Supplementing Industry-Specific Dynamic Positioning Requirements to Network Theory

E.L. Scheffers[1][*] and P. de Vos[1]

ABSTRACT

The trend towards fully autonomous navigation or reduced manning concepts, coupled with increased integration and interdependence of onboard systems due to the shift towards sustainable fuels and ever-increasing electrification and automation, has stressed the significance of ship systems' reliability. These developments reinforce the demand for a clear assessment of the robustness of main and auxiliary systems in early-stage ship design. Network theory offers a promising approach to address this demand. However, current graph measures do not align with industry-specific requirements for improving system robustness. This study aims to augment robustness evaluation components, such as modularity (independent subsystems), redundancy and reconfigurability, with additional considerations specific to Dynamic Positioning (DP) applications in the maritime industry. The enhanced robustness evaluation components are translated into graph measures. By employing these graph measures, different systems can be compared with respect to robustness, enabling informed decision-making in the trade-offs typical to early stages of the design process (e.g., cost versus redundancy). The proposed methodology combines the principles of network theory and industry-specific DP requirements to provide a comprehensive framework for evaluating the robustness of ship systems. System reliability can be assessed by integrating the identified robustness components and incorporating them into the graph measures. The early findings of this study show the potential to improve ship design processes by providing a systematic and quantifiable approach to enhance robustness.

KEY WORDS

Onboard Distribution Systems; Dynamic Positioning Regulations; Ship Design; Network Theory; Robustness; Reliability; Design Heuristics

INTRODUCTION

Safety and reliability are two of the most essential aspects in the process of ship design, as becomes particularly clear in the regulations for ships with Dynamic Positioning (DP) capability. A common way to express different levels of reliability for DP systems is by specifying the so-called "DP class" of the vessel. A Dynamic Positioned Vessel (DP Vessel) is:

> *A unit or a vessel which automatically maintains its position and/or heading (fixed location, relative location or predetermined track) by means of thruster force (ABS (2021)).*

The DP class regulations are subsequently based on increasing degrees of redundancy within the system. The high and

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well-defined redundancy facilitating maintaining a position is essential in the continuous operation of, for example, wind-turbine installation vessels, crew supply vessels and other offshore operations vessels because it increases the availability of the ships in more challenging conditions.

The first step of a theoretical DP system approach is to define the underlying principles of the system requirements. All requirements share a common goal: to increase the system's overall reliability. The number of definitions in this study, especially due to its interdisciplinary character, is high; the aim is to be explicit in the meaning of discussed concepts. Therefore, Table 1 provides an overview of reliability-related concepts from a marine engineering perspective. In Table 2, the right column contains the assumed working principle related to the system requirement. Most requirements are based on "component redundancy", whilst the aspects "distribution redundancy" and "independent subsystems" are both applied once.

The DP System is the complete installation necessary for dynamically positioning a vessel including, but not limited to the power system, thruster system, DP control system and independent joystick system (ABS (2021)). Regulations encompassing DP subsystems have been explicitly defined by IMO since 1994. The IMO acknowledges equipment class 1,2 and 3. The ABS levels of class notation, DPS-1, DPS-2 and DPS-3 are in line with the IMO classes and are stricter with regard to robustness requirements with an increasing level of DP class notation. Table 2 shows an overview of DP system requirements by subsystem and DP level (Clavijo et al. (2022)). The right column shows the related reliability principles, explained hereafter. In the development of these rules, experience and expert advice have been of leading influence. Therefore, we can consider the DP rules to be mainly based on empirical evidence, i.e. a posteriori knowledge. If we can design a framework in which we can understand the theoretical concepts behind the regulations, we can develop a priori knowledge with theoretical evidence. This understanding could aid in increasing the design space and possibly safer systems. The interdisciplinary scientific study of networks enables the use of tools or metrics based on graph theory. Network theory combines ideas from e.g. mathematics, physics and computer science to understand networks better. These networks can represent the system topology of the aforementioned DP subsystems. Using a network representation allows for system analysis in early design stages since the network can be defined using very limited To the authors' knowledge, no prior studies exist on the comparison between empirical DP regulations and theoretical network metrics.

Table 1: Robustness and Reliability Concepts

Concept	Definition
Robustness	The ability of distribution systems on board of (war)ships to withstand perturbations during system operation (Vos de & Stapersma (2018))
Reliability	The ability of a system to function as required without fault under given conditions during the given period quantified as the probability that a system will not fail or malfunction (Makoto ITO (2022))
Resilience	The ability of a system to withstand failure and to continue operations following failure (ABS (2021))
Redundancy	Ability of a component or system to maintain or restore its function when a single fault has occurred (ABS (2021)) The extent of degradation the structure can suffer without losing some specified elements of its functionality (Kanno & Ben-Haim (2011))
Component Redundancy	Achieved by the installation of multiple components (ABS (2021))
Distribution Redundancy	The presence of "independent alternative paths between source and demand nodes which can be used to satisfy supply requirements during disruption or failure of the main paths" (Goulter (1987))
Independent subsystems	Two or more component groups, each of which is capable of individually and independently performing a specific function (ABS (2021))

Paper Outlook

A comparison between empirical DP regulations and theoretical network metrics is a new approach. Therefore, the focus of this paper is 1) to provide a clear outline of the assumptions made to enable the comparison, 2) to introduce a selection

Table 2: Subsystem requirements (Clavijo et al. (2022)) and the corresponding reliability principles

Subsystem (Item)	Minimum system requirements			Reliability Principle
	Class 1	Class 2	Class 3	
Power subsystem				
Generators and prime movers	Non-redundant	Redundant	Redundant	Component redundancy
Switchboard	1	1 with bus-tie 1 with coupler	2 with bus-tie in separate compartments 1 with coupler	Distribution redundancy
Bus-tie breaker	No	1 (open or closed)	2 (open)	Independent subsystems
Power management	No 1	Yes 2	Yes 3	
Thruster subsystem				
Rudders	Non-redundant	Redundant	Redundant	Component redundancy
Thruster	Non-redundant	Redundant	Redundant	Component redundancy
Single lever for each thruster at main DP-control center	Yes	Yes	Yes	Component redundancy
Control subsystem				
Position reference system (PRS)	2	3	2 + 1 backup	Component redundancy
Vertical reference sensor (VRS)	1	3	2 + 1 backup	Component redundancy
Wind	2 2	3 3	2 + 1 backup 3	Component redundancy
Gyro	2 1	3 3	2 + 1 backup 3	Component redundancy
Uninterruptible power supply (UPS)	1 1	2 2	2 + 1 backup 3	Component redundancy
Independent joystick system (IJS)	Yes	Yes	Yes	Independent subsystems
Computer system: number of control computers	1 1	2 2	2 + 1 backup 3	Component redundancy
Consequence analyzer	No	Yes	Yes	
Backup control station	No	No	Yes	Backup

of network metrics and their working principles, and 3) to discuss the comparison and future research directions. The paper starts with the "translation" from system diagrams to networks and the related assumptions (Section "Method: Network Definition"). The next Section introduces a selection of reliability network metrics, classified using the theoretical reliability principles which are deduced from the DP regulations (Section "Method: Network Reliability Metrics"). The method, consisting of the network definition and reliability metrics, is applied to a case study of two DP systems (Section "Case Study"). Concluding this paper, we will discuss the results, reflect on the approach and draw final conclusions (Section "Conclusion")

METHOD: NETWORK DEFINITION

The DP System is the complete installation necessary for dynamically positioning a vessel (ABS (2021)). The following components or machines are always present in a DP system: electric power generation components such as engine-generator sets, multiple levels of electric power distribution via switchboards and distribution boards, electric converters, electric motors driving thrusters, a control system and finally, non-propulsion-related electric power consumers. When a comparable level of detail is maintained, most steps in translating a system to a network topology are straightforward. In each graph representation G of a network, components like generators, thrusters and converters are represented as nodes or vertices V; pipes, shafts and cables are represented as links or edges E so that a network becomes a combination of nodes and edges $G(V, E)$. The networks are assumed to be simple undirected, unweighted connected graphs, meaning that the network 1) does not contain two or more connections between a pair of nodes, there are no self-loops (connections starting and ending at the same node), 2) the edges are undirected (the start point and end point can be considered interchangeably), 3) all edges have weight 1, and 4) all nodes are connected via one or more paths (Newman (2010)). The first three of these network properties result in a simplified network representation, only considering the network properties present in the logical architecture representation as defined by Brefort et al. (2018). The edges are undirected because edge direction is considered a temporal aspect and, therefore, part of the operational architecture. Certain aspects, however, are more subjective in their representation approach. Therefore, they are explained separately in the following sections.

Distribution system components

The switchboard is a less straightforward component within the translation from system diagram to network topology. A switchboard as part of an electric system diagram is often represented as a (double) line or bar with different connecting lines entering and exiting this bar. The two extreme approaches to modelling a switchboard are shown in Figure 1a and Figure 1b respectively: the entire switchboard as a single point of failure. Meaning that, if something fails within the switchboard, in the model this is approached by a failure of the entire switchboard. The other extreme is disregarding the switchboard altogether and connecting the supplier nodes directly to all possible user nodes, as if the system is a complete bipartite graph (Newman (2010)). A failure within the switchboard influences a certain connection between this supplier and user but does not influence any of the other connections. Other approaches are, in terms of reliability, found between these extremes.

In this study, the switchboards are an essential part of the analysis since they are explicitly mentioned in the regulation overview in Table 2. Therefore, they must be included in the network. Considering switchboards as nodes within the network is in line with the node differentiation approach by Vos de (2018), who considered converter nodes (like generators) and hub nodes (like switchboards). This is approached by having the switchboards present as nodes connected to other nodes that represent the switchboard input and output ports. Whenever a switchboard is split by a switch or a bus-tie, a second node is added to the switchboard.
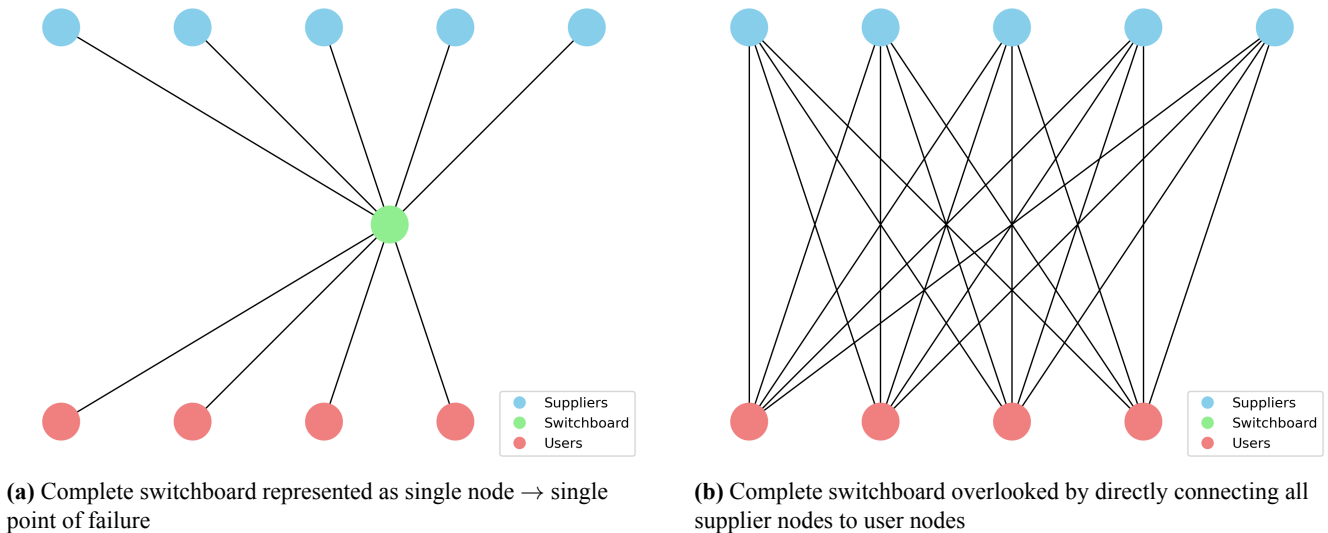
(a) Complete switchboard represented as single node → single point of failure

(b) Complete switchboard overlooked by directly connecting all supplier nodes to user nodes

Figure 1: Extremes of distribution component network representations

Control system

The control system is taken into consideration separately as part of simplifying the network representation. The control system is an essential part of the network; however, it is of such a different nature that it cannot automatically be compared using the same tools as the physical system components and connections. Moreover, the design freedom to determine the topology of the control system is so significant that the subjective choices made influence the network too significantly. This case study considers values of the network including and excluding the control system.

Spatial considerations

An important part of improving resilience is by placing redundant components in separate compartments. This spatial aspect is, within this study, only taken into consideration when it is explicitly present in the system diagram. This differentiation between spatial system design and logical system design is in line with Brefort et al. (2018) and his division between functional architecture, logical architecture and physical architecture in the analysis of onboard systems.

METHOD: NETWORK RELIABILITY METRICS

Component Redundancy

This reliability aspect refers to redundancy achieved by the installation of multiple components performing a certain function (ABS (2021)). In this study, we do not apply system diversification (using different yet functionally similar components) to prevent common cause failures from happening. The following two network metrics have been selected to be a proxy measure for component redundancy: effective resistance (Ellens & Kooij (2013)) and maximum flow (Newman & Girvan (2004)).

Effective Graph Resistance

Following the approach of (Ellens & Kooij (2013)), component redundancy facilitates parallel paths within a network and, therefore, increases with decreasing graph resistance. The effective graph resistance is based on the number of paths (parallel) and the length of paths (series) between different sets of nodes, which indicates the vulnerability of the connection between those nodes Ellens et al. (2011). In line with electrical resistance, a lower value suggests an "easier" flow between nodes. Therefore, we assume that the component redundancy increases with a decreasing graph resistance. Moreover, the effective graph resistance strictly decreases when an edge is added (Ellens & Kooij (2013)). The resistance between two nodes can be calculated using standard series and parallel resistance calculations. If each edge has a resistance $r = 1$ Ohm, two nodes (a and b) connected by a single path of length 2 have a resistance of

$$r_{a \to c} = r_{a \to b} + r_{b \to c} = 1 + 1 = 2 \text{ Ohm} \tag{1}$$

Where $r_{a \to c}$ is called the effective resistance or resistance distance between node a and b. Adding an extra path between these respective nodes of length 3 gives

$$
\begin{aligned}
\frac{1}{r_{a \to c}} &= \frac{1}{r_{a \to b} + r_{b \to c}} + \frac{1}{r_{a \to d} + r_{d \to e} + r_{e \to c}} = \frac{1}{2} + \frac{1}{3} = \frac{5}{6} \\
r_{a \to c} &= \frac{6}{5} \text{ Ohm}
\end{aligned}
\tag{2}
$$

The effective graph resistance R_G or Kirchhoff index is the sum over all pairs i, j of nodes. And can be calculated as (Ellens & Kooij (2013))

$$R_G = \sum_{1 \le i \le j \le N} R_{ij} = N \sum_{i=2}^{N} \frac{1}{\lambda_i} \tag{3}$$

Here, N is the number of nodes in the network and λ_i is the i-th eigenvalue of the Laplacian matrix L, which is defined as $L = D - A$. The degree matrix $D_{N \times N}$ contains the degree (number of edges connected a node) on the diagonal so $D_{i,i} =$ degree of node i. The adjacency matrix $A_{N \times N}$ has, generally speaking, non-zero values where nodes are adjacent (connected by an edge). In this study, we assume the networks to be undirected, unweighted graphs, thus $A_{i,j} = A_{j,i} = 1$ if node i and j are connected. Since we assume the networks to be connected as well, only the first Laplacian eigenvalue $\lambda_1 = 0$. Therefore, the sum of the eigenvalues starts at the second eigenvalue λ_2.

Note that effective graph resistance as an indicator of component redundancy is currently still subject to active academic discussion. This statement is in fact applicable to all graph metrics discussed here and their corresponding maritime reliability principles, as this is part of ongoing research.

Maximum Flow

The idea of component redundancy is to avoid single points of failure in the system. This translates to 'bottlenecks' when the system is considered as a flow network. These bottlenecks can be calculated using cut sets: a set of nodes or edges whose removal will disconnect a specified pair of nodes (Newman (2010)). The weight of each edge can physically be interpreted as the length or the capacity of that edge. Here, the capacity of each edge is set to 1 since we assumed the network to be unweighted; the primary reason for this assumption is the fact that length or capacity of the connections are unknown (as will very often be the case in early stages of ship/system design). This gives us the following definition for maximum flow: the maximum flow between a given pair of nodes in a network is equal to the sum of the capacity of the edges of the minimum edge cut set that separates the same two nodes (Newman (2010)). Calculating the maximum flow of a given network is an NP-hard problem; its value is approached using an algorithm. Algorithm 1 shows a basic greedy algorithm in order to explain an approach to $f_{textmax}$. In this study, maximum flow as approached by the push-relabel algorithm (Goldbergt & Tarjan (n.d.)), which is further explained in (Roughgarden (2016b)) but will not be detailed here. Most DP systems are required to have more than one source node (e.g., the generator sets) and more than one sink node (e.g. thrusters). Therefore, a synthetic source and sink node are added in the calculation of this metric, respectively connected to all "actual" source nodes and all "actual" sink nodes.

Algorithm 1 Greedy approach to Maximum Flow (Roughgarden (2016a))

  Input: G, V, E, c_e,   ▷ network, nodes, edges, edge capacity
  Output: $f_{\max,G}$ ▷ maximum flow between source node s and sink node t
 1: $f_e \leftarrow 0$ for all $e \in E$ ▷ initialise edge flow as all-zero flow
 2: **repeat**   ▷ path P is a walk with no nodes repeated
 3:   find $s - t$ path P such that $f_e < c_e$ for every $e \in P$ ▷ edge flow f_e can never be larger than capacity c_e
 4:   **if** no such path **then** halt with current flow $\{f_e\}_{e \in E}$
 5:   **else**
 6:    $\Delta \leftarrow \min_{e \in P}(c_e - f_e)$ ▷ Calculate available capacity of edges on path P
 7:    **for** all edges e **do**
 8:     $f_e \leftarrow f_e + \Delta$
 9:    **end for**
10:   **end if**
11: **until** $f_e \leftarrow f_{\max}$

Distribution Redundancy

Distribution redundancy refers to how well the redundant components can be utilised within the network. This aspect borders on reconfigurability: if a connection fails, can we still reach all relevant components via a different path? Therefore, the focus in selecting an appropriate metric for this aspect is on measures that express cycles, triangles and other cyclic topologies. The first metric we considered was the meshedness coefficient (Yazdani & Jeffrey (2012); Buhl et al. (2006)), which is the fraction between the total and maximum number of independent loops in a planar graph. This is a metric that has been applied to, i.a., water distribution networks (Yazdani & Jeffrey (2012)) and urban road networks (Buhl et al. (2006)). However, since onboard systems are designed within a three-dimensional space, we cannot guarantee that all networks are planar (can be drawn on a plane without having any edges cross (Newman (2010))). Therefore, the meshedness coefficient cannot be applied to onboard systems. Two other measures, however, can be applied to undirected non-planar networks: the clustering coefficient and the cycle basis.

Clustering Coefficient

In real-world networks, two properties are often found: a high clustering coefficient and robustness to random node failures. This clustering refers to the idea that "my friends are likely to be friends"; an expression for the triangle density within the network. Triangles facilitate two ways of reaching a certain point within the network, which we consider as distribution redundancy. Thus, the local clustering coefficient c_i of node i is defined as the number of edges among neighbours of i divided by the possible number of edges among its neighbours (Ellens & Kooij (2013)). The global clustering coefficient (over the complete network) is either expressed as the average of the local clustering coefficients or as six times the number of triangles divided by the number of triples (three connected nodes). In this study, we have chosen to apply the second definition for its focus on the complete network:

$$\tilde{c}_G = \frac{6 \times triangles_G}{N_2 - W_2} = \frac{trace(A^3)}{\sum_{i=1}^{N} d_i(d_i - 1)} \tag{4}$$

Where $\tilde{c}_G$ is the global clustering coefficient of network G, N_2 is the number of walks of length 2 (all sets of three connected nodes: $e_{a \to b}, e_{b \to c}$), W_2 is the number of closed walks (same begin and end node), A the adjacency matrix and d_i the degree of node i.

Circuit Rank

The second proxy for distribution redundancy is an extension of the clustering coefficient: the circuit rank or cyclomatic number Berge (2001). This metric provides the number of closed loops in the network that provide the base for all loops present and is equal to the number of independent cycles. The rank indicates a minimum number of edges to be removed to lose all cycles within the network and can therefore be considered as a minimum redundancy boundary. The circuit rank r_G is calculated as

$$r_G = E - V + C \tag{5}$$

Where E is the total number of edges in G, N the number of nodes and C the number of connected components, which $C = 1$ in case of a connected network.

Independent Subsystems

The last reliability aspect is perhaps most directly related to network metrics. Having two or more component groups capable of individually and independently performing a specific function can be seen as a specific network partitioning with additional requirements. Network partitioning is the grouping of nodes in communities or partitions. The quality of this network division can be expressed as modularity (Newman & Girvan (2004)). To maximise modularity is to maximise the difference between the actual number of edges in a community and the expected number of such edges (Traag et al. (2019)). Again, we need an algorithm to approach the optimal network division. The Leiden algorithm is applied to partition the network (Traag et al. (2019)). The main disadvantage of this current network-based modularity approach is that the different functions of the components are not taken into account when determining the communities.

CASE STUDY

The case study consists of two Dynamic Positioning Systems of class level 2 and 3. The systems are defined by Clavijo et al. (2022) and initially used to perform a Reliability, Availability and Maintainability (RAM) analysis. This is a theoretically defined system based on literature and system knowledge. In future work the authors aim to apply the network analysis to real-world systems. Figure 2 shows the two considered systems, each consisting of a power subsystem (red), thruster subsystem (yellow), and control subsystem (green).

As mentioned in Section "Control system", the control system is regarded separately in this work. Figure 3 presents the corresponding network representation of the complete DP2 system. This figure shows the difference in structure between the power and thruster subsystems versus the control subsystem; the degree distribution is clearly completely different. Due to this difference in nature, the DP system is analysed both including and excluding the control system components.

In line with the assumptions made in Section Method: Network Definition, we have constructed the DP2 and DP3 systems as shown in Figure 4. Based on a visual inspection of the networks, the DP3 system clearly has three main components in its main switchboard, whereas the DP2 system has two components. However, the connections between the transformers in DP2 seem to add to the overall reliability. Lastly, the double connection to one of the computer system components in DP3 creates an additional loop. This is expected to add to the distribution redundancy estimation.

Table 3 shows the different calculated network metrics (of subsystems) of the DP2 and DP3 systems. The first two networks show the metrics of the complete DP systems as shown in Figures 2 and 3. The last two columns contain the metrics of the simplified DP systems as shown in Figure 4. The bold green values indicate a "higher reliability", which is not for all metrics a positive correlation. First, the table is inconclusive in indicating the most reliable system based on the selected network metrics. The component redundancy, estimated using effective graph resistance and maximum flow, contradicts itself. This is also the case for the distribution redundancy metrics global clustering and circuit rank. However, the independent subsystem defined using network modularity is higher for the two DP3 network representations.
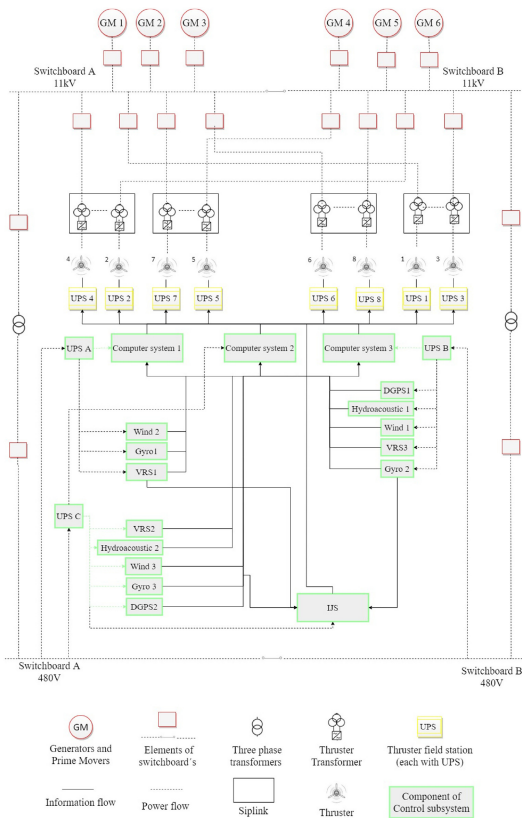
(a) DP2 System Diagram (Clavijo et al. (2022))
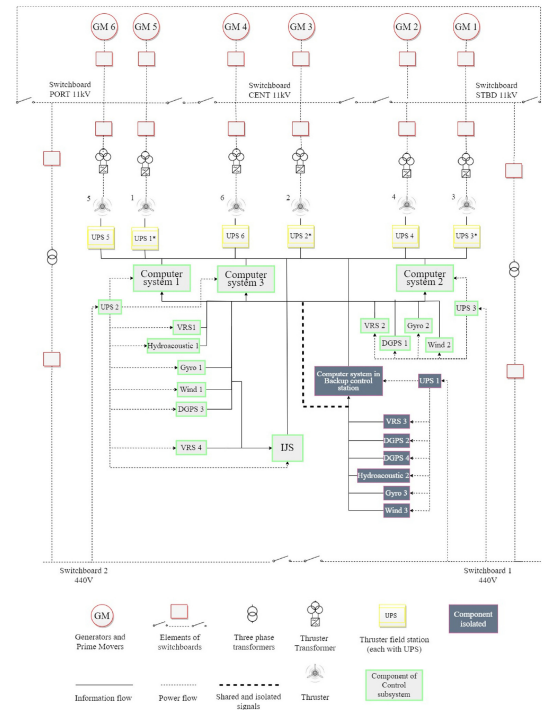
(b) DP3 System Diagram (Clavijo et al. (2022))

Figure 2: Dynamic Positioning System Diagram with the following Subsystems: Computer System (COMP), Generator/Prime Mover (GM), Main Switchboard (MSWB), Switchboard (SWB), Transformers (TF), Uninterrupted Power Supply (UPS)
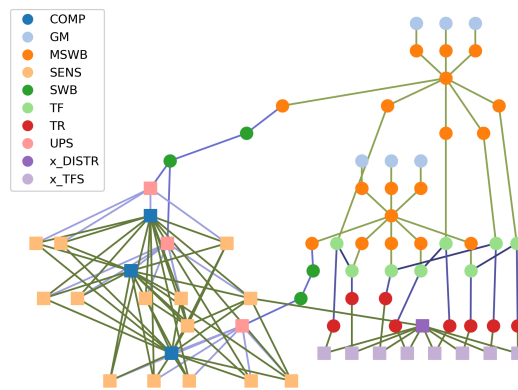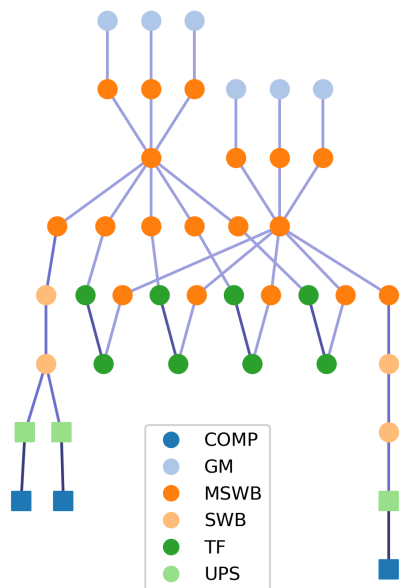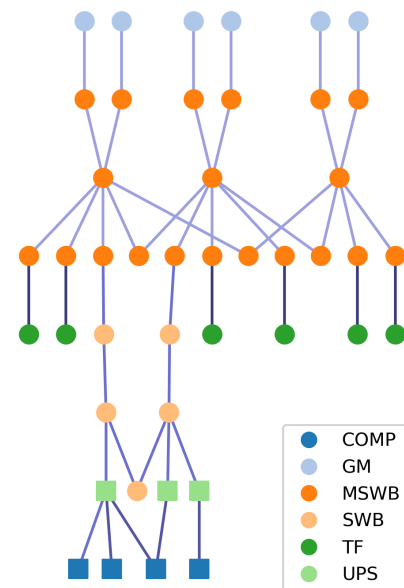

Figure 3: DP2 Network Representation with the following Subsystems: Computer System (COMP), Generator/Prime Mover (GM), Main Switchboard (MSWB), Sensors (SENS), Switchboard (SWB), Transformers (TF), Thrusters (TR), Uninterrupted Power Supply (UPS), Control System Components (x_DISTR and x_TFS). The square nodes are part of the control system and are separately considered.

(a) Network Representation of DP2 System

(b) Network Representation of DP3 System

Figure 4: Dynamic Positioning Network Representation with the following Subsystems: Computer System (COMP), Generator/Prime Mover (GM), Main Switchboard (MSWB), Switchboard (SWB), Transformers (TF), Uninterrupted Power Supply (UPS). This representation mainly shows the nodes not part of the control system (round nodes) whilst a few control system components (square nodes) have been included to show where they are connected to the other system components

Table 3: Network Metrics for the full DP Systems and for the Power and Thruster Subsystem; metrics sorted by Component Redundancy (1,2), Distribution Redundancy (3,4), Independent Subsystems (5) and General Network Metrics (6,7) and the value implicating "higher reliability" in **bold green**

	DP2 (incl control)	DP3 (incl control)	DP2 (excl control)	DP3 (excl control)
1) Effective Graph Resistance	**5043**	5498	**3203**	3257
2) Maximum Flow	3	**5**	1	**1,25**
3) Global Clustering	0,072	**0,163**	0	0
4) Circuit Rank	**58**	53	3	3
5) Modularity	0,480	**0,493**	0,496	**0,520**
6) Number of Nodes	73	74	42	44
7) Number of Edges	130	126	44	46

CONCLUSION

The goal of this study was to compare empirical DP regulations and theoretical network metrics. This was approached by 1) providing a clear outline of the assumptions made to enable the comparison, 2) introducing a selection of network metrics and their working principles, and 3) discussing the comparison and future research directions. We have translated two dynamic positioning systems into network representations and analysed these networks using selected network metrics. This selection was based on the assumed working principles behind the regulations in Table 2.

The resulting comparison shows that the selected network metrics do not affirm the working principles. The DP3 systems have a higher modularity and maximum flow indicating higher component redundancy, however, the higher effective graph resistance indicates the opposite conclusion. No conclusions can be drawn about the DP2 and DP3 power and thruster subsystems distribution redundancy since the networks contain no triangles (global clustering coefficient is 0) and the same number of closed loops (3).

Discussion and Outlook

This study has been an initial attempt to express regulations for dynamic positioning systems as network metrics. Despite the inconclusive results, we believe that a future framework based on network theory can aid ship designers and marine engineers in designing safer onboard systems. However, we like to emphasize that additional research is essential before completing such a framework:

- This case study used two DP systems based on literature. Having actual networks (complete systems or subsystems) to compare would be a major step in making the network metrics more applicable to real-world systems. In future research, we aim to study systems with a higher number of components. This might reduce the arbitrariness in defining the network and could therefore yield more reliable results.

- The research approach of this study contained a series of assumptions: definition of reliability principles → matching these principles with regulations → selecting network metrics as a proxy for the reliability principles. We have been aware of possible bias in these steps, however, a formal framework to make these steps would be recommended for future research. This framework should also contain a very good and very bad example of a DP system to facilitate bench-marking the studied networks and the corresponding metrics.

- The translation of the DP systems to networks included a number of assumptions as well. Whilst most of them have been described in Section "Method: Network Definition ", a significant assumption has been disregarded so far: the difference in network size between the DP2 and DP3 systems. The authors are aware that it is no common practice in network science to compare networks with different number of nodes (components). This size difference is, however, a network aspect that is inherent to systems onboard ships. Therefore, a comprehensive approach to this sizing problem and related normalisation concepts is recommended as future research.

- The aspect that makes the analysis of DP system regulations interesting, the fact that it sets requirements on different aspects of the integrated system, also makes it challenging to study. The DP systems often show a variety of components and connections. We consider the different components and connections to be a multilayer network: nodes and edges are part of a certain "layer" based on their respective type of flow. Interdonato et al. (2020) shows a range of possible approaches to simplify a multilayer network, motivated by reducing system "noise", being able to use already existing monoplex analysis methods, improved computational performance. The case study is presented as a multilayer network in Figure 5. The multilayer aspect is further disregarded in line with the motivations provided by Interdonato et al. (2020).
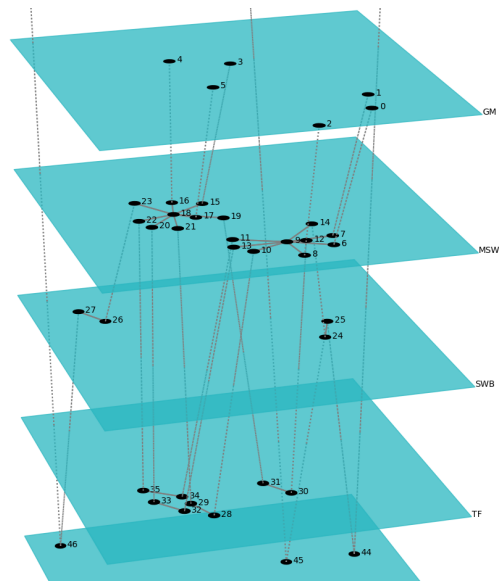
Figure 5: DP2 Multilayer Network Representation (close-up) showing the subsystems in different layers (blue "levels"): Generator/Prime Mover (GM), Main Switchboard (MSWB), Switchboard (SWB), Transformers (TF), Thrusters (TR)

CONTRIBUTION STATEMENT

E.L. Scheffers: Conceptualization; data curation, methodology; writing – original draft. **P. de Vos:** conceptualization; supervision; writing – review and editing.

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