

## A network tool to analyse and improve robustness of system architectures

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### Abstract

The architecture of a system is decided at the initial stage of the design. However, the robustness of the system is not usually assessed in detail during the initial stages, and the exploration of alternative system architectures is limited due to the influence of previous designs and opinions. This article presents a novel network generator that enables the analysis of the robustness of alternative system architectures in the initial stages of design. The generator is proposed as a network tool for system architectures dictated by their configuration of source and sink components structured in a way to deliver a particular functionality. Its parameters allow exploration with theoretical patterns to define the main structure and hub structure, vary the number, size, and connectivity of hub components, define source and sink components and directionality at the hub level and adapt a redundancy threshold criterion. The methodology in this article assesses the system architecture patterns through robustness and modularity network based metrics and methods. Two naval distributed engineering system architectures are examined as the basis of reference for the simulated networks. The generator provides the capacity to create alternative complex system architecture options with identifiable patterns and key features, aiding in a broader explorative and analytical, in-depth, time and cost-efficient initial design process.

**Key words:** network generator, robustness, modularity, system architecture patterns, network science

### 1. Introduction

The architecture of a system is formed by decisions taken during the initial design stage and affects the system throughout its lifecycle. Elias & Jain (2017) advised that ‘a system’s architecture profoundly influences the cost and success of a system throughout the entire lifecycle and the business processes it supports’. Crawley *et al.* (2004) define a system’s architecture as ‘an abstract description of the entities of a system and the relationships between those entities’. Wyatt *et al.* (2012) define a product’s architecture analogously as ‘a model of engineering artefact in terms of components linked by relations’. A system’s architecture (structure) realises behaviour that satisfies intended functions (Gero & Kannengiesser 2004). The architecture decides the characteristics of the system termed also as its

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attributes, lifecycle properties orilities such as flexibility, robustness, reliability and modularity, which are widely discussed in the engineering system literature (De Weck, Ross & Rhodes 2012). Different patterns of system architectures exist that can satisfy a desired function, which could be characterised by different attributes.

There are various challenges in establishing analytical and systematic approaches to formulate, analyse, evaluate and select the system's architecture in the early stages to accomplish the desired attributes. The first challenge is the low fidelity of available information or details about the system; the second is the establishment of high-level representations to model and study them. Also, explorative design of a system's architecture is often influenced by previous designs and intuitive expert opinions, which can cause design fixation effects (Purcell & Gero 1996). Additionally, the methods to perform analysis at the conceptual stages of system architectures are not quantitative (Elias & Jain 2017), and usually they examine the subsystems or specific attributes of a system (Zakarian, Knight & Baghdasaryan 2007; De Weck *et al.* 2012) causing them to be insufficient to manage the high-level abstraction of the system architecture and to examine the attributes of the architecture in combination. In view of the increasing challenges and complexity of modern engineering systems, network modelling and analysis is recommended in design research (Chen *et al.* 2018). Its application is an area of research that is continuously expanding (Braha & Bar-Yam 2004a, 2007; Baldwin, McCormack & Rusnak 2014; Parraguez, Eppinger & Maier 2015; Piccolo, Lehmann & Maier 2018), contributing to the development of new solutions that address engineering design problems.

This article presents a network generator, which is incorporated into the methodology of this article, which evaluates two attributes: modularity and robustness of technical and theoretical patterns. The generator has been developed as a network tool by combining knowledge of heuristics, literature-based engineering systems and network science and can be applied to system architectures dictated by their configuration of source and sink components structured in a way to deliver a particular functionality. The generator is developed to populate directed networks with source and sink nodes enabling robustness analysis. The simulated networks have generic similarities with engineering system networks. Two naval distributed engineering systems are studied as a point of reference as they are complex robust engineering systems.

The article is organised as follows. Section 2 presents the aim and objectives of this article. Section 3 presents a literature background on the network generator, patterns and key features, assessment, modelling and metrics of system architectures. Section 4 introduces the methodology of this article and explains the modularity and robustness metrics and methods of the assessment. Section 5 presents the preliminary work on the two naval distributed engineering systems. Section 6 explains the development of the generator and Section 7 presents the application of the network generator and discusses the assessment results of various simulated networks. Section 8 presents a redesign of the original naval distributed engineering system based on the experimental findings of Section 7. Finally, Sections 8 and 9 provide reflections, limitations and conclusions.

## 2. Research aim and objectives

The research study reported in this article aims to develop a network tool for simulating networks, allowing experimentation with various patterns and key

engineering features, as an aid in analysing and improving the robustness of system architectures in initial design stages. To achieve this aim, the following objectives are defined as guidelines for the structure of this article:

- (a) Identify patterns and features of system architectures.
- (b) Develop a generator into a computation tool.
- (c) Define the robustness and modularity assessment metrics and methods
- (d) Apply the generator to perform various experiments.
- (e) Develop a redesign example based on the experimental findings.

## 3. Literature background

This section provides a background to the literature on the generation and assessment of system architectures. It also presents the key concepts and elements employed in the development of the novel generator. Assessment of the system architectures focus on two properties: modularity and robustness, which are subsequently discussed. Finally, network modelling is proposed as the approach to model and analyse system architectures, and network-based metrics for modularity and robustness are reviewed.

### 3.1. Network generators

Network science is a field that contributes to the development of generators for experimental and analysis purposes. Albert & Barabási (2002) originally proposed a network model that generates scale-free networks that represent various real-world systems. In the communication-network literature, and particularly in relation to the internet, various works include network topology generators. An internet topology generator is a research tool to evaluate new application designs and system architectures and is often used in network research (Jin, Chen & Jamin 2000; Çetinkaya *et al.* 2011; Sterbenz *et al.* 2013). The generation allows simulations and experimentations, aiding understanding and analysis of the properties of the networks, by enabling the population of alternative topologies for evaluation and comparison purposes. Besides communication systems, and the internet examples, other engineering system studies have explored the advantages of using network generation. de Vos & Stapersma (2018) developed a generator for on-board energy-distribution systems using heuristic engineering knowledge in the context of ship distributed engineering systems.

Studies in the engineering design domain have also proposed computational network-generation approaches. Wyatt *et al.* (2012) proposed a computational support method for generating new concepts through design synthesis with network structure constraints. Moullec *et al.* (2013) proposed a system architecture generation using Bayesian networks. Luo (2015) developed a network generator to examine the impact of product architecture on evolvability. These are only some examples justifying the usefulness and utility of a generator in the context of system architectures. In line with these examples, this research proposes a novel network generator as a tool to analyse and improve robustness of system architectures. The advantages of developing a generator for the initial stages of design relate to the ability to analyse and examine the parameters of system architectures based on low fidelity of information. The key concepts that led to the development of the generator in this article are discussed in the following.

## 3.2. Patterns and key features of system architectures

The following sections provide a background on the patterns and key features (hub, source and sink) that led to the conception and development of the generator presented in Section 6.

### 3.2.1. Patterns

Alexander (1964) notably identified the concept of patterns as ‘the idea that is possible to create such abstract relationships one at a time and to create designs which are whole by fusing these relationships’. Minai, Braha & Bar-Yam (2006) stated that ‘pattern formation is an integral part of most complex systems’ functionality’. Various studies have adopted and discussed patterns in the literature. Rivkin & Siggelkow (2007) explored patterns for decision-making in complex systems and Selva, Cameron & Crawley (2016) proposed using patterns in system architecture decision-making. Hölttä-Otto *et al.* (2012) used patterns to study various modularity metrics, given that the degree of modularity of the various patterns could be anticipated. Min *et al.* (2016) used engineering patterns to study structural complexity, while Sharman & Yassine (2004) discussed various patterns to characterise complex product architectures, and Yassine & Naoum-Sawaya (2016) employed patterns to examine architecture, performance and investment in product development networks. Baldwin *et al.* (2014) proposed a methodology to identify hidden patterns in system architectures that was based on directed graphs, which allows the identification of direct and indirect dependencies. In their approach, they define three fundamental key patterns: core periphery, multi-core and hierarchical (Baldwin *et al.* 2014). For the engineering design process, Parraguez *et al.* (2015) used expected patterns characterised by network metrics and compared with empirical data to characterised by network metrics and compared with empirical data to analyse the flow of information through a complex project. In the field of applied engineering, in the context of early-stage ship design, Chalfant & Chryssostomidis (2017) proposed using patterns to provide ‘a high-level view of a system or portion of a system, consisting of a connected set of functional blocks plus general design rules and guidelines of creating a system’. Table 1 presents various patterns found in the literature.

### 3.2.2. Key features

Key components of system architectures can be characterised as hubs, sources or sinks, depending on their function in the system architecture. This characterisation of components at the initial stages of design can provide high-level information about the role of the component in the system architecture, without the need for specific details. By designing an architecture referring, for example, to a hub component instead of a switchboard or a source component instead of a generator, a generic hub–source–sink architecture can be devised, allowing the details to be decided at later stages.

#### 3.2.2.1. Hubs

Sosa, Mihm & Browning (2011) explained that ‘complex engineered systems tend to have architectures in which a small subset of components exhibits a disproportional number of linkages’. Such components are known as hubs. Sosa *et al.* (2011) studied the effects of hubs on quality (measured as the number of defects) based on empirical data. They found that there is an optimum number of

**Table 1.** Patterns in the literature

Reference	Type of patterns
(Sharman and Yassine, 2004)	Simple bus, multiple bus, auxiliary or weak or subsidiary buses, planar triangular clusters, tetrahedron of clusters, three-level design hierarchy.
(Yassine and Naoum-Sawaya, 2016)	Random, diagonal, block diagonal, local, hierarchical, dependent, small world, scale-free
(Höltkä-Otto <i>et al.</i> , 2012)	Integral, bus-like, modular
(Min <i>et al.</i> , 2016)	Integral, linear-modular, bus-modular
(Rivkin and Siggelkow, 2007)	Random, local, small-world, block-diagonal, preferential attachment, scale-free, centralised, hierarchical, diagonal, dependent
(Glazier <i>et al.</i> , 2015)	Ring, mesh, star, fully connected, line, tree bus
(Selva <i>et al.</i> , 2016)	Combining, assigning, partitioning, down-selecting, connecting (bus and star, ring, mesh tree), permuting
(Baldwin <i>et al.</i> , 2014)	Core periphery, multi-core, hierarchical

hubs that will give a positive influence on quality, highlighting the importance of the management of hubs during the early design stages.

Network science studies of hubs in engineering systems include Braha & Bar-Yam (2004a, 2007), Mehrpouyan *et al.* (2014), Braha (2016) and Piccolo *et al.* (2018). Specifically, studies (Braha & Bar-Yam 2004a; Piccolo *et al.* 2018) found that the engineering design process exhibits right skewed degree distribution, meaning a network with few high-degree nodes while the remaining nodes have low-degree nodes. In network science, scale-free networks with right skewed degree distribution are found to be highly robust against random disruptions, however vulnerable to failure in the event of target disruption (Albert, Jeong & Barabási 2000). Similar findings in the engineering design literature were confirmed for large-scale engineering design projects involving activities and people (Braha & Bar-Yam 2007; Piccolo *et al.* 2018).

The existence of hubs relates also to other network properties such as disassortativity and rich club. Braha (2016) found that ‘complex engineering networks tend to be uncorrelated or disassortative’, explaining that this characteristic ‘decrease the likelihood that the project spirals out of control’. Rich-club phenomenon characterises networks with interconnections among its hubs. Zhou & Mondragón (2004) investigated internet topologies, claiming that ‘the connectivity between rich nodes can be crucial for network properties, such as network routing efficiency, redundancy, and robustness’. Findings from the literature agree on the focus on hubs for the development of improvement approaches (Piccolo *et al.* 2018).

The definition of a hub suggested in this article is that a node is a hub if its degree is proportionally greater than the average of its neighbours. The notion of defining hubs as high-degree nodes when compared to neighbours is different from the definition adopted in scale-free networks with a power-law degree distribution that suggests that relatively high-degree nodes are automatic hubs. It is argued that the importance of a hub is due to its position in the neighbourhood of a network and cannot be directly inferred from the degree of distribution. As the hub is a key feature of systems, it was therefore chosen as a parameter in the development of the network generator described in this article.

### 3.2.2.2. Sources and sinks

A source component supplies energy, material or information to the sink components and is a feature of flow systems. The source and sink concept is used in engineering in reliability, robustness, and resilience work (Pumpuni-Lens, Blackburn & Garstenauer 2017; de Vos & Stapersma 2018). Max-flow optimisation problems use the concept of the source and sink (Pumpuni-Lens *et al.* 2017) in improving the resilience of complex engineering systems, as well as studies of reliability (Chao, Fu & Koutras 1995). Goodrum, Shields & Singer (2018) considered 'directed connectivity analyses, as well as sink-source flow analyses'. Chalfant & Chryssostomidis (2011) assessed electrical flow by employing the max-flow, min-cost algorithm. In the max-flow problem, sources supply a flow whereas sinks demand a flow, and the aim is 'to transport all the flow from the supply nodes to the demand nodes at minimum cost' (Selva *et al.* 2016). In terms of reliability, the literature suggests that 'the system is functioning if there is a connection from source to sink through working components' (Shanthikumar 1987; Chao *et al.* 1995). Moreover, hubs are noted as components between sources and sinks in distribution engineering system architectures (de Vos & Stapersma 2018).

In summary, theoretical patterns, hubs, sources and sinks are the key concepts used in the development of the novel generator (Section 6).

### 3.3. Assessment of system architectures

The architecture of an engineering system is analogous to a structural solution formulated during the synthesis process that intends to satisfy an overall function (Gero & Kannengiesser 2004). The International Council on Systems Engineering Walden *et al.* (2015) describes the architecting of systems as 'an analysis of interactions between system elements to prevent undesirable properties and reinforce desirable ones'. Typically, complex engineering systems consist of subsystems that are designed independently by different disciplines and are integrated together at the later stages of the design process. As a result, the complex system architecture is not intentionally formulated and the analysis and evaluation of desirable and undesirable properties may not take place at an early stage, leading to costly and time-consuming reformulations at later stages of design. The methodology of this article assesses two desirable attributes of the system, modularity and robustness, which are suggested to be assessed during the initial stages of the design.

### 3.3.1. Assessment attributes: modularity and robustness

Modularity and robustness are typically desired attributes, are at times conflicting (Walsh, Dong & Tumer 2019) and are analysed in isolation during the design process. Baldwin & Clark (2000) defined modularity as ‘a property of a system where the system can be divided into a different number of chunks called modules, which have strong intra-connections within the individual module and weak interconnections between modules’. Modularity is discussed widely as a beneficial property in the literature (Gershenson, Prasad & Zhang 2003). Modular architectures facilitate concurrent design and development and early testing and can be advantageous for lifetime operation and maintenance due to future savings in terms of repairs, replacements and reuse (Meehan, Duffy & Whitfield 2007). The design of a modular architecture can, however, lead to a more complex development due to the technological, planning and organisational requirements (Albers *et al.* 2019). Another profoundly essential attribute of modern engineering systems is robustness. Fricke & Schulz (2005) defined robustness as a ‘system’s ability to be insensitive towards changing environments’. Robustness is related to the survivability, changeability and resilience of systems (Fricke & Schulz 2005; Department of Defense 2011; Kott & Abdelzaher 2016). The need for robust systems is attributed to the management of their complex interdependence network, as ‘system robustness is a feature that consists of a comprehensive combination of system elements’ (Elmaraghy *et al.* 2012).

This article’s methodology (Section 4) defines modularity and robustness as the main assessment attributes as these are two critical and perhaps conflicting attributes of engineering systems.

### 3.4. System architecture modelling and metrics

Design structure matrix (DSM) modelling approaches are widely applied in engineering systems to represent the structures of product and system architectures and are valuable for modelling and analysis purposes (Eppinger & Browning 2012; Browning 2015). The DSM is simple to understand as a square matrix illustrating the relationships between matching elements positioned in the rows and columns of the matrix and offers an efficient and effective way to model and analyse systems. The relationships included in a component-based DSM relate with design dependencies such as spatial, energy, material and information (Pimmler & Eppinger 1994), and can be symmetrical or asymmetrical (Sosa, Eppinger & Rowles 2003). The majority of component-based DSMs are built based on a symmetric premise (non-directional) since the configuration of symmetric DSMs is simpler (Helmer, Yassine & Meier 2010). Most DSM analysis studies to date have focused on clustering components for modular architecture determination (Browning 2015). Researchers have also employed product DSMs to determine architecture patterns such as modules and cycles (Sharman & Yassine 2004; Fixson 2005; Sosa, Mihm & Browning 2013). The DSM is a useful way to represent a network, facilitating the application of network-based approaches (Sosa, Eppinger & Rowles 2007; Baldwin *et al.* 2014; Sarkar *et al.* 2014). Network science is the study of networks represented as nodes (vertices) of elements and edges (arcs) as the connections between the elements. Parraguez & Maier (2016) provided an overview of the challenges and key decisions when using network science to support design research. They advise that the first decision is to define

the overall research purpose (exploratory or explanatory) and the second is to select relevant network features. In line with the Parraguez & Maier (2016) guidelines, the research study report in this article has an exploratory nature, and the network conceptualisation of complex systems is unweighted (binary) and directed to enable robustness assessment. The following sections discuss network-based metrics for modularity and robustness.

### **3.4.1. Modularity network based metrics**

Network average nodal degree is suggested in the literature as a reverser indicator of modularity (Luo 2015). Sinha (2014) calculated modularity by adopting Newman's modularity index (Q). Braha & Bar-Yam (2004a) proposed the clustering coefficient as a measure of the potential modularity of complex design networks. Sosa *et al.* (2007) proposed a network approach to measure component modularity using various network metrics such as degree and centrality. Parraguez *et al.* (2015) used in combination centrality metrics and clustering coefficient to determine the level of process modularity in complex engineering design projects, stressing that it is difficult to evaluate global network topology properties such as modularity, where either centrality or clustering metrics are calculated in isolation. Section 4.2.1 elaborates further on the selected modularity metric that is employed to quantitatively assess the modularity of the networks.

### **3.4.2. Robustness network based metrics**

The most popular network science metrics discussed in the engineering system literature relate to algebraic connectivity, average path length and largest connected component. Algebraic connectivity is a network metric related to robustness. According to Mehrpouyan *et al.* (2014), 'algebraic connectivity is a good metric to be considered to determine the resilience of architecture of complex systems'. Yazdani & Jeffrey (2012) recommended an algebraic connectivity metric to measure the structural robustness of water distribution systems. However, algebraic connectivity is calculated while the network is intact, as a structural metric, and does not capture the behaviour after a disruption. Walsh, Dong & Tumer (2018) used the network average shortest path length metric to study the function of bridging components in engineering systems. Dynamic robustness has been studied by Braha & Bar-Yam (2007, 2004b), Piccolo *et al.* (2018) using the largest connected component, demonstrating that design networks are highly robust under random disruption but are highly vulnerable under targeted disruption. Papanastasiou *et al.* (2020) proposed a network-based metric tailored for a distributed engineering system that has source and sink components to study robustness. This metric is employed to assess the robustness of system architectures, as is further discussed in Section 4.2.2.

## **4. Methodology**

The methodology of this article is structured as follows. Section 4.1 outlines the inputs of the methodology. Section 4.2 explains the modularity and robustness metrics, which are used to evaluate the technical and theoretical networks. Section 4.3 provides information on the computational implementation of the methodology.



## 4.1. Inputs

The inputs of the methodology are defined as the networks: technical systems or theoretical patterns. The technical systems are described in more detail in Section 5 and are developed through data collected from the naval engineering systems. Inputs for the methodology also become the various simulated networks populated by the network generator (Section 7).

## 4.2. Assessment metrics and methods

The assessment part of the methodology is based on representing system architecture as a network, and computing modularity and robustness using the network metrics that function as evaluation indicators. The following sections describe the adopted methods and metrics.

### 4.2.1. Modularity metric and method

The Louvain community detection method is used to identify a modular configuration, in combination with a normalised Newman modularity index proposed by Magee, Whitney & Moses (2010). The Louvain community detection method (Blondel *et al.* 2008) is used to find the modules, and there is no requirement to define the number of modules. A subgraph is considered as a community if the density of interactions is higher than what could be anticipated in a random graph. The communities (modules) are discovered using spectral modularity maximisation established by the Louvain method. This method searches for communities/modules  $c_1, c_2, \dots, c_p$  that maximise a quality function  $Q$ , known as modularity, defined as

$$Q = \frac{1}{2m} \sum_{ij} \left( A_{ij} - \frac{k_i k_j}{2m} \right) \delta(c_i, c_j), \quad (1)$$

where  $m$  is the number of edges,  $\delta(m, n)$  is the Kronecker delta,  $A_{ij}$  are entries of the adjacency matrix and  $k$  is the degree of the node. Positive contributions to  $Q$  occur when an edge in the network connects nodes assigned to the same community. The quantity  $k_i k_j / 2m$  is the probability of an edge occurring in a random network with the same degree of distribution; thus,  $Q$  is sizeable only if there is a preponderance of like-to-like connections.  $Q$  is normalised to give values lying between  $-1$  and  $1$ . This quality function can be used for both unweighted and weighted networks. The Louvain community method output is a community (module), which is then used as the input to calculate the modularity metric. Parraguez *et al.* (2019) also used the Louvain method to study process modularity over time, concluding that the method identifies ‘real modules with a high degree of accuracy’.

Newman’s modularity metric Newman (2010) reflects the quality of division; therefore, higher values represent a greater readiness to divide the pattern into modules, which is advantageous. A problem with modularity is that it is difficult to compare modularity between networks. Magee *et al.* (2010) suggested a normalised Newman modularity metric to overcome this. A parameter  $f$  is introduced:

$$f = 1 - \frac{(p - 1)}{n}, \quad (2)$$

where  $p$  is the number of communities and  $n$  is the total number of edges of the network. The normalised version of the Newman modularity metric is given by

$$Q_n = \frac{Q}{f - \sum_{i=1}^k (a_i^2)}, \quad (3)$$

where  $a_i$  is the fraction of edges with at least one end node inside module  $i$ .

#### 4.2.2. Robustness metric and method

The robustness metric used is grounded on the principle that a function is satisfied post disruption if a set of source and sink components maintains a prescribed level of connectivity. This robustness metric is appropriate for any network where the ability to communicate between well-separated nodes is of paramount importance. A detailed description of the robustness metric is presented in the previous works of Paparistodimou *et al.* (2018, 2020). In short, sources and sinks are identified in the DSM, and the level of connectivity between sources and sinks is measured after a disruption. For robustness, this level must exceed a user-prescribed redundancy threshold criterion.

To compute the level of robustness, the adjacency matrix  $A$  of a network  $G$  is used to construct a new matrix  $S$ . This new matrix  $S$  is a binary matrix and catalogues the existence of paths/walks (of any length) between nodes in the network. One way to determine  $S$  is to compute the matrix exponential  $e^A$  and let  $S_{ij} = 1$  if and only if the corresponding entry of the exponential is non-zero, but other techniques can be used too. Labelling the sets of sources  $s = \{s_1, s_2, s_3, \dots, s_e\}$  and sinks  $t = \{t_1, t_2, t_3, \dots, t_k\}$ , the number of '1's in the corresponding intersection of rows and columns of  $S$  is enumerated. The proportion of '1's 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). This measure works equally on directed and undirected networks. More precisely, the robustness ( $R_{s,t}$ ) of the intact system architecture is measured using

$$R_{s,t}(G) = \frac{\sum_{i=1}^e \sum_{j=1}^k S_{ij}(s_i, t_j)}{ek}. \quad (4)$$

A disruption (loss of nodes/edges) generates a damaged network, represented by a network  $G'$  with adjacency matrix  $A'$ . Robustness is recalculated to give

$$R_{s,t}(G') = \frac{\sum_{i=1}^e \sum_{j=1}^k S'_{ij}(s_i, t_j)}{ek}. \quad (5)$$

Both (4) and (5) can be computed for all non-empty subsets of  $s$  and  $t$ .

##### 4.2.2.1. Calculating robustness using target and random strategies

The calculation of robustness under random and target strategies is an approach used in the engineering design literature (Braha & Bar-Yam 2007; Piccolo *et al.* 2018). In this article, eccentricity, a concept in network theory, is used to devise targeted attack scenarios. The eccentricity of a node,  $v$ , is the greatest geodesic distance between node  $v$  and any other (the geodesic distance is also known as the shortest path). The diameter  $d$  of a network is defined to be the maximal value of node eccentricity, and the radius  $r$  is the minimum. In targeted attack scenarios, components with the lowest eccentricity are sequentially attacked

because the lowest eccentricity components are the central components of the network and represent the core part of the system's functionality. Compared with random attacks on networks, targeted attacks tend to be more severe.

### 4.3. MATLAB computational tool

For the computations, the input used for MATLAB is the adjacency matrix representing the different networks. A new disrupted adjacency matrix is generated by removing the nodes in targeted and random attacks. Then, the robustness metric is calculated using the author's codes. MIT Strategic Engineering (2006) and Brain Connectivity Toolbox (Rubinov & Sporns 2010) codes were also used in order to calculate modularity and perform the target attacks based on eccentricity.

## 5. Preliminary work

The empirical work presented in this section included meetings with subject-matter experts (SMEs) and collection of data from the system design, engineering drawings and operational requirements. A senior power and propulsion engineer was involved in the development of binary DSMs for the two technical systems. These data are used to describe the two technical system architectures with DSMs. In the DSMs, the notation '1' shows a directed relationship from the row element to the column element. Network representations were derived based on the formulated DSMs that are presented in appendix A.

### 5.1. Technical systems Type A and B

Two warship designs with the same functional requirements were selected for the empirical work. Type A was an older legacy design and Type B was a modern design. These ship systems were selected to provide representative complex systems describing a ship's systems and operational functions. These included diesel generators (DGs), high-voltage (HV) and low-voltage (LV) switchboards, transformers, interconnectors, propulsion motors, electrical distribution centres (EDCs) and the various auxiliary cooling pumps. In naval design, systems are inherently highly redundant and robust to satisfy operational needs and survivability requirements.

Figure 1 depicts the network representation of Type A. Diesel generators (DGs) (1–4) are the main power source components that supply electrical power to the ship components via high-voltage switchboards (HV SWBDs), low-voltage switchboards (LV SWBDs) and EDCs. Propulsion can be provided by electrical power or from the gas turbines (GTs) and gearbox. Auxiliary systems, low-pressure seawater system (LPSW) support power and propulsion functions and chilled-water plants are used for combat systems. Figure 2 shows the Type B network. Power is generated by two DGs and two GT alternators, which supply the HV system for the two propulsion motors and via transformers to the LV system power to the whole ship systems. The GTs are dependent on the seawater system for cooling (GT Cooler and GT Module). The chilled-water plants cool the transformers, the filters associated with the propulsion motors and the radar equipment in the fore and aft masts. The auxiliary seawater system cools propulsion converters and motors.

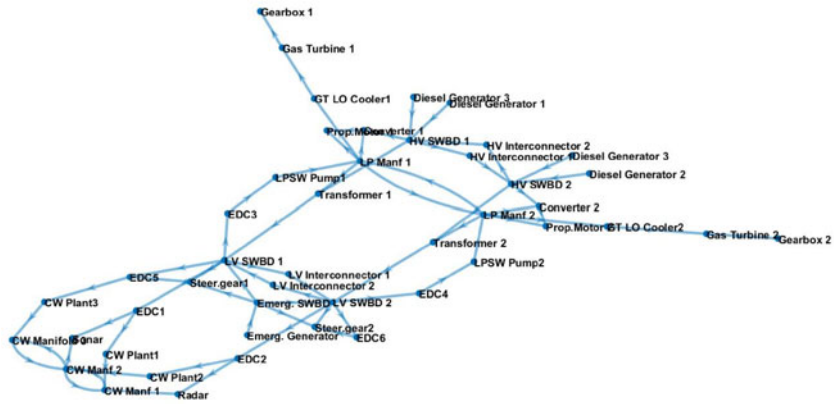


Figure 1. Technical network Type A.

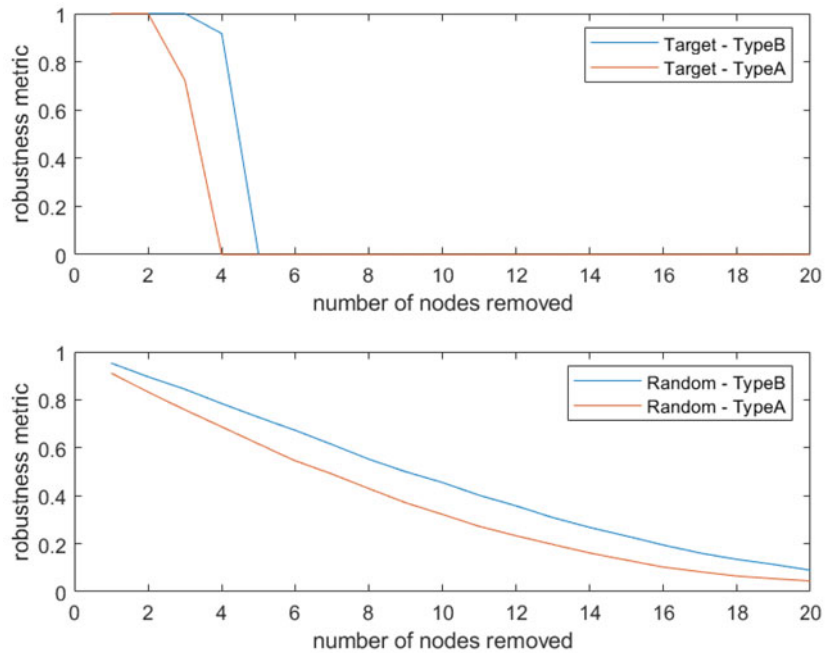


Figure 2. Technical network Type B.

Both networks (Figures 1 and 2) are shown to have a cyclical configuration, reflecting the interdependency of subsystem components. For example, electrical power generation requires LPSW cooling, but the LPSW pumps require electrical power to function. Such interdependencies create the cyclical (loop) pattern. The cyclical pattern enables the functionality of these complex and robust Type A and B technical systems.

### 5.2. Robustness and modularity results

This section presents the results of the assessment of the two technical system architectures based on modularity and robustness metrics and methods. Figure 3 shows the robustness response curves for random and targeted disruptions. For



**Figure 3.** Robustness calculations for Type A and B technical systems.

random attacks, Type B is more robust than Type A, consistent with expert opinion. However, in targeted attacks, the overall response of the two systems falls rapidly as increasing numbers of nodes are removed. Type B displays better robust behaviour under attacks when up to four central components are removed; with five or more, the robustness collapses. Large targeted disruptions suggest multiple distributed attacks; however, the systems are designed to survive a single event, meaning that multiple attacks are not representative of the operational environment.

In naval designs, spatial separation of critical duplicated components minimises the damage profile and limits the number of nodes lost. The development of future improved designs with a more linear robustness response to targeted attacks could provide improved survivability and operational capability in an evolving threat environment.

Table 2 shows the Newman modularity index for the two architectures. Type A has a higher degree of modularity, with simpler systems and fewer interconnections, whereas Type B has a lower modularity, with increased levels of interconnections (due to additional redundancy) designed to give improved robustness.

It is observed that efforts to increase the level of robustness through additional redundancy in Type B lead to a more complex architecture compared to Type A. The Type A design is a more compact and less complex distributed system allowing to be installed into a smaller platform (less costly solution). The Type B design requires considerably more volume and is a more complex system due to the need for higher automation to successfully operate, requiring a larger platform (higher cost). Even so, Type B is a more robust solution and is a more modern and advance

**Table 2.** Modularity calculations for Type A and B technical systems

Technical systems	Modularity
Type A	0.63
Type B	0.48

design. The experts consider that the Type A network has considerable benefits in respect to cost and operation.

### 5.3. Empirical observations

The empirical observations presented in this section were derived in a meeting led by the first author, with participants from industry and academia. A network science academic, two engineering design academics, one senior power and propulsion engineer and research and technology engineering manager deliberated the network representations and the robustness and modularity results of Type A and Type B technical systems. While observations 1 (Section 7.2), 2 and 3 (Section 3.2.2) are also found to be mentioned in the literature, observation 4 was established based on the discussion. Following are the four key observations derived:

- (1) The network representations (Figures 1 and 2) are cyclical. This observation is consistent with identified literature covering other domains such as mechanical assemblies, electrical circuits and system of system architectures as discussed in Section 7.2. This suggests that a component-based system architecture can be designed based on a cyclical main structure pattern.
- (2) Main hub components have source and sink components connected to them and are critical for the robustness of the system. For example, electrical supply from the generators feeds HV SWBDs representing a source style hub pattern, whereas EDCs demand from LV SWBDs representing a sink style hub pattern. This verifies that a source–hub–sink pattern exists in component-based system architectures.
- (3) The level of connectivity between hubs is designed to maintain functionality after disruption. In Type A and Type B, the hub components have alternative path connectivity designed for redundancy. This implies that a hub connectivity pattern occurs in component-based system architecture.
- (4) At a lower level of decomposition, hubs display bus-modular, star, or hierarchical style patterns. This suggests that structural patterns can be identified at a hub level.

The four empirical observations in combination with the literature findings on theoretical patterns presented (Section 3.2.1) and hubs, sources and sinks (Section 3.2.2) stimulated the development of the network generator (Section 6) and the experiments (Sections 7.1 and 7.2).

## 6. A novel network generator

This article presents a novel network generator, developed from the relevant literature on engineering design and network sciences (Sections 3.2.1 and 3.2.2)

and with empirical observation of distributed engineering systems (Section 5.3). While the observations in Section 5.3 were based on naval examples, the generator has been developed as a network tool that can be applied to system architectures dictated by their configuration of source and sink components structured in a way to deliver a particular functionality. The generator does not aim to produce feasible solutions, but rather, theoretical complex patterns that have similarities with engineering systems based on minimum detail information. The generator has the capacity to select theoretical patterns of the main structure, hubs and parameters of the hubs, such as hub size, density and level of connectivity among hubs, while classifying the components as sources or sinks combined with a threshold criterion.

Theoretical patterns are developed in the generator as unweighted networks whereas directionality is included to create source and sink nodes at the hub level. Source nodes feed hubs; in contrast, hubs feed the sink nodes. For distributed engineering systems, the energy, materials and information flow from source to sink components. It is therefore important to identify this directionality of the flows in the architecture in order to allow the assessment of robustness.

Nine parameters can be chosen by the user to fine-tune the generator in order to populate tailored simulated networks. The first two parameters (1 and 2 in Table 4) control the number of nodes and the type of main structure of the simulated network. The main structure patterns used in parameter 2 of the generator are presented in Table 3. Min *et al.* (2016) stated that commonly 'system architectures are categorized into three different configurations: integral, linear-modular, and bus-modular architecture . . . many engineering systems are configured as or resemble one of these architectural configurations to some degree'. The bus-modular, path, hierarchical and integral patterns were selected as options based on the engineering design literature (Sharman & Yassine 2004; Hölttä-Otto *et al.* 2012; Papatodimou *et al.* 2017). Additionally, the cyclical pattern was included as an option based on the observations from the preliminary empirical investigation (Section 5.3) that were consistent with references in the literature (Whitney 2003; Agarwal, Pape & Dagli 2014; Chalfant & Chrysostomidis 2017).

The article suggests that these five main structure pattern options can form the basis for the creation of various and different style simulated networks, establishing a broad range of applicability for the proposed generator. The five network main structure patterns presented (Table 3) were generated based on DSMs (examples are depicted in appendix B).

The simulated networks can be further tailored using the additional parameters of the generator. Parameters 3, 4 and 5 in Table 4 determine the number, density and type of pattern of the hubs, respectively, on the main structure. The pattern of the hub can be defined to mimic one of the main structures or can be randomised between pattern options. A level of randomisation is included in the generator with respect to the position of the hubs in the main structure. The next two parameters (6 and 7 in Table 4) define the probability that a hub's node links to sources or sinks. Nodes with edges pointing to hubs become sources; nodes pointed to by hubs are sinks. The remaining nodes of the network are assumed to be intermediate components. Parameter 8 in Table 4 is a redundancy threshold criterion variable that defines the level of redundancy of the source (e.g., 0.5 indicates double redundancy in the number of sources).

**Table 3.** Network generator parameter 2: main structure patterns

Reference	Options
(Höltkä-Otto <i>et al.</i> 2012; Sharman and Yassine 2004)	Bus modular (BM)
(Höltkä-Otto <i>et al.</i> 2012; Min <i>et al.</i> 2016)	Path (P)
(Baldwin and Clark 2000; Rivkin and Siggelkow, 2007; Sharman and Yassine 2004; Yassine and Naoum-Sawaya 2016)	Hierarchical (HI)
(Höltkä-Otto <i>et al.</i> 2012; Sharman and Yassine 2004)	Integral (IN)
(Agarwal <i>et al.</i> 2014; Chalfant and Chryssostomidis 2017; Whitney 2003)	Cyclical (CY)

**Table 4.** Parameters of network generator

Parameters	
1	Number of nodes in the network ( $n$ )
2	Type of pattern of the main structure <i>Bus modular, path, hierarchical, integral, cyclical</i>
3	Number of hubs ( $k$ )
4	Density of hubs ( $m_x$ )
5	Type of pattern of hubs (Ty) <i>Bus modular, path, hierarchical, integral, cyclical</i>
6	Probability that hub's nodes are sources ( $P_{so}$ )
7	Probability that hub's nodes are sinks ( $P_{sk}$ )
8	Redundancy threshold criterion (RTC)
9	Level of connectivity among hubs (pal)

The final parameter 9 in Table 4 gives the level of connectivity among hubs (termed pal). The parameters of the generator are summarised in Table 4. The simulated networks populated by the network generator are not expected to follow a power-law degree distribution. Evidence of this is in the findings of the technical systems previously presented (Type A and B). Previous studies on climate control and aircraft engine systems (Sosa *et al.* 2011), bicycle drivetrain, automobile drivetrain and aircrafts (Walsh *et al.* 2019) indicate that technical systems do not always exhibit a power-law degree distribution. Also, the degree distributions of the design process network studied by Piccolo *et al.* (2018) were found not to be power laws.

Section 7 presents various experiments developed by varying the different parameters of the network generator.



**Table 5.** Experimental set-up variable: main structure pattern

Parameters	Experimental set-up	
1	Number of nodes in the network ( $n$ )	40–80
2	Type of pattern of the main structure	
	S1	Bus modular (BMC)
	S2	Path (PM)
	S3	Hierarchical (HE)
	S4	Integral (IN)
	S5	Cyclical (CY)
3	Number of hubs ( $k$ )	1–10
4	Density of hubs ( $m_x$ )	5–20
5	Type of pattern of hubs (Ty)	
	Ty1	Hierarchical
	Ty2	Bus modular
	Ty3	Integral
	Ty4	Path
6	Probability that hub's nodes are sources ( $P_{so}$ )	1/3
7	Probability that hub's nodes are sinks ( $P_{sk}$ )	1/3
8	Redundancy threshold criterion (RTC)	0.5
9	Level of connectivity among hubs (pal)	0.5

## 7. Application: generation and assessment of theoretical patterns

The network generator experiments used Monte Carlo techniques to examine the influence of the parameters on modularity and robustness under both random and targeted attacks. A total of 2,500 instances were simulated for each experimental run. While experimenting with one parameter, the other parameters of the generator were randomly varied in the range of the limits set for each parameter or remained fixed at nominal values as shown in Table 5. The limits of the ranges of the parameters were derived with respect to the two technical systems (Section 5). The user can define the limits of the experimental ranges depending on the purpose behind the use of the network generator. The Monte Carlo approach based on ranges defined in Table 5 was adopted for all the experiments that are presented (Sections 7.1 and 7.2). The first author discussed in individual meetings with the SMEs the experimental results of this section.

### 7.1. Experimental set-up: varying the main structure pattern

For the following experimental set-up (Table 5), five experiments were performed for each of the main structure patterns under examination (S1 = bus modular, S2 = path, S3 = hierarchical, S4 = integral and S5 = cycle). This means for each experiment the main structure was constant, whereas the other parameters

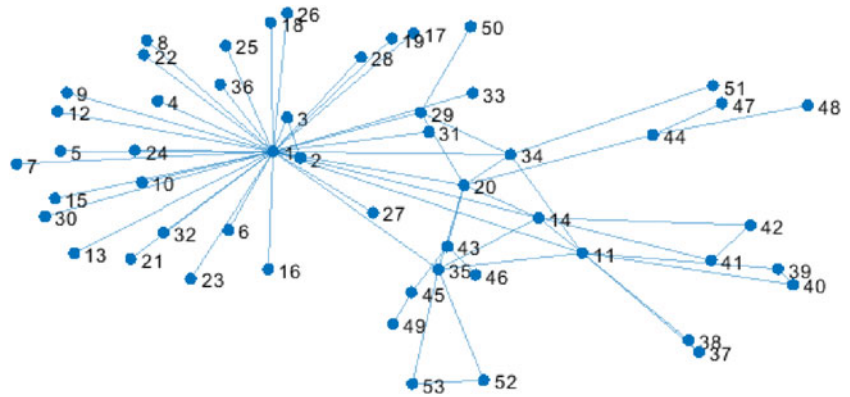


Figure 4. Random instance of a hybrid bus-modular main structure network (S1).

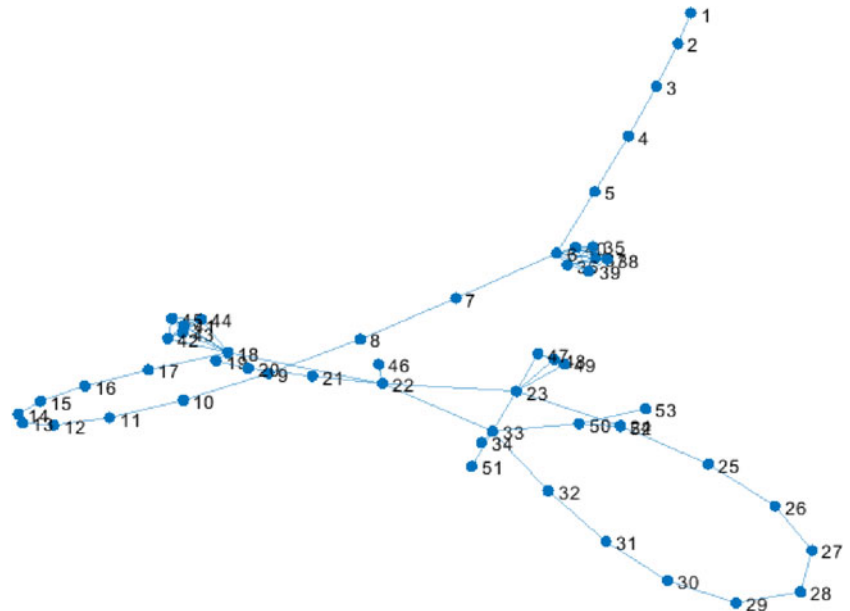


Figure 5. Random instance of a hybrid path main structure network (S2).

(1, 3, 4 and 5) were randomly selected for each instance within the predefined range and options of Table 5. The remaining parameters (6, 7, 8 and 9) were fixed. For each experiment, the robustness under random and targeted attacks and the modularity of the simulated networks were calculated. Random instances are shown in Figures 4–7 as examples of the simulated networks.

Figure 8 shows a reduction in robustness for an increasing number of random and targeted disruptions for all hybrid patterns. The hybrid ‘integral’ simulated network with a high number of interconnections exhibited the highest robustness under both targeted and random attacks. However, this high level of connectivity is not an efficient feasible arrangement; as Chan, Akoglu & Tong (2014) explained: ‘ideally, a fully connected network is the most robust; however,

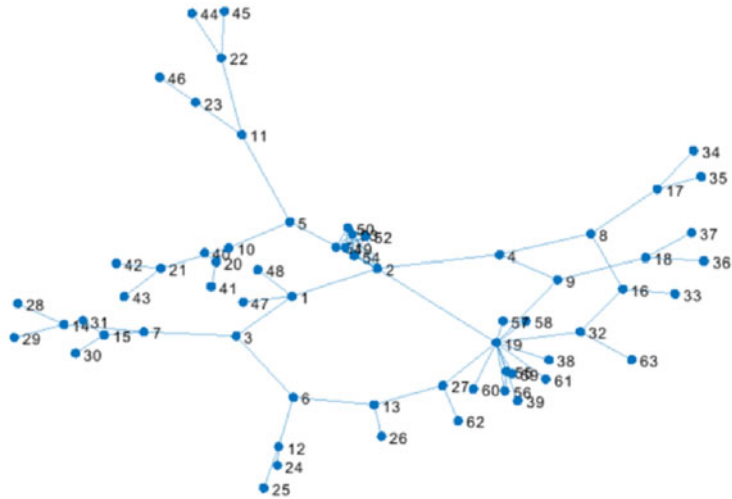


Figure 6. Random instance of a hybrid hierarchical main structure network (S3).

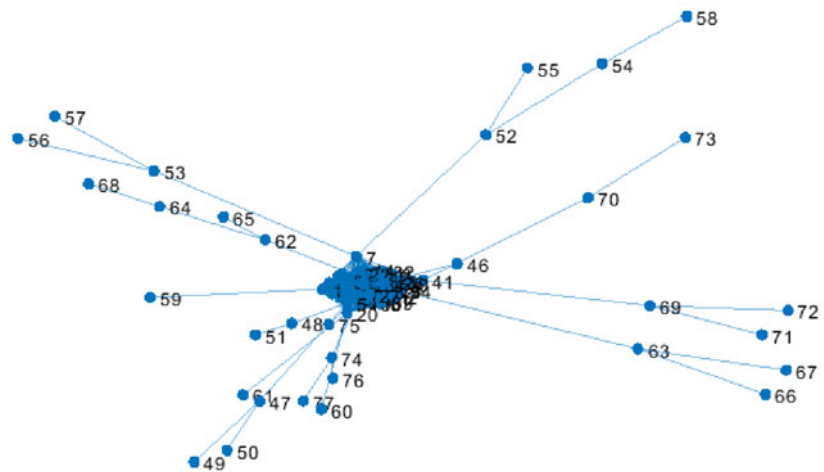
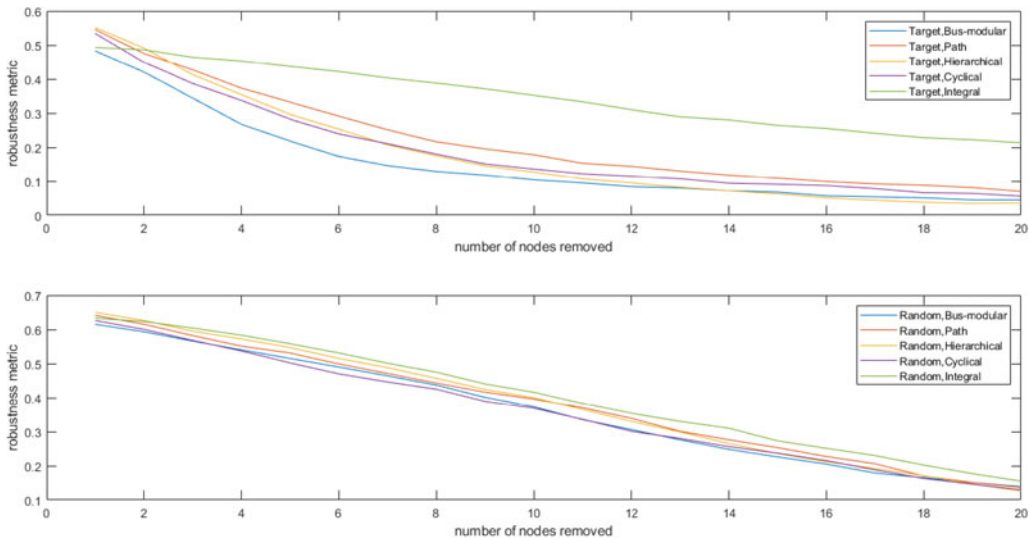


Figure 7. Random instance of a hybrid integral main structure network (S4).

it is not feasible to design such real-world networks due to constraints in physical space, budget, etc.’ The hybrid bus-modular network had the worst performance under targeted disruptions. Disruption of the most central component of the bus-modular pattern influences the whole pattern, leading to increased vulnerability, although it has acceptable levels of modularity. The ‘cyclical’ pattern has a more straightforward, low connection, low-cost arrangement, with potentially the most desirable robustness under targeted disruption. The initial examination of the results for the simulated cyclical pattern suggests that it could provide improved robustness behaviour compared to the two naval design systems previously assessed in Section 5.2.

The simulated cyclical pattern did not have as sharp loss of the robustness under the four or more target component attacks as that in Figure 3 of the naval



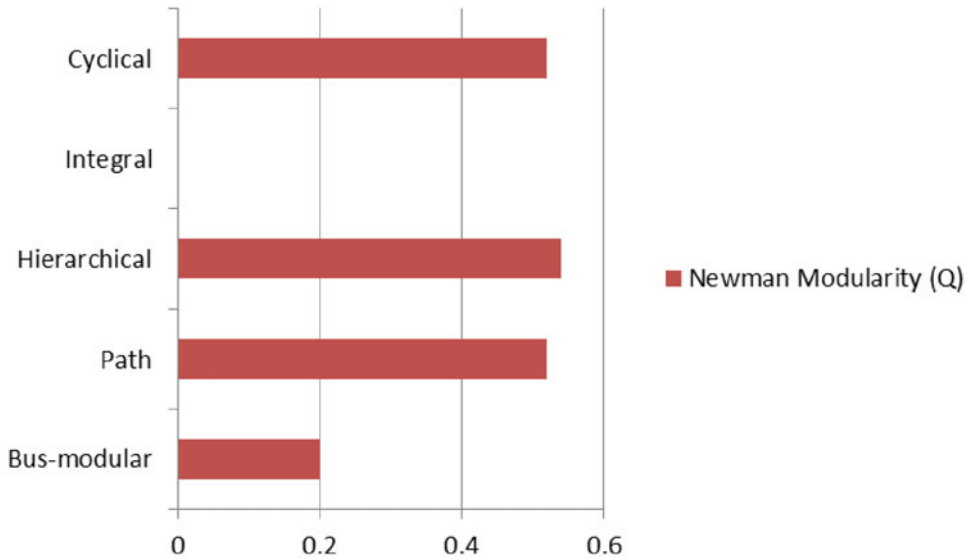
**Figure 8.** Robustness calculations varying the main structure patterns.

design systems. The robustness of the architecture patterns to random attacks is broadly similar, showing an almost linear decline as the number of nodes removed increased. However, with targeted attacks, all of the patterns showed a rapid nonlinear reduction in robustness, with variations between the patterns examined. This implies that the choice of pattern is important, particularly in environments where target disruptions can occur.

The topology of the design process bipartite network presented in Piccolo *et al.* (2018) shares trivial commonalities with the bus-modular simulated network (Figure 4). The Piccolo *et al.* (2018) network is larger (259 nodes) than the networks simulated in this article by a factor of between 3 and 6. Nevertheless, the decay of robustness presented in Piccolo *et al.* (2018) has a similar profile to the results in Figure 8; in particular, targeted attacks of central nodes result in a much sharper deterioration of robustness in comparison to random attacks. The fact that there are some similarities even though the measures of robustness are different and the network architectures have only trivial commonalities is worthy of further research.

The results (Figure 9) show the modularity assessment. The path (PM), hierarchical (HE), and cyclical (CY) hybrid patterns provided the best modularity results, between 0.52 and 0.54, whereas the two technical patterns exhibited a comparable degree of modularity, between 0.63 and 0.48. The integral (IN) pattern is highly interconnected and could not be readily divided into modules, giving a  $Q$  value close to zero. This experiment with the generator provided an overview of the effects of the different main structure patterns on robustness and modularity.

In the next step of the study, it was decided further experiments should focus on the cyclical main structure pattern.



**Figure 9.** Modularity calculations varying the main structure patterns.

## 7.2. Cyclical main structure pattern experiments

The cyclical pattern shares similarities with respect to its configuration with the two technical systems (Type A and B) presented in Section 5. As was observed in Section 5.3, the two technical systems have a cyclical network configuration, showing a loop-style pattern with the main hubs identified and additional connectivity among the hubs and other components. The existence of closed loops (cycles) was a key observation in the Type A and B technical systems. In addition, relevant references were found in the literature that supports further exploration. For example, Chalfant & Chryssostomidis (2017) discussed ship propulsion configuration, explaining that there could be two styles, a cyclical and an integral (mesh): ‘[it] may require closed-loop paths for operability as in lube oil and chilled water systems, or may allow many redundant paths through a complex mesh-restorable network as in an electrical distribution system’. Whitney (2003) argued that patterns (motifs) that generate functions are cyclical (closed loops) in the context of technological networks such as mechanical assemblies and electronic circuit. Moreover, a study by Agarwal *et al.* (2014), which aimed to identify an appropriate system of system architecture to satisfy multiple objectives, including robustness and modularity, found that a circular graph was the best pattern. These reasons motivate further experimentation with the cyclical pattern.

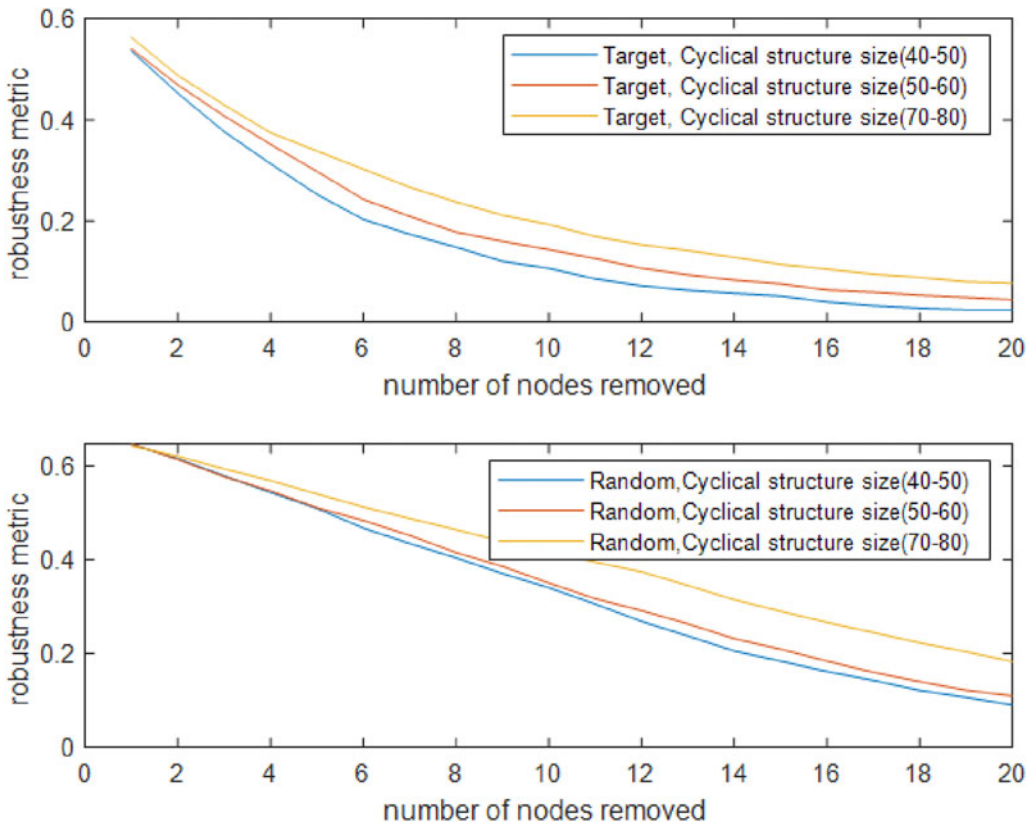
### 7.2.1. Experimental set-up: varying the number of nodes

The first experiment (Table 6) for the cyclical main structure pattern focused on variations in the number of nodes of the network and possible effects on the level of robustness and modularity.

Figure 10 shows a rational behaviour with the robustness response falling as the number of disruptions increased. There was broadly similar behaviour for

**Table 6.** Experimental set-up variable: number of nodes

No.	Parameters	Experimental set-up		
1	Number of nodes in the network ( $n$ )	$n = 40-50$	$n = 50-60$	$n = 70-80$



**Figure 10.** Robustness calculations varying the number of nodes (size of network).

**Table 7.** Modularity calculations varying the number of nodes (size of network)

Hybrid cyclical pattern	Modularity
$N = 40:50$	0.48
$N = 50:60$	0.51
$N = 70:80$	0.55

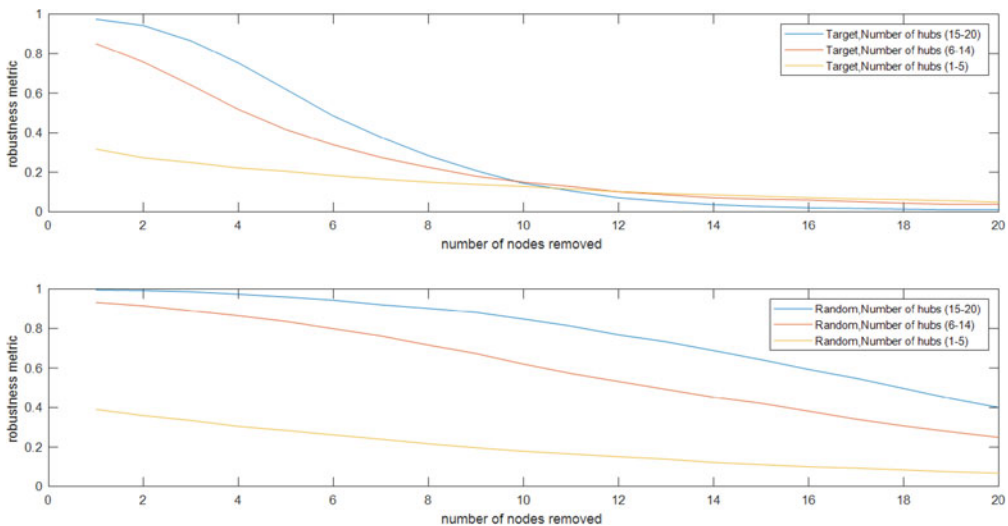
all sizes of the cyclical pattern for both random and targeted disruptions, with a small reduction in robustness as the size of the main structure was reduced. It can therefore be deduced that scaling a cyclical pattern will not crucially influence robustness. With respect to modularity, the Table 7 results indicate that the modularity increases slightly as the size of the cyclical pattern increases.

**Table 8.** Experimental set-up variable: number of hubs

No.	Parameters	Experimental set-up		
3	Number of hubs	$K = 1-5$	$K = 6-14$	$K = 15-20$

**Table 9.** Modularity calculation varying the number of hubs

Hybrid cyclical pattern	Modularity
Number of hubs = 1:4	0.57
Number of hubs = 5:7	0.50
Number of hubs = 8:10	0.50



**Figure 11.** Robustness calculations varying the number of hubs.

From the previous results with a broader size range (from 40 to 80), the degree of modularity was 0.52. The findings suggests that the size of the main structure pattern does not significantly affect either its robustness or its modularity.

**7.2.2. Experimental set-up: varying the number of hubs**

The experimental set-up in Table 8 presents the variation in the number of hubs.

It can be observed that increasing the number of hubs initially protects the network from targeted hubs but then leads to an increased vulnerability once the scale of the attack passes a certain threshold (in Figure 11, this threshold is 10 nodes) whereas for random attacks no such threshold is apparent. Large-scale targeted attacks will tend to remove complete hubs. In the simulated network, the increased frequency of hubs also increases the frequency of removal of interconnections between hubs in target attacks, which might explain the phenomenon observed here as the removal of these ‘arteries’ proves catastrophic.

But in random attacks the chances of disrupting an artery are diminished and the added communicability provided by a plethora of hubs proves beneficial to robustness. Such contradictory behaviour highlights the need for balance in the design.

In technical systems, hubs may be designed with spatial separation from each other because the designer aims to avoid a single disruption affecting more than one hub simultaneously. In the case of an extended disruption of the system that can damage more than one hub, the robustness decreases significantly. The findings suggest that the number of hubs should be carefully considered, given the expected operational environment of the system: many hubs could be detrimental to robustness, and so the spatial separation of hubs in terms of the physical design is fundamental. However, addressing only the spatial location of hubs does not resolve the problem, as an intelligent attacker may be aware of the location of hubs and intentionally disrupt them simultaneously. Technical system architectures have specific structures, where the increased number of hubs suggests increased redundancy and improved robustness. In network science, the number of hubs is considered to be a point of vulnerability in scale-free networks (Albert *et al.* 2000). However, in the simulated networks small in size (40–80 nodes) and with a limited number of hubs, the vulnerabilities introduced by hubs are more considerable only if an extensive targeted attack occurs in the system, rather than an attack of a smaller magnitude.

Sosa *et al.* (2011) argued that ‘the presence of hubs has a significant effect on system quality (measured by the number of defects in the system)’ and concluded that there is an ‘optimal presence of hubs which minimize the number of defects in the system’. Their work is different from the experiments presented herein, as the focus of their study is on quality. However, our results provide further evidence that there is an optimal number of hubs in the design of technical systems. The redundant hubs are the ones that are readily available to take over the functionality in the case of a targeted attack on a hub, as they are designed to avoid such targeted attack effects. However, determining the correct number of hubs in a technical system is not a straightforward task and requires a careful investigation and consideration of the expected operational environment in which a system is designed to survive.

Keeping the number of hubs in the simulated cyclical network small gives a higher level of modularity than when there are a larger number of hubs. Since there is a constant level of interconnections between hubs in the generator, their number will increase as the number of hubs increases. The higher interconnectivity reduces the ability to divide the network pattern into modules, and hence reduces the modularity.

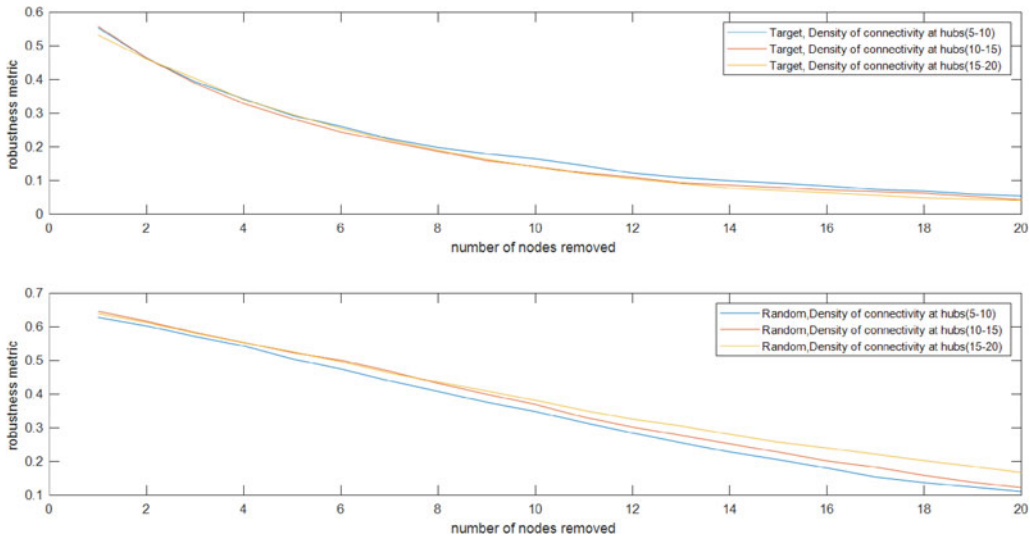
The experimental findings indicate that a smaller number of hubs positively affect modularity in the development of coherent modules; however, robustness falls under targeted attacks. The important finding is that robustness has a cut-off point, meaning that for disruptions that are extensive in magnitude, an increase in the number of hubs in the architecture provokes a sharper decline in robustness.

These experimental findings is used to inform the redesign of Type A (Section 8). The original designs, Types A and B (Figure 4), show that the level of robustness of the two naval designs collapses with more than four or five central components removed. As was previously discussed, a more linear degradation of robustness is preferable. The naval technical systems have in total four main



**Table 10.** Experimental set-up variable: density of hub

No.	Parameters	Experimental set-up		
4	Density of hubs	$m_x = 5-10$	$m_x = 10-15$	$m_x = 15-20$



**Figure 12.** Robustness calculations varying the density of hubs.

hubs ( $2 \times$  LV SWBDs and  $2 \times$  HV SWBDs). The simulated networks shown in Figure 11 suggest the possibility of improved robustness by increasing the number of hubs above five given that disruptions that remove more than ten central nodes simultaneously are not expected to occur during operational life. The worst-case scenario in naval design examples only considers single attack events and not multi-attacks. In this case, increasing the number of hubs can positively affect robustness under target and random disruptions. This finding can provide insights to guide the selection of new design options. Section 8 implements this experimental result in the redesign of the Type A technical system. As another example, a future warship power system design may have six to eight discrete power generator modules ‘DG Source feeding HV hub’ configured, separated and controlled to deliver specific functions on board.

**7.2.3. Experimental set-up: varying the density of hub**

The experimental set-up in Table 10 is focused on the variation in the density of hubs.

The density (i.e., the number of source/sink interconnections, for example, the number of consumers/sinks connected to a hub) of the hubs does not significantly influence the robustness of the patterns under targeted or random disruptions as shown in Figure 12. There is a marginal indication that robustness with higher density hubs is slightly reduced under targeted attacks and slightly increased following random attacks.

**Table 11.** Modularity calculations varying the density of hubs

Hybrid cyclical pattern	Modularity
Density of hubs = 5:10	0.56
Density of hubs = 10:15	0.51
Density of hubs = 15:20	0.52

**Table 12.** Experimental set-up variable: hub pattern

No.	Parameters	Experimental set-up			
5	Type of pattern of hubs	Hierarchical	Bus modular	Integral	Path

The results of experiments on the density at the hub level in Table 11 suggest that the modularity falls slightly to a limiting value as the density of the hub increases. This may be explained by the increased level of interconnections between hubs as the hub size increases. The density of hubs does not drastically influence either the robustness or the modularity of the system architecture. The experimental findings indicate that the density of hubs is not a significant factor in influencing the robustness of the architecture. The density of the hub relates to the number of source and sink nodes connected to the hub. This finding could be useful when designing the system architecture, because additional or fewer sink and source components could be added onto the hubs. In practice, the numbers of sources and sinks at the hub level are considered key elements for designing redundancy in the architecture. However, the experimental findings suggest that a reduction in the number of sources and sinks could be an aspect of trade-off in a future redesign given that other redundancy design strategies are adopted. This is implemented in the Type A redesign (Section 8), where the number of sources is reduced at the hub level and an additional hub is designed in the architecture.

**7.2.4. Experimental set-up: varying the hub pattern**

Table 12 shows an experimental set-up on the variation in the patterns of the hubs.

The robustness of architectures subjected to targeted disruptions was found to be insensitive to the type of hub pattern style (apart from a path pattern). Path patterns at the hub level showed the worst robustness under both random and targeted disruptions, as any loss of node reduced it.

In general, robustness improved as the level of interconnectivity increased. The simulated networks of this experiments show that a bus-modular hub level pattern has acceptable performance (Figure 13) while at the main structure level, a bus modular has the worst performance (Figure 8). Bus-modular-style hub level patterns are also identified in the two naval design examples. The power and propulsion expert gave the following example: ‘In ships’ electrical systems there are separate generators and switchboards. Power to ships’ equipment is taken from the EDCs, which are located throughout the ship. Each EDC has a changeover switch connecting either the normal supply from one switchboard or an alternative supply from the other switchboard. To reduce vulnerability, the switchboard/EDC

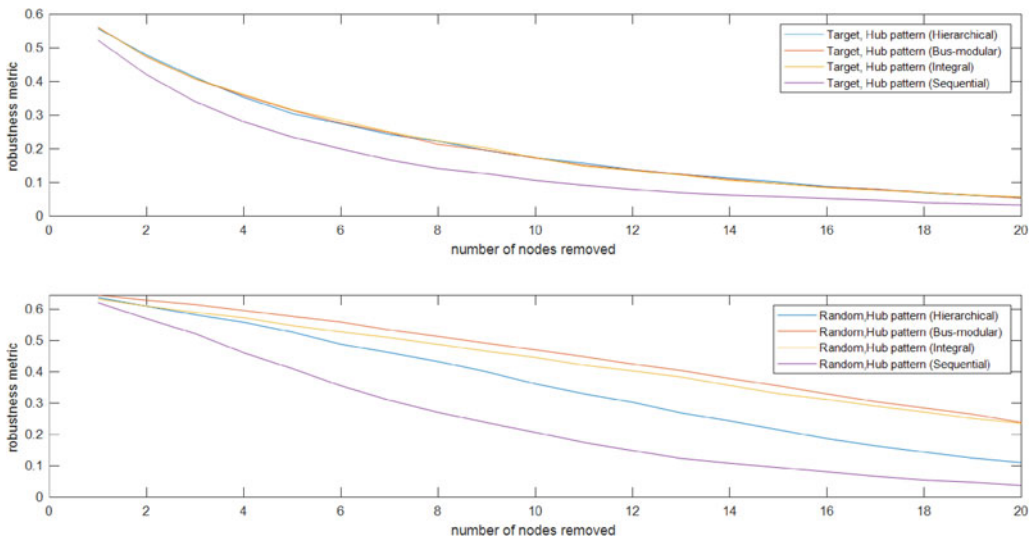


Figure 13. Robustness calculations varying the hub pattern.

Table 13. Modularity calculations varying the hub pattern

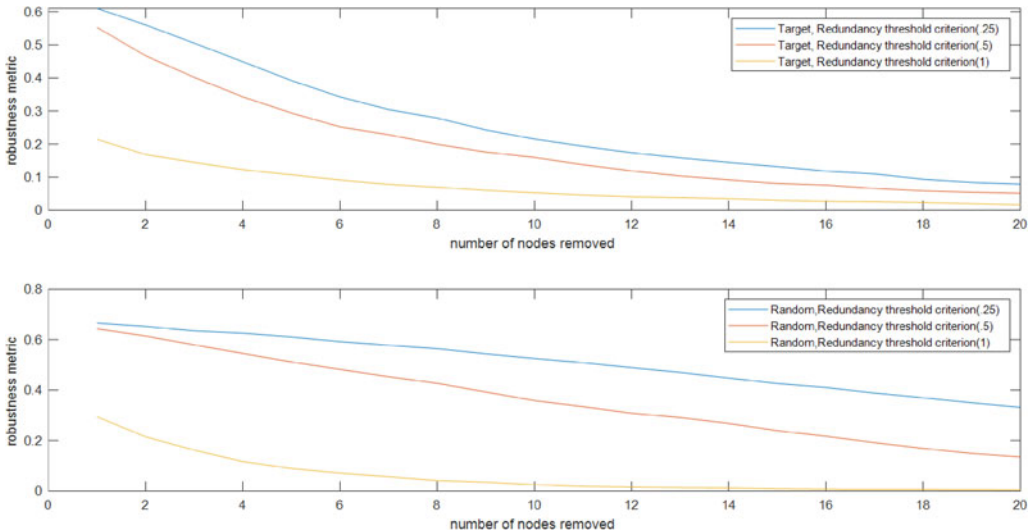
Hybrid cyclical pattern	Modularity
Hierarchical hubs	0.66
Bus-modular hubs	0.59
Integral hubs	0.29
Path hubs	0.65

cables run on opposite sides of the ship. The interconnections between EDCs and equipment are typically a single path, which tends to increase system vulnerability. For some of the critical ship systems, additional changeover switches are located close to the equipment to provide additional normal and alternative supplies from adjacent EDCs'. This arrangement suggests two 'bus-modular' patterns, with 'star' interconnections at a hub level. The choice of hub pattern may have less effect on robustness in the case of targeted disruptions; however, for random disruptions, it may be more beneficial to design bus modular or integral hub patterns because of increasing reliability and availability of engineering systems.

The baseline hybrid cyclical patterns have a modularity of 0.52 (Figure 9) that is based on random allocations of hub patterns (bus modular, path, hierarchical, cycle and integral). The results in Table 13 show a significant reduction in modularity, when it is defined as integral hub patterns (the hub pattern is not randomly selected). This means that the integral pattern at the hub level can influence the overall degree of modularity. All of the other hub configurations show higher modularity when compared with the baseline, indicating also that the hub pattern is an influential factor in controlling the degree of modularity.

**Table 14.** Experimental set-up variable: redundancy threshold criterion

No.	Parameters	Experimental set-up		
		RTC = 0.25	RTC = 0.5	RTC = 1
8	Redundancy threshold criterion	RTC = 0.25	RTC = 0.5	RTC = 1



**Figure 14.** Robustness calculations varying the redundancy threshold criterion.

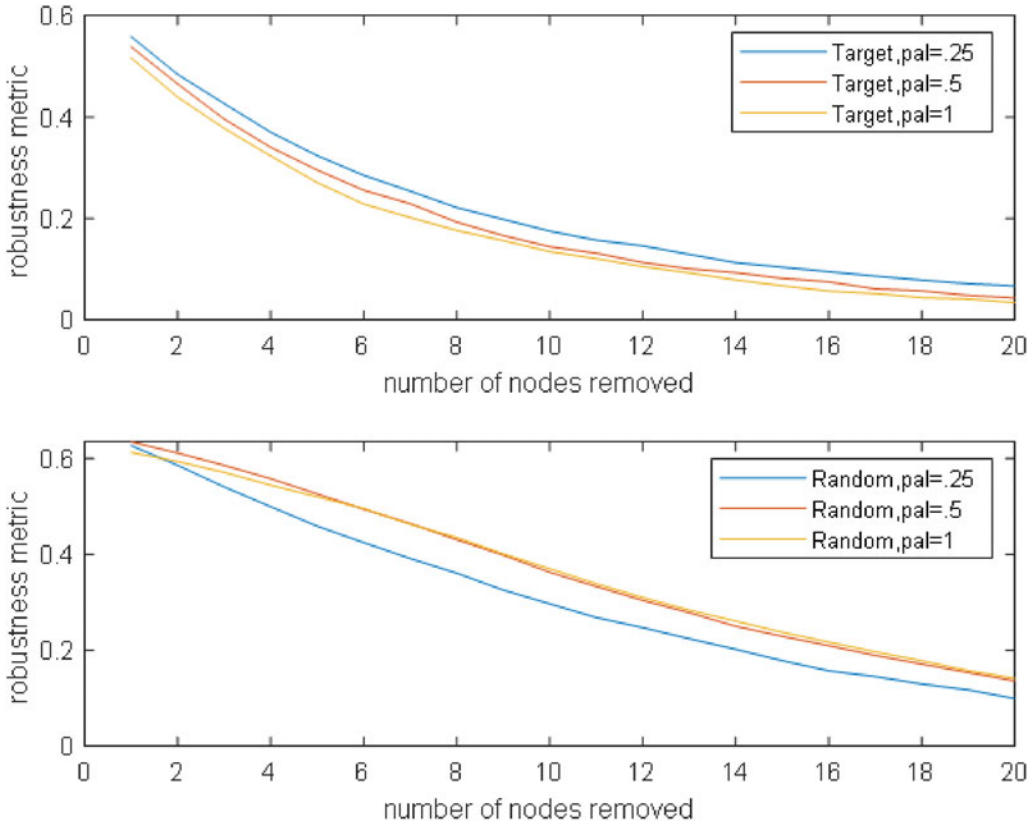
**7.2.5. Experimental set-up: varying the level of redundancy threshold criterion**

The experimental set-up of Table 14 concentrated on the variation in the redundancy threshold criterion that relates with the level of redundancy between source and sink nodes in the system architecture.

The redundancy threshold criterion represents the level of redundancy of sources: 0.25 = four times the redundancy, 0.5 = double the redundancy and 1.0 = no redundancy. The results in Figure 14 show that double the redundancy of sources in the architecture improved overall robustness under random and targeted attacks. However, with four times the redundancy, there was only marginal improvement in the robustness. The experimental findings suggest a decreasing benefit in robustness as the level of redundancy is increased above the double redundancy. In the naval design example, this finding suggests that an optimum level of redundancy exists, given the associated additional costs, weight, space requirements and maintenance. The proposed generator can provide an early indication of the relative merits of levels of redundancy at the initial stage of design. This may suggest areas where the initial design efforts might examine new redundancy approaches without compromising robustness. For example, this finding guided the redesign of Type A (Section 8), which included three instead of four alternative independent redundancy paths between the source and the sink to satisfy power functionality.

**Table 15.** Experimental set-up variable: level of connectivity between hubs

No. Parameters	Experimental set-up
9	Level of connectivity among hubs pal = 0.25 pal = 0.5 pal = 1



**Figure 15.** Robustness calculations varying the connectivity between hubs.

**7.2.6. Experimental set-up: varying the level of connectivity between hubs**

Table 15 presents the experimental set-up of varying the level of connectivity between hubs.

The level of connectivity among hubs was controlled in the proposed generator using the ‘pal’ parameter. The pal parameter indicates the level of hub interconnectivity: pal = 0.5 means that 50% of hubs are connected; pal = 1 means that all hubs are interconnected. The results in Figure 15 show that for high connectivity among hubs, robustness is better for random disruptions than targeted disruptions. In targeted disruptions with high levels of interconnectivity, the loss of central nodes reduces the robustness. In random disruptions, the high levels of hub interconnection provide alternative pathways and a higher robustness score.

**Table 16.** Modularity calculations varying the connectivity between hubs

Hybrid cyclical pattern	Modularity
pal = 0.25	0.55
pal = 0.5	0.53
pal = 1	0.49

**Table 17.** Modularity calculations for Type A and Type A redesign technical systems

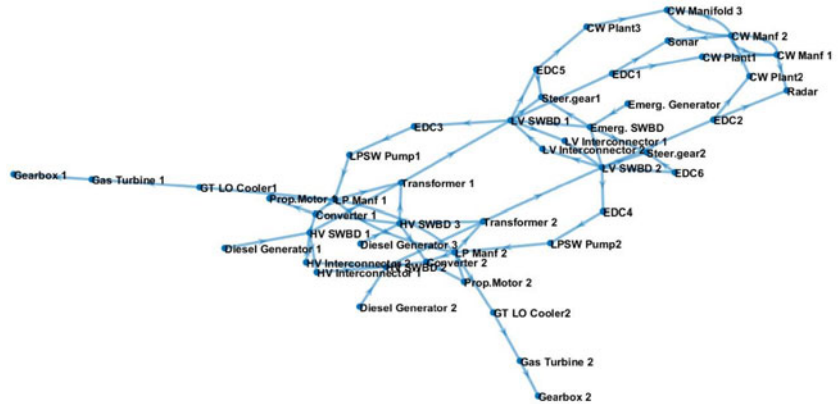
Technical systems	Modularity
Type A	0.63
Type A redesign	0.56

Simulated patterns with less connectivity among hubs were found to be more robust against targeted attacks than patterns with more connectivity. In contrast, under random attacks, patterns with high connectivity perform better. This finding suggests that if there are only a few hubs, then low connectivity between them can reduce the damage from targeted attacks. This applies to any relatively small size network whose degrees do not follow a power-law distribution.

With respect to modularity as shown in Table 16, a lower level of connectivity among hubs improves modularity, whereas high connectivity among hubs reduces the degree of modularity in the simulated networks. The level of connectivity among hubs was found to be an influential parameter, on the basis of the experiments performed. The level of connectivity among hubs has different effects on robustness and modularity. This experimental finding guided the development of the redesign of Type A (Section 8): while it is decided to add a hub (HV Switchboard 3) to the improved design, it was decided that this additional hub would not directly feed the other hubs.

## 8. Redesign of technical system Type A

In order to demonstrate the value of the new network generator, a redesign of the Type A technical system presented in Section 5 is developed. The redesign of Type A was driven on the experimental results achieved in Section 7. The experimental findings of Section 7.2.2 indicated that the addition of one HV SWBD would improve the robustness of the architecture, whereas the findings of Section 7.2.3 imply that the reduction in the number of sources (density of hub) may be an acceptable trade-off. Section 7.2.5 proposed three alternative independent paths between sources and sinks for the power function. The experimental findings of Section 7.2.6 suggested that the additional hub (HV Switchboard 3) should not be connected directly to the other hubs (HV Switchboards 1 and 2). Following the experimental findings, the Type A redesign proposal includes one additional HV SWBD and reduced the total number of DGs from four to three. The redesign of Type A is shown in Figure 16.



**Figure 16.** Technical network Type A redesign.

The redesign of Type A was developed without changing the total number of system components (one HV SWBD was added and one DG removed) to allow a comparison of networks of the same size. For the Type A system, the cost of a DG was higher than the cost of an HV SWBD, which means that the Type A redesign is a cost-improved solution. Moreover, the Type A redesign involves hub patterns of a single-source DG supplying power to an HV SWBD hub. This is advantageous as electrical synchronisation problems can be avoided by having only one DG supply for each HV SWBD (not two DG supplies to one HV SWBD). The simpler source–hub pattern would improve integration time and cost. The redesign of Type A was discussed with experts, who verified that the Type A redesign is a rational and feasible solution.

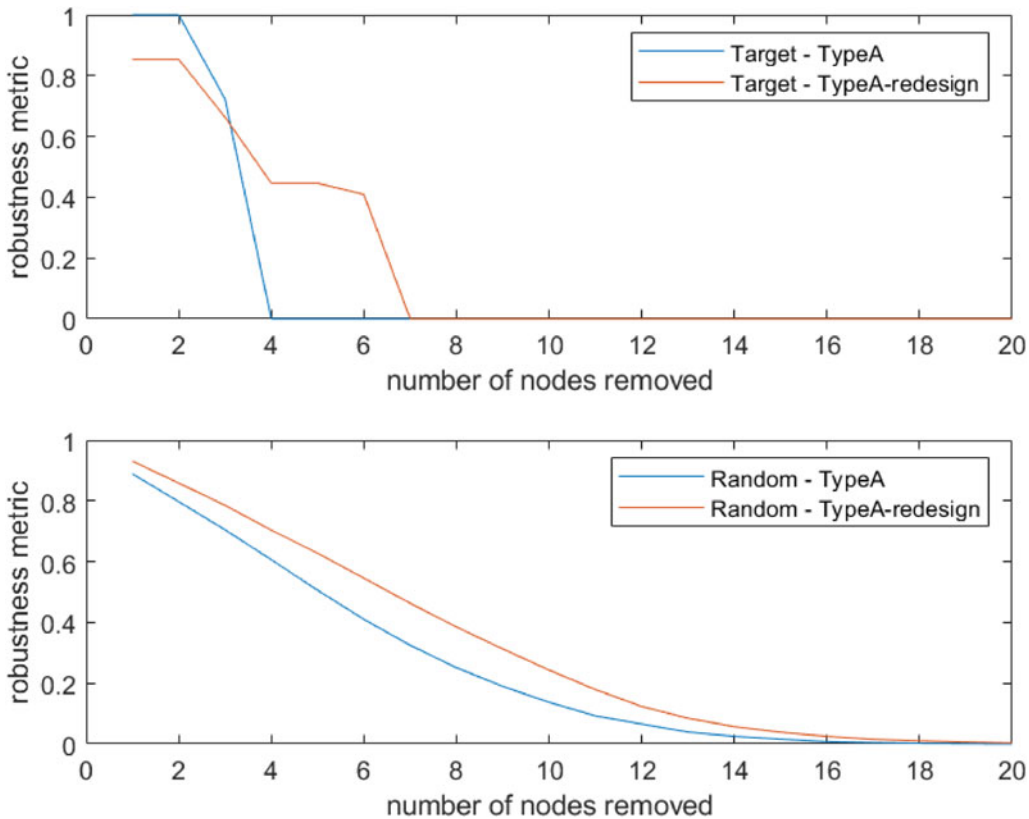
The results (Figure 17) show a graceful degradation of robustness compared to the original Type A under targeted central component attacks and also an improved robustness under random attacks.

However, the modularity results in Table 17 show that the redesign of Type A has a lower degree of modularity.

Previous designs and expert opinions typically influence decisions on the number and the connectivity of the components, defining the system architecture, during the initial design phase. Such decisions have a significant impact on the time of development, system costs and robust behaviour. Typically the robustness of the system is assessed for the design chosen, not for alternative options, and a detailed analysis takes place at the later stage of the design process when more information is available. Type A redesign demonstrates the value of the novel network generator to support exploratory and analytical approaches during the initial system design phase.

## 9. Reflections

In the design research literature, scholars have simulated networks and compared them with the original examples in order to identify areas of improvement. Piccolo *et al.* (2018) developed two null models: one that conserves degree distribution and a second that preserves the number of edges but redistributes them randomly between nodes. In contrast, the network tool proposed in this article focuses on a different aspect, namely, the simulation attempts to preserve structural patterns



**Figure 17.** Robustness calculations for Type A and Type A redesign technical systems.

(e.g., cyclical pattern) and features (e.g., hubs). It should also be noted that hubs are identified in the network not simply because they have degree but because their degree is high relative to their neighbours. In the case of networks without the power-law degree distribution seen in preferential attachment, this relative measure is suggested to be more appropriate.

Comparing the simulated networks that the generator produces against the range of technical networks exhibited in the recent work of Walsh *et al.* (2019), it is demonstrated that the generator populates networks that share attributes of other existing technical systems. It is observed that the technical networks reported in Walsh *et al.* (2019) exemplify instances of the artificial models proposed in this article. Focusing on the component-based networks reported in Walsh *et al.* (2019), it is observed that the bicycle drivetrain has a cyclical hub with hubs linked to paths, and the automobile drivetrain has a path as a backbone with a bus-modular hub. The aircraft network has a hybrid structure with a path backbone and hubs that are generally integral, but there is also a level of interconnection between hubs (around 25% here).

A limitation of this study is that the robustness problem that is examined in this article relates to the immediate instance after a disruption and does not include the dynamic aspects of robustness concerning error propagation and



spread. Future works could adapt the generator to dynamically assess robustness. Moreover, the generality of the proposed network generator remains to be further investigated. Future research will also include applications of the generator in different technical system contexts for evaluation and validation purposes.

### 10. Conclusion

This article presented a network generator as a tool to analyse and improve robustness of system architectures. The methodology in the article assessed the level of the robustness and modularity of two naval engineering system architectures and various simulated networks. The application of the generator included experiments investigating the effects of variance of its parameters on robustness and modularity. The experiments focus on varying parameters of the cyclical main structure pattern as the configurations resembled the two naval systems.

The proposed generator can help the system architect to develop a set of candidate theoretical system architectures at the initial design stage, prior to the development of detailed simulation or prototype models, by motivating novel paradigms and informing analysis. In theory, the network generator can stimulate the creation of intentional complexity in the structure of systems, by populating complex networks with identifiable patterns and features. The ability to demonstrate early evidence of compliance with the design requirements also provides an additional benefit for system architects.

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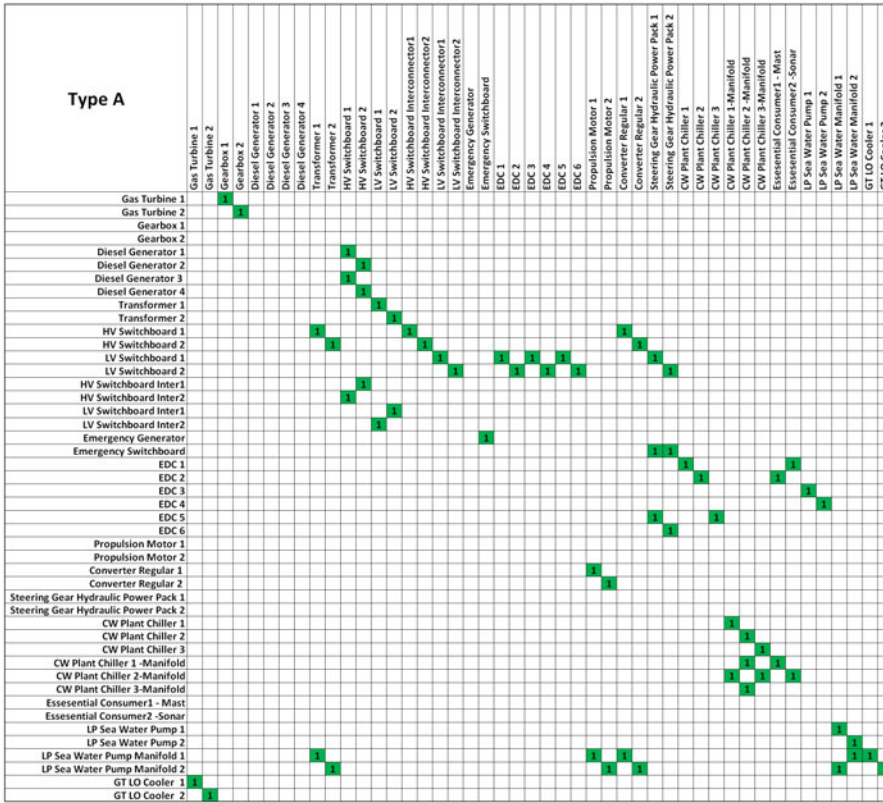


Figure 18. Type A – design structure matrix.

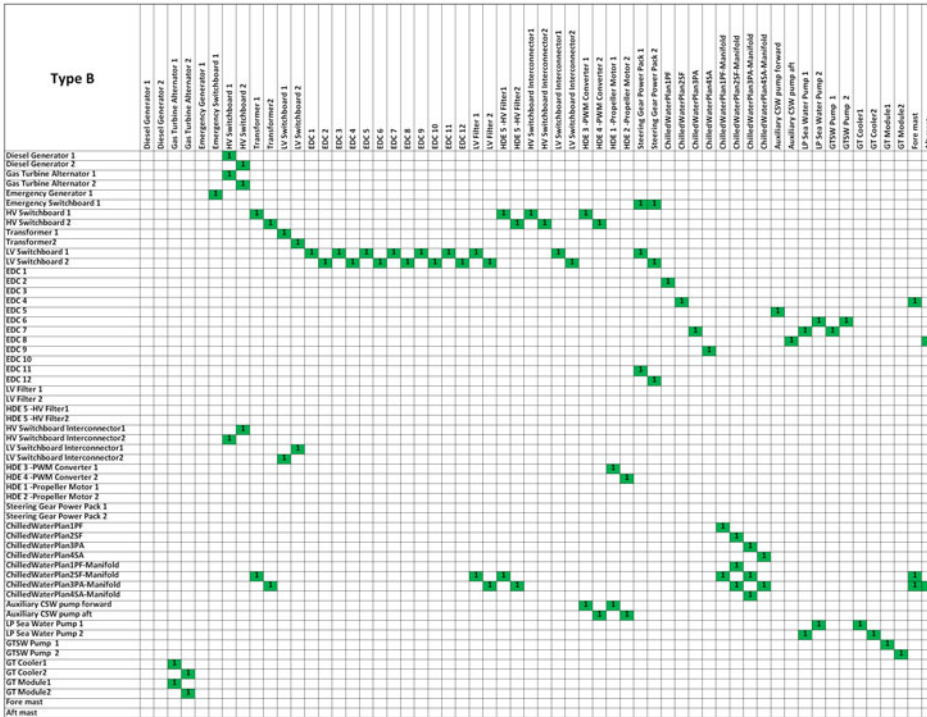
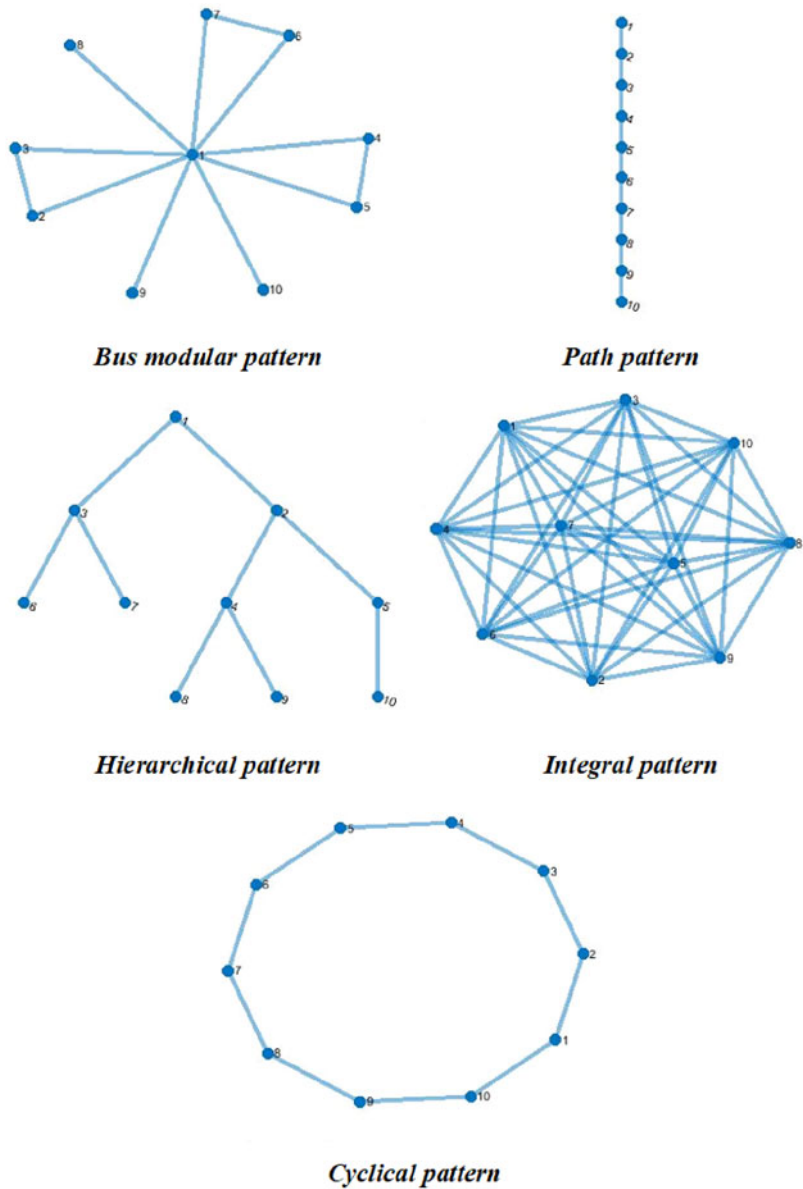


Figure 19. Type B – design structure matrix.

Appendix B



**Figure 20.** Examples of the main structure pattern options (parameter 2 network generator).

References

Agarwal, S., Pape, L. E. & Dagli, C. H. 2014 A hybrid genetic algorithm and particle swarm optimization with Type-2 Fuzzy sets for generating systems of systems architectures. In *Procedia Computer Science*, pp. 57–64.

- Albers, A., Bursac, N., Scherer, H., Birk, C., Powelske, J. & Muschik, S.** 2019 Model-based systems engineering in modular design. *Des. Sci.* **5**, 1–33.
- Albert, R. & Barabási, A. L.** 2002 Statistical mechanics of complex networks. *Rev. Mod. Phys.* **74**, 47–97.
- Albert, R., Jeong, H. & Barabási, A.-L.** 2000 Error and attack tolerance of complex networks. *Nature* **406**, 378–382.
- Alexander, C.** 1964 *Notes on the Synthesis of Form*, vol. 5. Harvard University Press.
- Baldwin, C., McCormack, A. & Rusnak, J.** 2014 Hidden structure: using network methods to map system architecture. *Res. Policy* **43**, 1381–1397.
- Baldwin, C. Y. & Clark, K. B.** 2000 *Design Rules: Volume 1. The Power of Modularity*. MIT Press.
- Blondel, V. D., Guillaume, J.-L., Lambiotte, R. & Lefebvre, E.** 2008 Fast unfolding of communities in large networks. *J. Stat. Mech. Theory Exp.* **2008**, P10008.
- Braha, D.** 2016 The complexity of design networks: Structure and dynamics. In *Experimental Design Research*, pp. 129–151. Springer.
- Braha, D. & Bar-Yam, Y.** 2007 The statistical mechanics of complex product development: empirical and analytical results. *Manage. Sci.* **53**, 1127–1145.
- Braha, D. & Bar-Yam, Y.** 2004a Topology of large-scale engineering problem-solving networks. *Phys. Rev. E* **69**, 016113.
- Braha, D. & Bar-Yam, Y.** 2004b Information flow structure in large-scale product development organizational networks. *J. Inf. Technol.* **19**, 244–253.
- Browning, T.** 2015 Design structure matrix extensions and innovations: a survey and new opportunities. *IEEE Int. Eng. Manag. Conf.* **63**, 27–52.
- Çetinkaya, E. K., Broyles, D., Dandekar, A., Srinivasan, S. & Sterbenz, J. P. G.** 2011 Modelling communication network challenges for Future Internet resilience, survivability, and disruption tolerance: a simulation-based approach. *Telecommun. Syst.* **52**, 751–766.
- Chalfant, J. & Chryssostomidis, C.** 2017 Application of templates to early-stage ship design. In *2017 IEEE Electric Ship Technologies Symposium (ESTS)*, pp. 111–117. IEEE.
- Chalfant, J. S. & Chryssostomidis, C.** 2011 Analysis of various all-electric-ship electrical distribution system topologies. In *2011 IEEE Electric Ship Technologies Symposium, ESTS 2011*, pp. 72–77.
- Chan, H., Akoglu, L. & Tong, H.** 2014 Make it or break it: Manipulating robustness in large networks. In *Proceedings of the 2014 SIAM International Conference on Data Mining*, pp. 325–333. Society for Industrial and Applied Mathematics.
- Chao, M. T., Fu, J. C. & Koutras, M. V.** 1995 Survey of reliability studies of consecutive-k-out-of-n:F & related systems. *IEEE Trans. Reliab.* **44**, 120–127.
- Chen, W., Heydari, B., Maier, A. M. & Panchal, J. H.** 2018 Network-based modeling and analysis in design. *Design Science* **4**.
- Crawley, E., de Week, O. L., Eppinger, S. D., Magee, C., Moses, J., Seering, W., Schindall, J., Wallace, D. & Whitney, D.** 2004 The influence of architecture in engineering systems. In *Pap. Present. MIT Eng. Syst. Symp.*, vol. 29.
- de Vos, P. & Stapersma, D.** 2018 Automatic topology generation for early design of on-board energy distribution systems. *Ocean Engng* **170**, 55–73.
- De Weck, O. L., Ross, A. M. & Rhodes, D. H.** 2012 Investigating Relationships and Semantic Sets amongst System Lifecycle Properties (Ilities). In *Third Int. Eng. Syst. Symp. CESUN 2012*, Delft Univ. Technol., 18–20 June 2012 18–20.
- Department of Defense** 2011. FACT SHEET: Resilience of Space Capabilities.

- Elmaraghy, W., Elmaraghy, H., Tomiyama, T. & Monostori, L.** 2012 Complexity in engineering design and manufacturing. *CIRP Ann. - Manuf. Technol.* **61**, 793–814.
- Elias, G. M. & Jain, R.** 2017 Assessing systems architecture: an exploratory framework. *International Journal of Business Information Systems* **24** (2), 127–173.
- Eppinger, S. D. & Browning, T. R.** 2012 *Design Structure Matrix Methods and Applications*. MIT Press.
- Fixson, S. K.** 2005 Product architecture assessment: a tool to link product, process, and supply chain design decisions. *J. Oper. Manag.* **23**, 345–369.
- Fricke, E. & Schulz, A. P.** 2005 Design for changeability (DfC): principles to enable changes in systems throughout their entire lifecycle. *Syst. Eng.* **8**, 342–359.
- Gero, J. S. & Kannengiesser, U.** 2004 The situated function-behaviour-structure framework. *Des. Stud.* **25**, 373–391.
- Gershenson, J. K., Prasad, G. J. & Zhang, Y.** 2003 Product modularity: definitions and benefits. *J. Eng. Des.* **14**, 295–313.
- Glazier, T. J., Cámara, J., Schmerl, B. & Garlan, D.** 2015 Analyzing resilience properties of different topologies of collective adaptive systems. In *Proc. - 2015 IEEE 9th Int. Conf. Self-Adaptive Self-Organizing Syst. Work. SASOW 2015*, pp. 55–60.
- Goodrum, C. J., Shields, C. P. F. & Singer, D. J.** 2018 Understanding cascading failures through a vulnerability analysis of interdependent ship-centric distributed systems using networks. *Ocean Engng* **150**, 36–47.
- Helmer, R., Yassine, A. & Meier, C.** 2010 Systematic module and interface definition using component design structure matrix. *Journal of Engineering Design* **21** (6), 647–675.
- Hölttä-Otto, K., Chiriaca, N. A., Lysy, D. & Suh, E. S.** 2012 Comparative analysis of coupling modularity metrics. *J. Eng. Des.* **23**, 790–806.
- Jin, C., Chen, Q. & Jamin, S.** 2000. Inet: Internet topology generator. *Options*.
- Kott, A. & Abdelzaher, T.** 2016. Resiliency and robustness of complex, multi-genre networks. [arXiv:1601.06731](https://arxiv.org/abs/1601.06731).
- Luo, J.** 2015 A simulation-based method to evaluate the impact of product architecture on product evolvability. *Res. Eng. Des.* **26**, 355–371.
- Magee, C., Whitney, D. & Moses, J.** 2010. ESD.342 Network Representations of Complex Engineering Systems [WWW Document]. Massachusetts Inst. Technol. MIT OpenCourseWare. URL <https://ocw.mit.edu/courses/engineering-systems-division/esd-342-network-representations-of-complex-engineering-systems-spring-2010/> (accessed 11.11.19).
- Meehan, J. S., Duffy, A. H. B. & Whitfield, R. I.** 2007 Supporting ‘Design for Re-use’ with Modular Design. *Concurr. Eng.* **15**, 141–155.
- Mehrpouyan, H., Haley, B., Dong, A., Tumer, I. Y. & Hoyle, C.** 2014 Resiliency analysis for complex engineered system design. *Artif. Intell. Eng. Des. Anal. Manuf. AIEDAM* **29**, 93–108.
- Min, G., Suh, E. S. & Hölttä-Otto, K.** 2016 System architecture, level of decomposition, and structural complexity: analysis and observations. *Journal of Mechanical Design* **138** (2).
- Minai, A. A., Braha, D. & Bar-Yam, Y.** 2006 Complex engineered systems: a new paradigm. In *Complex Engineered Systems*, pp. 1–21. Springer.
- Newman, M.** 2010 *Networks: an Introduction*. Oxford University Press Inc.
- Moullec, M.-L., Bouissou, M., Jankovic, M. & Bocquer, J. C.** 2013 Toward system architecture generation and performances assessment under uncertainty using Bayesian networks. *J. Mech. Des.* **135**, 041002.

- MIT Strategic Engineering**, 2006. Matlab Tools for Network Analysis (2006–2011). MIT, Cambridge, Available at: [http://strategic.mit.edu/downloads.php?page=matlab\\_networksAccess11/11/2019](http://strategic.mit.edu/downloads.php?page=matlab_networksAccess11/11/2019).
- Paparistodimou, G., Duffy, A., Knight, P., Whitfield, I., Robb, M. & Voong, C.** 2018 Network-based metrics for assessment of naval distributed system architectures. In *Proceedings of the International Naval Engineering Conference and Exhibition (INEC)*; <https://doi.org/10.24868/issn.2515-818x.2018.030>.
- Paparistodimou, G., Duffy, A., Voong, C. & Robb, M.** 2017 System architectures assessment based on network metrics. In *19th International Dependency and Structure Modeling Conference, DSM*. Aalto University Design Factory.
- Paparistodimou, G., Duffy, A., Whitfield, R. I., Knight, P. & Robb, M.** 2020 A network science-based assessment methodology for robust modular system architectures during early conceptual design. *J. Eng. Des.* **31** (4), 179–218; doi:[10.1080/09544828.2019.1686469](https://doi.org/10.1080/09544828.2019.1686469).
- Parraguez, P., Eppinger, S. D. & Maier, A. M.** 2015 Information flow through stages of complex engineering design projects: a dynamic network analysis approach. *IEEE Trans. Eng. Manag.* **62**, 604–617.
- Parraguez, P. & Maier, A.** 2016 Using network science to support design research: from counting to connecting. In *Experimental Design Research: Approaches, Perspectives, Applications*, pp. 153–172.
- Parraguez, P., Piccolo, S. A., Perisic, M. M., Storga, M. & Maier, A. M.** 2019 Process modularity over time: modeling process execution as an evolving activity network. *IEEE Trans. Eng. Manag.* 1–13.
- Piccolo, S. A., Lehmann, S. & Maier, A.** 2018 Design process robustness: a bipartite network analysis reveals the central importance of people. *Des. Sci.* **4**, 1–29.
- Pimmler, T. U. & Eppinger, S. D.** 1994 Integration analysis of product decompositions. In *Int. Des. Eng. Tech. Conf. 6th Des. Theory Methodol. Conf. Minneapolis, USA, 11–14 Sept. 1994*, pp. 343–351. ASME.
- Pumpuni-Lens, G., Blackburn, T. & Garstenauer, A.** 2017 Resilience in complex systems: an agent-based Approach. *Systems Engineering* **20** (2), 158–172.
- Purcell, A. T. & Gero, J. S.** 1996 Design and other types of fixation. *Des. Stud.* **17**, 363–383.
- Rivkin, J. W. & Siggelkow, N.** 2007 Patterned interactions in complex systems: implications for exploration. *Manage. Sci.* **53**, 1068–1085.
- Rubinov, M. & Sporns, O.** 2010 Complex network measures of brain connectivity: uses and interpretations. *Neuroimage* **52** (3), 1059–1069.
- Sarkar, S., Dong, A., Henderson, J. a. & Robinson, P. a.** 2014 Spectral characterization of hierarchical modularity in product architectures. *J. Mech. Des.* **136**, 0110061.
- Selva, D., Cameron, B. & Crawley, E.** 2016 Patterns in system architecture decisions. *Syst. Eng.* **19**, 477–497.
- Shanthikumar, J. G.** 1987 Reliability of systems with consecutive minimal cutsets. *IEEE Trans. Reliab.* **R-36**, 546–550.
- Sharman, D. M. & Yassine, A. A.** 2004 Characterizing complex product architectures. *Systems Engineering* **7** (1), 35–60.
- Sinha, K.** 2014 *Structural Complexity and its Implications for Design of Cyber Physical Systems*. Massachusetts Institute of Technology.
- Sosa, M., Mihm, J. & Browning, T.** 2011 Degree distribution and quality in complex engineered systems. *J. Mech. Des.* **133**, 101008.

- Sosa, M. E., Eppinger, S. D. & Rowles, C. M.** 2007 A network approach to define modularity of components in complex products. *J. Mech. Des.* **129**, 1118.
- Sosa, M. E., Eppinger, S. D. & Rowles, C. M.** 2003 Identifying modular and integrative systems and their impact on design team interactions. *J. Mech. Des.* **125**, 240.
- Sosa, M. E., Mihm, J. & Browning, T. R.** 2013 Linking cyclicity and product quality. *Manuf. Serv. Oper. Manag.* **15**, 473–491.
- Sterbenz, J. P. G., Çetinkaya, E. K., Hameed, M. A., Jabbar, A., Qian, S. & Rohrer, J. P.** 2013 Evaluation of network resilience, survivability, and disruption tolerance: analysis, topology generation, simulation, and experimentation: invited paper. *Telecommun. Syst.* **52**, 705–736.
- Walden, D. D., Roedler, G. J., Forsberg, K., Hamelin, R. D. & Shortell, T. M.** 2015 *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities*. John Wiley & Sons.
- Walsh, H. S., Dong, A. & Tumer, I. Y.** 2019 An analysis of modularity as a design rule using network theory. *J. Mech. Des. Trans. ASME* **141**, 031102.
- Walsh, H. S., Dong, A. & Tumer, I. Y.** 2018 The role of bridging nodes in behavioral network models of complex engineered systems. *Design Science* **4**,
- Whitney, D. E.** 2003 *Network Models of Mechanical*, Chap 17.
- Wyatt, D. F., Wynn, D. C., Jarrett, J. P. & Clarkson, P. J.** 2012 Supporting product architecture design using computational design synthesis with network structure constraints. *Res. Eng. Des.* **23**, 17–52.
- Yassine, A. A. & Naoum-Sawaya, J.** 2016 Architecture, performance, and investment in product development networks. *J. Mech. Des.* **139**, 011101.
- Yazdani, A. & Jeffrey, P.** 2012 Applying network theory to quantify the redundancy and structural robustness of water distribution systems. *J. Water Resour. Plan. Manag.* **138**, 153–161.
- Zakarian, A., Knight, J. W. & Baghdasaryan, L.** 2007 Modelling and analysis of system robustness. *J. Eng. Des.* **18**, 243–263.
- Zhou, S. & Mondragón, R. J.** 2004 The rich-club phenomenon in the internet topology. *IEEE Commun. Lett.* **8**, 180–182.