off of their effects on robustness to be assessed. The methodology supports the formulation of robust module configurations for given levels of redundancy in the system architecture; a trade-off assessment of the effect of the different levels of modularity and redundancy on robustness.

A robustness evaluation indicator metric is proposed that was based on the principle that source and sink components are required to remain sufficiently connected to support functional continuity after a disruption. The level of connectivity to achieve functional continuity relates also with the redundancy level designed in the architecture. Module disruptions to the system architecture were used as an input to calculate the robustness evaluation indicator metric.

A distributed system consisting of the electrical power system, propulsion, and steering, chilled water and sea water systems from a naval ship was used as a basis to evaluate the methodology. Modularity was found to affect the robustness of systems in different ways depending on its level, and the existing level of redundancy in the architecture.

This methodology is best used during the early concept phase of a design of system architecture, particularly when there is a range of options to assess. The broad description of the system and main functions can be expressed with a minimum of detail. It may be of particular use where novel concepts are to be assessed, minimising the imposition of existing design constraints. In addition, the development of network representations of the system functions may identify areas where small changes or concessions could lead to improvements in design with reduced complexity or redundancy.

The early indications of modularity and robustness can identify problem areas where alternatives can be easily assessed and recommendations made for the next, more detailed design cycle, including reduced system complexity; system layout, concentration and separation; and, potential areas of redundancy.

One limitation of the research is that it does not investigate how modularity supports the system's robustness dynamically. The independence of modules means that they can fail without propagating the effects to the whole system, thus reducing the possibility of a spread of disruptions. Another limitation is that other factors that influence robustness such as the style of the pattern and the complexity of the architecture were not investigated. A future research direction will be to apply the methodology in different types of system architecture and to investigate how other characteristics and properties of the system architecture affect the modularity, redundancy, and robustness.

The research demonstrates the development and evaluation of a novel robust modular system architecture assessment methodology. The methodology intends to aid with the selection of components to be grouped into robust modules and that offers a trade-off analysis of the redundancy, modularity, and robustness relationship in the early conceptual stages of design. This allows experimentation with the different combinations of the levels of modularity and redundancy to achieve robustness of system architecture. Such knowledge at the early conceptual stages of design supports more informed decisions on the selection of the right robust modular system architecture that is aligned with the design requirements of the system. It is recommended that the formulation of robust modular system architecture can function as a valuable foundation to basis detailed design decisions, and positively contribute on realising cost, development time and survivability advantages.

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