Network-based metrics for assessment of naval distributed system architectures

Giota Paparistodimou[1]*, Alex Duffy[1], Philip Knight[1], Ian Whitfield[1], Malcolm Robb[2], Caroline Voong[2]

[1] *University of Strathclyde, Glasgow, UK*

[2] *BAE Systems Maritime - Naval Ships, Glasgow, UK*

* Corresponding Author. Email: giota.paparistodimou@strath.ac.uk

Synopsis

The architecture of a system is generally established at the end of the conceptual design phase where sixty to eighty percent of the lifetime system costs are committed. The architecture influences the system's complexity, integrality, modularity and robustness. However, such properties of system architecture are not typically analytically evaluated early on during the conceptual process. System architectures are defined using qualitative experience, and the early stage decisions are subject to the judgement of stakeholders. This article suggests a set of network-based metrics that can potentially function as early evaluation indicators to assess complexity, integrality, modularity and robustness of distributed system architectures during conceptual design. A new robustness metric is proposed that assesses the ability of architecture to support a level functional requirement of the system after a disruption. The new robustness metric is evaluated by an electrical simulation software (MATPOWER). A ship vulnerability assessment software (SURVIVE) was used to find potential disruptive events. Two technical case studies examining existing naval distributed system architectures are elaborated. Conclusions on the network modelling and metrics as early aids to assess system architectures and to choose among alternatives during the conceptual decision phase are presented.

Keywords: naval distributed system, evaluation indicators, network-based metrics, and robustness metric.

1. Introduction

The early, rapid assessment and analysis of distributed system architectures on naval platforms has gained increasing importance as detail and maturity is demanded much earlier in naval platform programmes. A distributed system is defined by Brefort et al. (2018) as "a specific type of system that is disbursed through the vessel". The highly interdependent collections of the distributed systems that make up a modern naval combatant qualify them as a complex system. Complexity is suggested as a reason for the increase in costs and development time in navy ships (Dobson, 2014; Rebentisch et al., 2016). In respect to naval platforms, an essential requirement is that of survivability and the assessment of the vulnerability of a platform and its systems through the design process. Correspondingly, robustness reflects on the survivability and resilience of such complex systems

A field that has flourished in recent years is the one of network science, which offers the basis for metrics that are useful in the engineering system context. Such mathematically driven metrics can potentially function as evaluation indicators offering numerical values for objectively assessing system architectures alternatives. This article investigates if network-based metrics can support early architectural decisions. Computing metrics as evaluation indicators can support designers to assess the architectures of their systems, and managers to make informed decisions among alternative options to develop the system architecture.

The article explores a set of network metrics for assessing distributed system architectures. The network-based metrics focus on evaluating a system architectures' properties such as complexity, integrality, modularity and robustness. A new robustness metric is proposed. MATPOWER and SURVIVE are utilised the first for evaluation purposes and the second to find the potential disruptive events. Next, the article applies a set of network-based metrics on two generic naval distributed system architectures. Finally, reflections on their potential to serve as early assessment indicators during the conceptual phases are given.

2. Background literature

Early architectural decisions have a decisive influence on the connectivity of naval distributed system architectures. Different decisions can arrive at distinctive distributed system architectures for the same technical specification requirements. Such distinctive system architectures can have different degrees of complexity, integrality, modularity and robustness.

The connectivity amongst components of system architectures influences their structural complexity, integrality and modularity. Keane et al. (2017) recommended designing out complexity by proposing the ship density as a measure of complexity. The authors stated, "density measures how tightly systems and equipment are

http://doi.org/10.24868/issn.2515-818X.2018.030

arranged within a hull structure". The pattern of the ship's distributed system architectures affects the ship's density. In the engineering design context, Luo (2015) used the interaction density metric to measure the integrality of system architectures. Rebentisch et al. (2016) assessed the changes in technical systems and their effects on cost and duration based on structural topological complexity. Gravil et al. (2014) investigated design modularity as a cost-effective solution for submarine life extension and capability preservation.

A key design objective for a naval ship is to reduce design vulnerabilities, to increase ship's survivability. Besides, robustness is suggested to enhance survivability. The Department of Defense (2011) defined robustness as "architectural properties and system of systems design feature to enhance survivability and resist functional degradation". Moreover, Kott and Abdelzaher (2014) advised that robustness is a precondition for resilience.

INCOSE (2015) describes architecting of systems as "an analysis of interactions between system elements to prevent undesirable properties and reinforce desirable ones". The minimum necessary complexity is desired for a "good" architecture, and the most simple is the "best" design (Crawley et al., 2004; Maier and Rechtin, 2000): therefore, excessive complexity is an undesirable property of a naval distributed system architecture. A sufficient level of modularity and robustness are desirable properties in naval distributed system architectures, as the first is considered as an enabler to balance lifecycle cost and development times, whereas the second is a requirement to achieve resilience and survivability. However, robustness, modularity and complexity are interrelated. Crawley et al. (2004) acknowledged that "robust functionality drives essential complexity". Raz and DeLaurentis (2017) examined the influence of modularity and complexity on survivability and dependability in system of systems architectures and suggested that "modular architectures are more dependable and survivable". In contrast, Mehrpouyan et al. (2014) advised for complex engineering system designs that "modular physical system architectures that maybe have the unintended downside of making the system less tolerant to failure". Therefore, assessing such properties of system architectures, together, can aid in understanding their trade-offs, and more efficiently architect systems.

Scholars have proposed using network methods for analysing naval distributed systems (de Vos, 2014; Rigterink, 2014). Ship vulnerability has been examined using networks (Goodrum et al., 2018). Their low requirements for information to develop network models, allows them to be useful for the early design phases. This article investigates if complexity, integrality, modularity, and robustness as architectural properties are beneficial to be assessed early in the process and suggests a set of network metrics to perform this assessment.

Baldwin and Clark, (2000) defined ***complexity*** as "the presence of many, varied parts, patterns or elements, connected in a way that makes an object difficult to understand fully". The same authors 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". Luo (2015) defined ***integrality*** in system architecture as "if there are many inter-influence links among components". In this article, the ***robustness*** of a system architecture is defined as "the ability of instantiated system architecture to support a level of functional requirements, after disruption".

3. System architecture network assessment metrics

3.1. Complexity

Sinha (2014) suggested that a graph energy metric could function as a measure of structural topological complexity and is the "sum of singular values of the adjacent matrix" and is proposed that "encapsulates the impact of topological differences in the connectivity structures, function as a measure of topological complexity" (Sinha, 2014). The equation for graph energy is presented:

$$E(A_{ij}) = \sum_{i=1}^{n} \sigma_i \qquad (1)$$

where A_{ij} the adjacency matrix, σ_i the singular values of network.

3.2. Integrality

Interaction density metric (K) defined as the "average number of components that each component influences" and is interpreted as an indicator of integrality (Dong, 2002; Luo, 2015) in the engineering design literature. This refer to the average nodal degree of network science (Newmann, 2003). The equation is:

$$K = \frac{m}{n} \qquad (2)$$

Where n the number of components (nodes), m the number of connections (edges).

3.3. Modularity

In the broader network science literature, there is the well-known Newman modularity index (Q) (Newman, 2010). This metric has been adopted in engineering system literature by Sinha and Suh (2017) as per equation (3):

$$Q = \sum_{i=1}^{k} (e_{ii} - a_i^2) \quad (3)$$

Whereas “e_{ii}: fraction of edges with both ends nodes in the same module i (intra-module connections), a_i: fraction of edges with at least one end node inside module i (inter-module connections), k: number of modules”.

3.4. A new robustness network-based metric

In this article, a novel robustness metric to measure the ability of system architecture to support a level of functional requirements, after disruption, is presented. The metric evaluates the ability of architecture to maintain sufficient connectivity among sources (supply) and sinks (demand) components after a disruption. A threshold criterion is considered where the threshold corresponds to the minimal number of connections from sources to sinks required to support a level of functional requirement. For example, in a system where two of four generators (sources) must be connected electrical distribution centres (sinks) for regular electrical power functional requirement then the threshold criterion is defined as 0.5. Then an average of weighted combinations of source availability is formed to calculate the total robustness metric.

Proposition: The architecture supports the system’s functional requirements if sufficient connectivity is maintained among sources and sinks after a disruption. Sufficient connectivity is associated with a threshold value that is decided based on the number of connected sources necessary to support the respective level of functional requirements.

3.4.1. *Formulation of the new robustness metric*

Measuring connectivity among sources and sinks before and after disruption

For a system architecture that is represented a graph G, and has an adjacency matrix A_{ij}, a new matrix S is constructed, that is a binary matrix that catalogues paths/walks (of any length) between nodes in the network: $\mathrm{S_{ij}} = 1$ if and only if there is a path in the network linking node i to node j. One straightforward way to compute S is to compute the matrix exponential e^A and then $\mathrm{S_{ij}} = 1$ if and only if the corresponding entry of the exponential is nonzero. For a number of *“e”* sources and *“k”* sinks, the sets of sources $\mathrm{s} = \{\mathrm{s_1}, \mathrm{s_2}, \mathrm{s_3}, \dots, \mathrm{s_e}\}$ and sinks $\mathrm{t} = \{\mathrm{t_1}, \mathrm{t_2}, \mathrm{t_3}, \dots, \mathrm{t_k}\}$ are chosen in system architectures and the number of 1s in the corresponding intersection of rows and columns of S is computed. The proportion of 1s to 0s gives a measure of interconnectivity between the sources and sinks interconnectivity of the network. This can be recalculated after the network is subject to disruption (i.e. loss of nodes or edges). The measure works equally on directed and undirected graphs. More precisely, the robustness R of the intact system architecture is measured with the quantity:

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

A disruption (loss of nodes/edges) generates damaged system architecture: that is represented a graph G' , and has an adjacency matrix A'_{ij}, and robustness is recalculated by evaluating the connectivity among sources and sinks after disruption to give:

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

Both (4) and (5) can be computed for all non-empty subsets of S, in which case multiplying each term in the double sum by f_i: an indicator variable set to 1 if source i is on and 0 if it is off.

Setting a threshold criterion

A threshold criterion is applied based on the level of redundancy of the architectures and enumerate values of $\mathrm{R_{s,t}}$ which exceed the threshold criterion. For example, if triple redundancy the threshold criterion is defined as 0.33, quadruple redundancy (require one source and architecture has four sources) then threshold criterion is defined as 0.25. To test the various combinations of sources, all cases with a common number of sources (i,say) available are grouped together and the number that satisfy the threshold criterion is the robustness, is denoted by R_i. By varying the threshold criterion and calculating the robustness metric, the effects of the redundancy of the additional sources on robustness of the system architecture can be tested.

Average of weighted combination of alive sources

For a number of *"e"* sources, all $2^e - 1$ combinations of available sources are tested (excluding the case of all sources unavailable as that inevitably leads to loss of functional continuity). The information contained in the individual values of the robustness is condensed into a single term. This is done by calculating an average of weighted combination where the robustness of alive sources (R_i) is weighted by a value inversely proportional to the number of states with i sources available (a binomial coefficient). Specifically, setting weight (w_i) to be the reciprocal of the binomial coefficient e-choose-i, (experts input could also be used to inform the weight values) a weighted robustness (R_w) is calculated:

$$R_w = \frac{1}{e}\sum_i w_i R_i \qquad (6)$$

A total robustness metrics for a system architecture

For a system with functional requirements $l = \{1 \dots q\}$ the total robustness (R_t) of the system architecture is postulated as per equation (7), when these are combined to satisfy the main functional requirement of the system:

$$R_t = \prod_{l=1}^{q} R_w \qquad (7)$$

The equation (7) remains to be further investigated and tested.

3.5. Robustness metric investigation

In this article, MATPOWER electrical simulation software was used, for evaluation purposes. Firstly, the robustness metric is calculated, and then MATPOWER results are presented.

3.5.1. Robustness metric results

A generic system architecture of a ship power system is used here as an example. Figure 1 presents the generic ship power system architecture network. The system architecture is assessed if it can support the distribution of ship power from the sources (1, 2, 3, and 4) and sinks (11-22) after a disruption. Figure 1 presents the network of the system architecture 1,2,3,4 are generators, and 11-12 the electrical distribution centres-EDCs, the high voltage-HV Switchboards are by 5-6 nodes, HV interconnectors by 25 and 26, transformers are 7 and 8 nodes, low voltage-LV Switchboard 9-10 nodes, and LV interconnectors are 23 and 24 nodes.

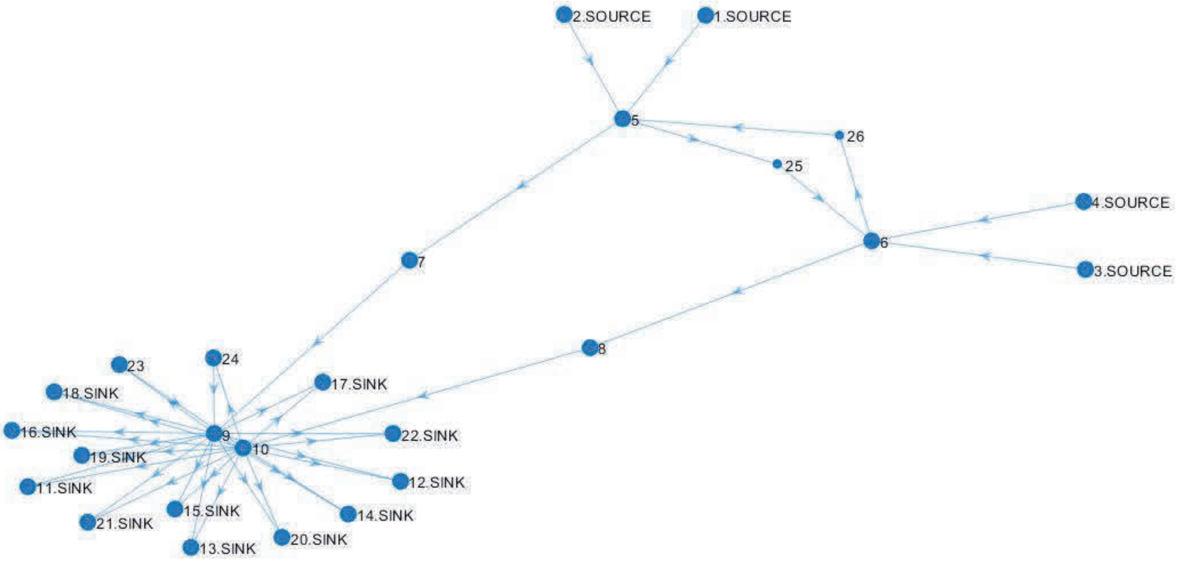

Figure 1: Network modelling representation of the generic ship power system architecture

Table 1 describes the calculation based to all the combinations of sources with sinks. A weighted factor (see Section 3.5.1) was included to consider for the different combinations. The architecture robustness metric is calculated for a target disruption of aft HV Switchboard to give an actual calculation of a simple example. The threshold criterion is here, defined as 0.5, meaning that the architecture requires two sources to support functional requirement. The architecture has total four sources (2 sources are for redundancy).

Table 1: Robustness metric calculations for generic system architecture

System Architecture	**Disruption event: Removal of aft HV switchboard**	**Network robustness metric**	
		Weight combination (w_i)	**Robustness metric (R_i)**
Sources: i=4 (four available generators) **Sinks: All EDCs**		1	1
All combinations of **Sources: i=3 (three available generators)** **Sinks: All EDCs**		1/4	2
All combinations of **Sources: i=2 (two available generators)** **Sinks: All EDCs**		1/6	1
Sources: i=1 (one available generator) **Sinks: All EDCs**		1/4	0
Average of weighted combination			0.4167

The average of weighted combination of robustness metric depends on the weights considered and the threshold criterion. These could be defined differently for the various system architectures and the functional requirements.

3.5.2. Evaluation with MATPOWER

In order to evaluate the results of the new robustness metric a network model of the ship's power system was created and simulated using MATPOWER. In the first instance, the nominal maximum power throughput for each cable was calculated and the rating of each cable was calculated using a capacity multiplier, in line with Koc et al. (2013). Each node of the power network was sequentially withdrawn from service, simulating targeted disruptions. A power flow study was then re-run and the number of load served, generators online, and ratio of operational cables to total cables were calculated. The power throughput of each cable was assessed against its capacity and withdrawn from service if it was found to be overloaded. This process was repeated until a steady state was reached where final values relating to survivability of the network were calculated.

Table 2: MATPOWER results for generic system architecture

System Architecture	**Disruption event: Removal of aft HV switchboard**	**MATPOWER empirical metric**
		Link survivability (LS)
Sources: i=4		0.43

The empirical metric used in MATPOWER to evaluate robustness metric is also adopted from Koc et al. (2013). This article has defined link Survivability (LS) "as the fraction of lines that are still in operation after a cascading failure" and has the following assumptions: 1) "A line is considered to be operational if it is not tripped by the protection mechanism and if it is not disconnected from generators so that it still delivers power after the cascading failure", 2) "The capacities of individual transmission lines are assumed to be proportional to their tolerance parameter". Table 2 results indicate that 43% of the connections in the architecture remain operational after a disruption of the aft HV switchboard. The results generated from MATPOWER model presented Table 2; give comparable results with Table 1. Additional experiments and comparisons will be performed in future research to evaluate the robustness metric further. In Section 5, the robustness metric will be applied in combination with other network-based metrics, to assess technical case studies system architectures.

4. Technical case studies

Two case studies are elaborated that examine existing naval distributed system architectures that have similar functional requirements from two different ships. These are: 1) providing and distributing power, 2) providing power for propulsion and steering, 3) providing chilled water-cooling for propulsion, power and weapons and 4) providing seawater cooling for power, propulsion and weapons. The set of sources and sinks corresponding to functional requirements are defined for the system architectures in Table 3.

4.1. Description of the technical case studies and data collection approach

Data collection was based on subject matter expert (SME) meetings and technical documentation including engineering drawings and technical specifications. The outcome was to describe the power, propulsion and auxiliary systems (chilled and LP seawater cooling) into a logical architecture (Brefort et al., 2018) using a design structure matrix (DSM) (Browning, 2015) and then transformed it into a multi-flow network. Only major components were included, for example; valves were not modelled. Flow relationships among components where represented in a directed network, which was converted into an undirected network that represented tangible structural connectivity (cables and pipes) among components. The flow-directed network was the basis to calculate the robustness metric, whereas, basis to calculate complexity, modularity and integrality metrics was the structural-undirected nework.

4.1.1. Case study A: System architecture A description

Type A generates power through two diesel generators and two gas turbines alternators, which supply power to the high voltage (HV) system for the two propulsion motors and power to the whole ship systems. Gas turbines (GT) are dependent on the seawater system for cooling (GT Intercooler and GT Lubricating Oil Module). The HV switchboards are connected to transformers, which connect to LV switchboards, which supply power to the whole ship systems. The chilled water plants cool the transformers. The auxiliary seawater cooling pumps cool propulsion converters and motors. Overall, there are many dependencies between the power and propulsion systems and cooling. This suggests that Type A is an integral and complex architecture.

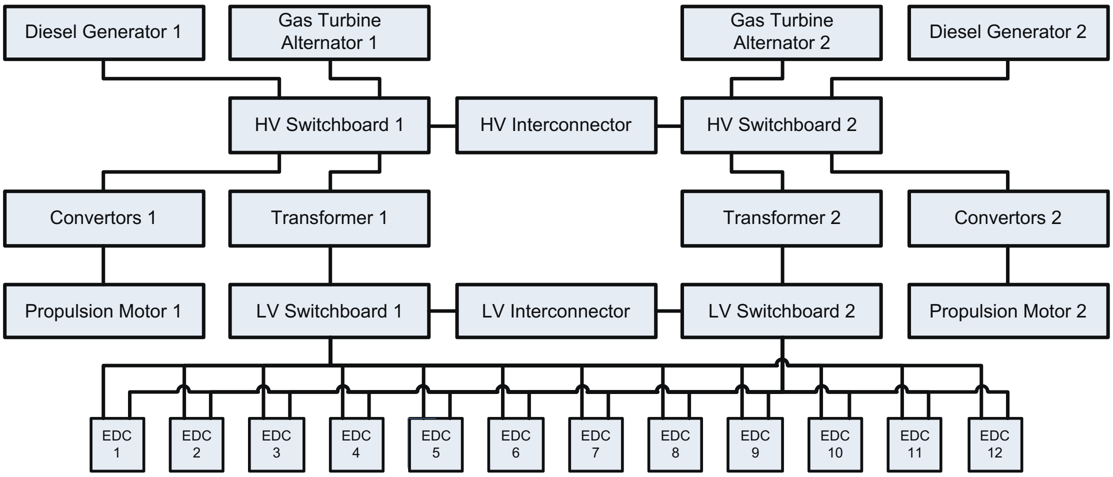

Figure 2: Electrical power and propulsion representation of system architecture A

4.1.2. Case study B: System architecture B description

Type B generates power with four diesel generators, which supply two propulsion motors mounted on the propulsion shafts, and power to the whole ship systems. Also, two gas turbines are connected to gearboxes that drive each shaft directly. Gas turbines lubrication coolers depended on seawater for cooling. The two 600 V switchboards are connected through two motor generator sets to the 440 V switchboard. The motor generators set, and propulsion motors required cooling through low-pressure (LP) seawater system. The chilled water system only supplies weapons and other systems, thus does not influence the power and propulsion. Type B is considered a less complex architecture, as it has fewer dependencies to a simpler LP seawater cooling system architecture, and there are no dependencies between power and propulsion and the chilled water-cooling system.

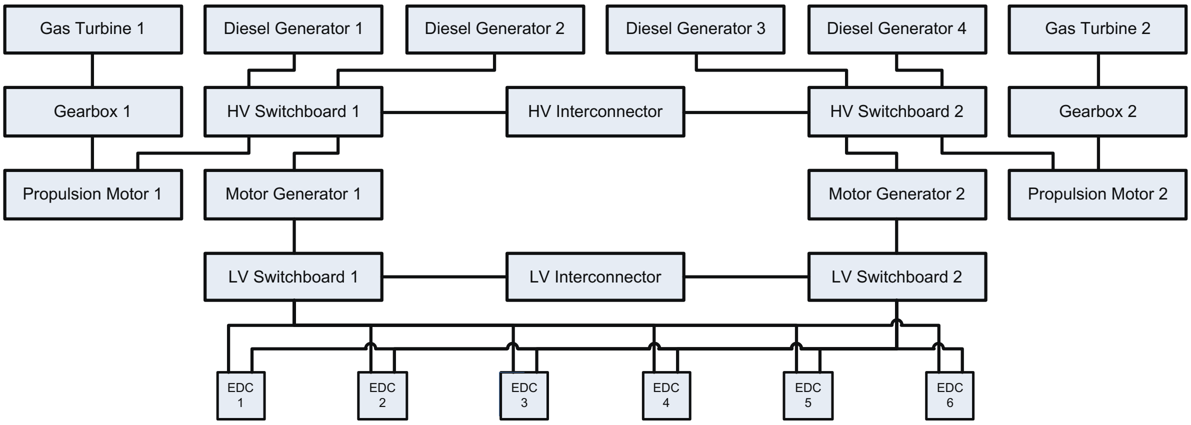

Figure 3: Electrical power and propulsion representation of system architecture B

4.2. Description of sources and sinks corresponding to functional requirements

Table 3 describes the set of sinks and sources corresponding to the functional requirements for system architectures Type A and B, of the two technical case studies described in Section 4.1.1 and 4.1.2.

Table 3: Functional requirement and their corresponding sources (S), and sinks (T) for Type A and B

Functional requirement		**Corresponding sources and sinks**	
		Type A	**Type B**
1	Supply electrical power and distribute to EDCs	S: two diesel generators and 2 gas turbines	S: four diesel generators
		T: 12 EDCs	T: 6 EDCs
2	Supply power for one propulsion and steering	S: two diesel generators and two gas turbines	S: two gas turbines and two of diesel generators
		T: two propulsion motors	T: two propulsion motors or gearboxs
3	Supply cooling through the chilled water to power, propulsion and weapons	S: four chilled water plans	S: three chilled water plans
		T: two transformers, HV & LV filters, fore & aft masts	T: mast & sonar
4	Supply cooling through sea water to power, propulsion and weapons	S: two LP, GT, and auxiliary seawater pumps	S: two LP seawater pumps
		T: two propulsion converters & motors, GT intercoolers and GT lubricating oil modules	T: two motor gen sets, propulsion converters and motors, GT lubrication coolers

4.3. Disruptive events

In SURVIVE software a generic ship power and propulsion systems based on a technical reference specification, and general arrangement was modelled as a reference platform. The SURVIVE software provides an assessment of the vulnerability of a whole ship, its systems and individual equipment against defined threats, allowing the evaluation and comparison of platform designs. SURVIVE was used here as a reference tool to find the disruptive events as inputs to calculate the robustness metric for the two technical case studies system architectures. The threat type was set as a generic missile striking the ship above the water line. For each strike, the set of irreparable equipment was extracted. The strikes start from aft of the ship and progress through the longitudinal direction forward – the first strike is at the most aft and tenth strike most forward of the generic reference ship.

Table 4: Example of various disruptive events extracted from SURVIVE

Strikes	**Set of irreparable equipment**
1	1 x EDS
2	4 x aft EDS
3	5 x aft EDC
4	6 (EDC, Propulsion converter and motor aft, HV aft switchboard, LV aft switchboard, aft transformer)
5	1 x middle ECS
6	6 (EDC, Propulsion converter and motor fwd., HV fwd. switchboard, LV fwd. switchboard, fwd. transformer)
7	4 x fwd. EDS
8	1 x fwd. EDS
9 &10	No irreparable equipment

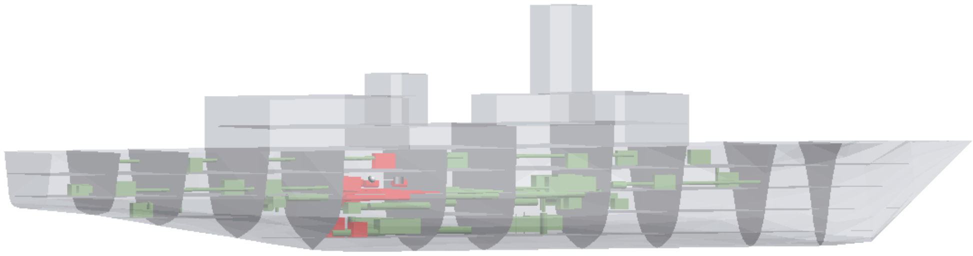

Figure 2: Survive software Strike 4: An example of worst case disruptive scenario

5. Description and discussion of the results

The set of network metrics that was discussed in Section 3, were applied on the technical cases studies described in Section 4. The computation of the network metrics was performed in MATLAB using codes from the MIT Strategic Engineering (2006) and using the author' codes. All results from the set of network-based metrics are collected and tabulated in Table 5. The discussion is retrospective as both the system architectures exist and are in operation; however, it serves to exemplify the use of the set of network metrics and gains in forecasting the level of architectural properties such as complexity, integrality, modularity and robustness of system architectures during the early stages of the system development.

Table 5: Network-based metrics results

Architectural properties measured by network-based metrics	**System architectures**	
	Type A	**Type B**
Complexity - graph energy $(\frac{C3}{n})$	1.43	1.37
Integrality - average nodal degree (K)	4.5	3.95
Newman modularity (Q)	0.47	0.51
Robustness $(R_{w\,power})$	0.83	0.83
Robustness $(R_{w\,propulsion})$	0.87	1
Robustness $(R_{w\,chilled\,water})$	1	1
Robustness $(R_{w\,seawater})$	0.72	1
Robustness (R_{total})	0.53	0.83

The results of the network-based metrics show that Type A architecture is less modular, more complex, and integral than Type B. This agrees with the SME experience about Type A architecture because of its high density of connectivity. On average, each component has a high number of connections. This characteristic signifies shared functionality amongst components in the architectures, thus lack of functional autonomy of components. This agrees with Newman modularity metric, which is lower for Type A architecture. The graph energy network metric is employed, as an indicator of architectural complexity, which shows that Type A architecture is more complex than Type B. This is in agreement with the technical case study as Type B system architecture is a less complex architecture, having less interconnectivity amongst its components and with simple auxiliary subsystems.

Worst-case disruption scenarios for the system architecture is informed by SURVIVE software and are noted as strikes four and six as per Table 4. The robustness metric was calculated under this worst-case disruption based on Section 3.4.1. As explained in Section 3.4.1, a threshold criterion is defined that relates with the redundancies and the level of connectivity necessary to be maintained in the architecture after disruption to support a level of functional requirement. Herein, the threshold criterion is taken as 0.25, to allow comparisons among the different architectures, give that both are high in redundancies. The robustness metric test: if at least one source maintains connectivity with the respective sinks after the disruption. Calculated values higher than the threshold criterion suggest that the architecture is robust enough to support a respective level of functional requirement under disruption. Both architectures were found sufficiently robust to satisfy the threshold criterion defined. The total robustness metric is calculated as 0.53 for Type A architecture, which is lower than the 0.83 for Type B. This is primarily because of the high connectivity among the power, propulsion, and seawater cooling components of the Type A architecture, which is reflected by the robustness results calculated. By calculating a robustness metric under a worst-case disruption and comparing its results among the different architecture types, it could be assessed that Type A is inherently less architecturally robust than Type B architecture. Future research will additionally evaluate the robustness metric under diverse types of disruptions and technical systems.

6. Comparison of robustness metric and other approaches

Comparing among the three approaches it can be noted that: the SURVIVE can generate various types of disruptive events but does not focus on the low-level connectivity among the components of the interconnected systems, the robustness metric does not capture the location of the components in the hull of the ship, and the MATPOWER approach can only be applied to electrical systems. In general, network-based modelling and metrics are suggested as a basic abstract modelling method and the metrics as aids during early architecting conceptual decision-making process to help the development and agreement of baseline system architecture, and to be used in combination with traditional engineering tools. Limitations of network modelling and metrics are the assumption of similarity among the nodes, and the lack of details about the properties of the nodes.

7. Conclusions

In this article, a new robustness metric is suggested, to address the lack of an early analytical approach to assess the robustness of an architecture of distributed system architectures. The new robustness metric is applied in combination with other existing literature network-based metrics, to assess robustness, complexity, integrality and modularity of two naval distributed system architectures. The set of network metrics provided reasonable results, retrospectively for the systems. Such metrics could function as early evaluation indicators to support an assessment during the conceptual stage of system architectures. An early assessment of distributed systems can aid to make decisions and chooses that lead to architectures that are inherently less complex and integral, and more architecturally robust and could be more easily partitioned into modules. Future research will investigate how to incorporate such network-based metrics into a system architecture assessment approach as an aid during early conceptual design phase.

Acknowledgements

The authors would like to thank Willi Galloway for his help on developing the design structure matrix for the two technical system architectures, Gordon Mckinstry for the help with the development of the MATPOWER model and Irina Maltopol with her help with SURVIVE modelling. The views expressed in this article are that of the authors and do not represent the views and opinions of BAE Systems. This work is funded by University of Strathclyde and BAE Systems Ph.D. scholarship.

References

Baldwin, C.Y., Clark, K.B., 2000. Design Rules: Volume 1. The Power of Modularity. The MIT Press, Cambridge, Massachusetts, London, England.

Brefort, D., Shields, C., Habben Jansen, A., Duchateau, E., Pawling, R., Droste, K., Jasper, T., Sypniewski, M., Goodrum, C., Parsons, M.A., Kara, M.Y., Roth, M., Singer, D.J., Andrews, D., Hopman, H., Brown, A., Kana, A.A., 2018. An architectural framework for distributed naval ship systems. Ocean Eng. 147, 375–385.

Browning, T., 2015. Design Structure Matrix Extensions and Innovations: A Survey and New Opportunities. IEEE Int. Eng. Manag. Conf. 63, 27–52.

Crawley, E., Week, O.L. De, Eppinger, S.D., Magee, C., Moses, J., Seering, W., Schindall, J., Wallace, D., Whitney, D., 2004. The influence of architecture in engineering systems. Pap. Present. MIT Eng. Syst. Symp. 29.

de Vos, P., 2014. On the application of network theory in naval engineering - Generating network topologies, in: 12th International Naval Engineering Conference and Exhibition. pp. 130–137. Amesterdam, Netherlands.

Department of Defense, 2011. FACT SHEET: Resilience of Space Capabilities.

Dobson, A.T., 2014. Cost Prediction Via Quantitative Analysis of Complexity in Ship Building. MSc Thesis, Massachusetts Institute of Technology, USA

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 Eng. 150, 36–47.

Gravil, K., Hayes, C., Mistery, A., 2014. How to exploit fundamental design modularity to obtain cost-effective life extension and through-life capability management for submarines, in: 12th International Naval Engineering Conference and Exhibition. pp. 270–285. Amsterdam, Netherlands.

INCOSE, 2015. Systems Engineering Handbook 4E.

Keane, R.G., Mierzwicki, T., Grogan, G., 2017. Designing Out Complexity Early: A Path to Affordable Flexible Warships. Nav. Eng. J. 129, 25–40.

Koc, Y., Warnier, M., Kooij, R.E., Brazier, F.M.T., 2013. A robustness metric for cascading failures by targeted attacks in power networks. 2013 10th IEEE Int. Conf. Networking, Sens. Control. ICNSC 2013 48–53.

Kott, A.; Abdelzaher, T. 2014 Resiliency and Robustness of Complex Systems and Networks. Adapt. Dyn. Resilient Syst. 67, 67–86.

Luo, J., 2015. A simulation-based method to evaluate the impact of product architecture on product evolvability. Res. Eng. Des. 26, 355–371.

Maier, M.W., Rechtin, E., 2000. The Art of Systems Architecting - Second Edition, New York.

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.

Newman, M., 2010. Networks: an introduction.

Newmann, M.E.J., 2003. The structure and function of complex networks. SIAM Rev. 45, 167–256.

Raz, A.K., DeLaurentis, D.A., 2017. System-of-Systems Architecture Metrics for Information Fusion: A Network Theoretic Formulation. AIAA Inf. Syst. Infotech @ Aerosp. 1–14.

Rebentisch, E., Schuh, G., Riesener, M., Breunig, S., Pott, A., Sinha, K., 2016. Assessment of Changes in Technical Systems and their Effects on Cost and Duration based on Structural Complexity. Procedia CIRP

Rigterink, D.T., 2014. Methods for Analyzing Early Stage Naval Distributed Systems Designs, Employing Simplex, Multislice, and Multiplex Networks. PhD Thesis, University of Michigan, USA.

Sinha, K., 2014. Structural Complexity and its Implications for Design of Cyber Physical Systems. PhD Thesis, Massachusetts Institute of Technology, USA.

Sinha, K., Suh, E.S., 2017. Pareto-optimization of complex system architecture for structural complexity and modularity. Res. Eng. Des. 29, 1–19.