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On the application of network theory in naval engineering

Generating network topologies

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SYNOPSIS

Network topology of technical systems (i.e. the way in which components of technical systems are connected to each other through connections like pipes, cables, shafts, etc.) in naval vessels is quickly fixed in current design methods. This means the vulnerability of these systems is also quickly fixed. Variation in network topology may lead to new, unknown topologies that have better survivability characteristics. Therefore a new approach to designing technical systems is explored in this paper. This approach applies mathematical network theory in a naval engineering context. Basic concepts of network theory are explained and then used to make automatic network topology generation possible. Preliminary results using a first version of a network topology generation algorithm are presented and discussed. Future work within the PhD research of which this network topology generation is one aspect is then described.

INTRODUCTION

Where do the initial designs of ship machinery systems in naval vessels originate from? How is a functional specification of a platform system transformed into an initial design of that system? These and other questions concerning the conceptual design of ship systems have inspired a research that aims to apply mathematical network theory in a naval engineering context. The reasons to research this possible application of network theory will be explained later in this paper. For now only the potential benefits of this approach are listed: the possible discovery of new network topologies (i.e. the way in which components of technical systems are connected to each other through connections like pipes, cables, shafts, etc.) may lead to improved performance and reliability of systems, the possibility to analyse more network topologies in early ship design stages which leads to a mitigation of risks for required major design alterations during detailed design and improved accuracy of initial cost calculations.

The idea for this approach spawned from *van Oers* [1]. He assumed that the number and dimensions of large components of machinery systems are already known in early ship design stages and started from there with his automated ship configuration to place those components on board using a packing approach. Naval architects are supported by this approach as it helps them to cover the complete design space in early ship design while being able to quickly focus on promising ship configurations at the same time. In his recommendations *van Oers* states that “Developing the parametric model can only start after the ship’s systems and the design requirements are available. Designing the systems and deriving requirements are both important (due to their impact on the resulting ship design), and time-consuming. Hence, support for this part of the design process is essential” [1]. Because of this recommendation and because of the question whether similar benefits of such an automated conceptual design approach can be achieved in marine engineering as were done for naval architecture, a follow-up PhD research, named MOSES-CD, was defined. One of the differences between *van Oers* [1] and MOSES-CD is that where the packing approach was used for automated ship configuration by *van Oers*, another field of mathematics is identified to help with the automated conceptual design of technical systems in naval vessels; namely network theory. This paper aims to describe the progress of this research and will show some preliminary results on the application of network theory in naval engineering.

In the first section of this paper, following this introduction, the early design process of technical systems on board naval vessels is evaluated. At the end of this section the conclusion is reached that network topologies of technical systems are rarely varied in early ship design stages, mainly because of time limitations. The main drawback of this situation is that the designer cannot be sure whether the most suitable network topology has been chosen. To address this drawback and enable variation in network topology network theory is needed, therefore the second section of this paper introduces some basic concepts of network theory after which the third section discusses automatic network topology generation (NTG) using these basic concepts. Then preliminary results of this approach are shown, which is followed by a section with a discussion of the results and research and a description of future work. After this section the paper is concluded.

Author’s Biography
Peter de Vos is lecturer / researcher at the Marine Engineering specialisation of Delft University of Technology. He graduated cum laude in 2008 on the dynamic simulation of a PEMFC + fuel reformer power plant for naval vessels. He has since been involved in many research projects focussing on the design and dynamic behaviour of complex marine systems and has attended to many educational activities concerning marine engineering. In 2010 he started a PhD research.

DESIGN OF TECHNICAL SYSTEMS IN NAVAL VESSELS

The ambition to build a new (class of) naval vessel(s) is first materialized in a mission statement which defines the purpose of the future naval vessel. The mission of the ship is subsequently divided into several functions and sub-functions of the ship in a functional decomposition, ref. [2] and [3]. Once a functional decomposition is known marine engineers can start designing actual systems consisting of components and connections between them.

This step in the design process can be perceived as “materializing” the defined functions of (sub-)systems, i.e. the (sub-)functions of the ship are transformed into technical system for the first time. This does not mean that actual systems are being build; a lot more detailed design and engineering is still needed before actual building of the ship and its components can start. What is meant is that this step is the first time in the design process that known equipment is linked with the “ideas behind the new ship”. Ideas are turned into drawings representing real technical systems; obviously this step is still very early in the design process. But it is a major step and the question that is now raised is: how does a marine engineer manage to do this (i.e. turning ideas into technical systems)? This is a rather philosophical question as practical marine engineers often hardly distinguish between function and technical systems or components. It is for instance very natural for a marine engineer that the function mobility is provided by the propulsion system and the function cooling is provided by a heat exchanger. Thus a marine engineer immediately starts thinking in solutions (systems and components) when confronted with a design objective.

These solutions are often visualised using block diagrams this early in the design. Such block diagrams show the system’s components and the connections between them. The block diagrams can be independent of the field of engineering that the represented system belongs to; i.e. principal block diagrams. But field-specific block diagrams are perhaps better known; e.g. one-line (or single line) diagram for electric systems, piping diagrams for hydraulic systems and a propulsion system diagram for the largest mechanical system on board. The main difference between field-specific block diagrams and principal diagrams is the application of field-specific symbols representing field-specific components.

The function of such diagrams is however similar in all cases: to show the main components of the system and the overall topology of the system, i.e. the way the components are connected. This system lay-out is decided upon by the marine engineer on basis of expected operational modes and previous experience. The block diagram is used by the marine engineer to “get a feeling” of the operational performance of the system.

The operation of the system is however not the main focus of naval architects and cost calculation engineers in these early design stages. Naval architects generally want to know the number of components and their main dimensions so they can place the components in concept designs of the complete ship. Cost calculation engineers need to know the number of main components as well and the possible manufacturers of these components so they can gather cost data on the system. Apparently the focus is on components and the connections between components have lower priority during these early design stages. The connections are left to be figured out in more detail in later design stages. Clearly this works well when overall concept design and cost calculation are the main objectives of the early design stages. However as soon as other performance aspects of the ship needs to be taken into account, e.g. survivability, this approach fails and the connections become very important. That is why in this research the focus is on the connections between components; trying to find ways to make it possible to take these connections into account in early ship design.

Generally the above applies to any technical network or (energy) distribution system on board naval vessels. Some typical examples of these systems including their components and connections are listed in Table 1.

Table 1 Examples of technical distribution systems on board naval vessels, their main components and connections

Systems	*Main components*	*Connections*
Electric power distribution system	Generators, Electric Motors, Switchboards	Electric cables
FiFi system	Pumps, Nozzles, Valves	Pipes
Chilled water distribution system	Pumps, Heat exchangers, Valves	Pipes
Propulsion system	Diesel Engines, Propellers, Gearboxes	Shafts
Data acquisition network	Sensors, Computers, Routers	Network cables
Control signals network	Computers, Actuators, Routers	Network cables
Fuel loading and distribution system	Pumps, Tanks, Valve(s) chests	Pipes
HVAC system	Air Conditioning Units, Rooms, Valves	Ducts
Ballast water system	Pumps, Tanks, Valves	Pipes
Etc.		

Some of these systems are considered in early design stages, while others are not considered at all and their design is entirely left to later design stages (if their main components are sufficiently small and cheap). If a system is considered the focus is on the main components and the topology of the systems is rarely studied in more detail as stated above.
Using current methods studying the topology by making variations to it is indeed a time-consuming activity, which is probably one of the more important reasons to not do this in early ship design stages. Next to this, variation of network topology may be considered unnecessary as well-known *fixed templates* exist for most distribution systems and depending on the expected operational modes of the system one of these templates is chosen or copied from previous designs. Sometimes the network topology template is varied in early design stages, e.g. whether to apply CODOG, CODELOG or IFEP configuration for the propulsion system of a naval surface combatant can be a topic of discussion, as also became clear during INEC 2012, ref. [4] & [5]. And even in this case of the fairly small network of propulsion systems the study on variation in topology focusses on a limited amount of *fixed templates* for network topology.

The purpose of the research described in this paper is to find out possible benefits if this fixed template approach is completely abandoned. What network topologies would arise if we start with a blank sheet of paper (*tabula rasa*)? Would we find the same network topologies that are now captured in the fixed templates or would we find new topologies with additional benefits like better survivability characteristics? Such questions need to be answered using network theory, which is the study of network structures. Basic concepts of this field of mathematics are introduced in the next section, after which these concepts are applied to generate network topologies using the *tabula rasa* approach.

BASIC CONCEPTS IN NETWORK THEORY

The most fundamental concepts in network theory are the vertex (or node) and the edge (connection between vertices) [7]. In technical systems on board naval vessels the components as listed in the middle column of Table 1 would be the vertices of the network and the connections as listed in the right column would be the edges of the network. The network topology, i.e. the way vertices are connected by edges, is defined by the adjacency matrix which is an *nxn*-matrix with n being the number of vertices. In an undirected network element a_{ij} of the adjacency matrix equals one if an edge exists between vertex i and j and zero otherwise. Thus the adjacency matrix can be used to make a graph that represents the network topology visually, i.e. in a way that is closer to the more familiar block diagram approach. An example is given below.

But first an important difference in the way networks are represented in network theory and marine engineering is explained. There is no "main line" in network theory since edges cannot have edges connected to them (edges can only be connected to vertices). This means that a representation of a network like in Figure 1 would not be encountered in network theory. The main line itself would be considered a vertex (a component), which is not as strange as it may seem since the main line in such diagrams represents for instance a switchboard in an electric system.

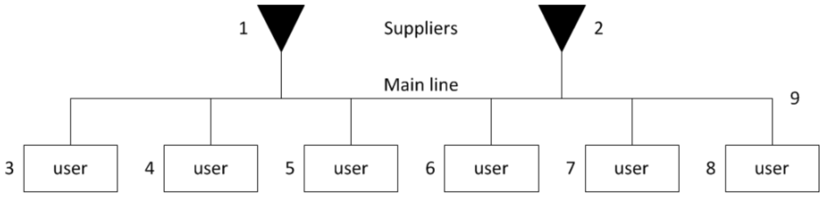

Figure 1 "Tree distribution" (figure taken and adapted from [6]).

Figure 1 shows what is considered a typical marine engineering representation of a network topology. The suppliers can be generators, pumps or diesel engines for instance. The main line may be a switchboard, a main pipe line or a gearbox (although it is rare to find six mechanical power users connected to a gearbox). The users are consumers of whatever the suppliers are supplying (e.g. electric power, hydraulic power or mechanical power).
As said in network theory the main line is a vertex itself. Such a vertex has many edges connected to it. This brings us to the introduction of a "hub", which is a vertex inside a network with an unusual high degree (the degree of a vertex is the number of edges connected to it) compared to other vertices inside the same network. Hubs are found in many networks, including the ones on board naval vessels. In their review and synthesis paper on the hub network design problem O'Kelly and Miller state that hubs "allow the construction of a network where direct connections between all origin and destination pairs can be replaced with fewer, indirect connections" [8], i.e. a network that resembles the topology of Figure 1 instead of that of Figure 2. Such hub

network topologies “ reduce and simplify network construction costs, centralize commodity handling and sorting and allow carriers to take advantage of scale economies through consolidation of flows” [8]. Although the paper of O’Kelly and Miller focusses on transportation networks, the mentioned arguments to introduce hubs in networks are just as valid in energy distribution systems on naval vessels. Furthermore hubs in these systems may have an important function; which is converting the effort and flow variables of the energy flow to higher or lower values, e.g. a gearbox converting a high rotational speed of connected engines to a lower level for the propeller or a transformer inside a switchboard converting a high voltage level to a lower voltage level. What is not mentioned in [8] but is mentioned in [6] is that the tree distribution of Figure 1 is much more vulnerable (in case of a break in the main line the whole system fails) than the star distribution of Figure 2. This is a good example of how closely related vulnerability and network topology are, which is a good reason to research variation of network topology of technical systems on board naval vessels.

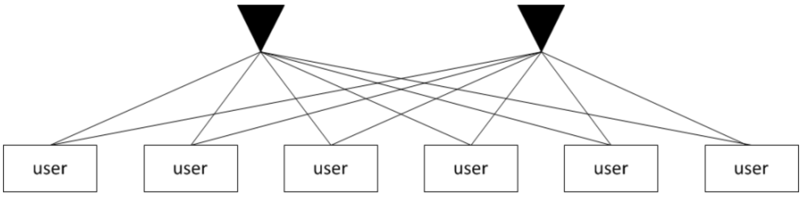

Figure 2 “Star distribution” (figure taken from [6]).

Now the hub has been discussed as a separate vertex we can build the adjacency matrix of the network shown in Figure 1 as an example. The vertices have been numbered starting with the suppliers then the users and finally the hub. The adjacency matrix is:

$$A = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \end{pmatrix}$$

As said a graph can be made using this adjacency matrix to make a more visual representation of the network closer to the familiar block diagram. A short algorithm that was developed within this research shows the network of Figure 3, which may be compared to Figure 1.

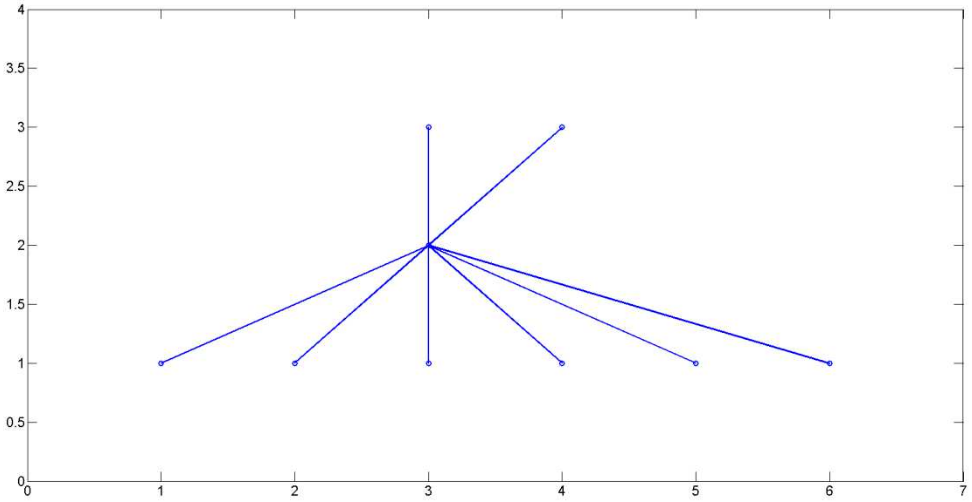

Figure 3 Network theory representation of tree distribution as shown in Figure 1.

Although the figures do not exactly look similar they do represent the same simple network topology, which proves network theory can be applied in a naval engineering context. Now let’s see if we can use it to speed up network topology variation so more topologies can be studied in early ship design stages.

NETWORK TOPOLOGY GENERATION (NTG)

Now that basic concepts of network theory have been introduced we can address the research question posed at the end of the section on technical system design: “What network topologies would we find if we start the design of technical systems on board naval vessels with a blank sheet of paper?” This approach is called the *tabula rasa* approach which differs from the *fixed template* approach that is normally used by having no connections between components defined at the start of technical system design. Instead the connections are generated randomly to see what network topologies would arise.

It was soon discovered that completely random NTG would not make much sense and result in enormous computational times for actual systems since the number of possible networks is given by (ref. [7]):

$$N_{\text{networks}} = 2^{\left(\frac{n\cdot(n-1)}{2}\right)}$$

Now imagine a network consisting of four suppliers, two hubs and ten users (e.g. the top level of a single line diagram with four generators, two switchboards and ten large electric power consumers or distribution boards connected to them). That network would consist of 16 vertices, so the number of possible networks according to the formula above would be $1.3292\cdot10^{36}$. Clearly such a high number of possible network topologies would not support a marine engineer with designing this system; it would merely confuse him/her to the point that he/she gives up.

So additional constraints on the network to be designed are necessary. These constraints should follow from what a designer already may know about the system. For instance, a logical constraint would be “the system needs to be fully interconnected” meaning that a path should exist between all users and at least one supplier. Otherwise put, each user needs to be reached, either via a hub or directly, to be able to receive energy.
Such a constraint could be met by starting differently. With the above formula it is assumed all vertices are placed on our blank sheet of paper and we just start drawing lines between them and count the number of possibilities. Now let’s start by placing one supplier and one user on our sheet of paper. There is only one option following from the fully interconnected constraint; there is a line between the supplier and the user. Now place the next user. There are two options; either the user is directly connected to the supplier as well (another star connection) or the user is connected to a hub that now “appears” on the initial line between user 1 and the supplier (in this case it is assumed users cannot be connected in series; otherwise there would be three options). Now place the third user. There are three options; connect to the supplier, connect to the existing hub or connect to a new hub. Now place a second supplier. Many options exist; direct connections between supplier 2 and users 1, 2 and 3, connections to existing hub(s), connections to new hubs (which then in turn need to be connected to users again). Thus this approach quickly runs in to problems as well because of the many choices to make.

Now a parametric approach is proposed. By parameterizing NTG steering of the generation process becomes possible. So far two steering parameters have been defined that can help establish this. The first is:

$$hd = \frac{nh}{nv} = \frac{nh}{nu + ns + nh}$$

Where hd is the hub density defined by the number of hubs (nh) divided by the number of vertices (nv). The number of vertices is the sum of the number of users (nu), number of suppliers (ns) and number of hubs (nh). The second steering parameter is:

$$st = \frac{ne_{act}}{ne_{pos}}$$

Where st is the “starness” of a network defined by the actual number of edges (ne_{act}) in the network divided by the possible number of edges (ne_{pos}) in the network. This second steering parameter can be used at different levels of the network. “stus” for instance is the parameter defining starness of direct connections between users and suppliers. In a similar manner “stuh” is the starness between users and hubs and “stsh” is the starness between suppliers and hubs.

Using these steering parameters an algorithm has been written to automatically generate network topologies. Edges are still randomly placed within this algorithm to ensure that the network topology is unknown beforehand thereby still making it possible to discover unknown topologies. But now the algorithm continues to run until a pre-defined set value for the steering parameters has been reached, which leads to fully interconnected, somewhat realistic networks. Two methods exist in the current algorithm. Method 1 uses set values for the hub density and the starness of the overall network. Method 2 does not require the hub density but uses set values for the starness on different levels of the network, i.e. stus, stuh and stsh. Results of this algorithm with both methods using different set values and a different number of components are shown in the next section.

RESULTS

The NTG algorithm is still under development as can be concluded from the text in the previous sections. Still, using the formulas for steering parameters hd and st, preliminary results can be shown for different values of these steering parameters and for different values for the number of vertices. These results for different network topologies are shown in Figure 4. The main conclusion is that it is indeed possible to automatically generate network topologies using the described approach which means we can start researching network topology of technical systems on board naval vessels in more detail. The figures on the left hand side in Figure 4 are generated using the first method (hd and st as steering parameters), the figures on the right hand side are generated using the second method (stus, stuh and stsh as steering parameters). The top 4 figures show different networks using the same set values for the steering parameters and the same number of vertices. These figures prove that different network topologies are found because of the random function that is used in the NTG algorithm. The bottom 4 figures shows the diversity in number of vertices the algorithm can handle. The average runtime of the algorithm for generating two networks using both methods is below 0.05 seconds (even for the larger networks at the bottom of Figure 4). This feature is important to allow for filling the entire design space of network topologies; i.e. the complete range of possible solutions for the distribution system a marine engineer is designing.

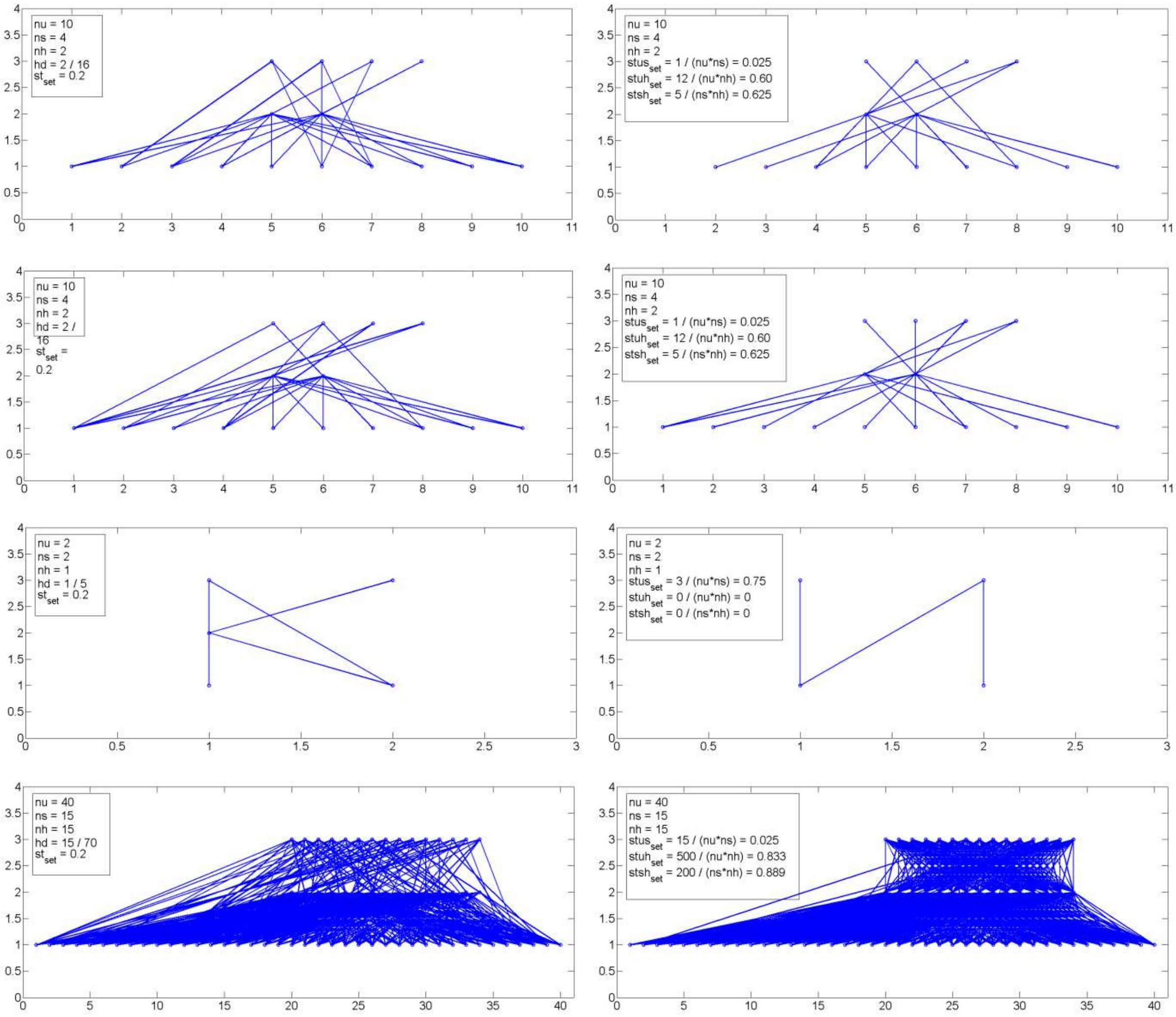

Figure 4 Results of automatic network topology generation algorithm for different values of number of vertices and steering parameters.

DISCUSSION AND FUTURE WORK

Clearly a lot of work still needs to be done, the results shown should be considered preliminary results only. A first critique on the current networks would be that they only consist of three layers; suppliers, hubs and users. Actual distribution systems on board naval vessels have many more layers, especially if you take the integration of systems into account. These systems are highly integrated since a user in one type of energy distribution system may well be the supplier in another energy distribution system. Increasing the number of layers is therefore part of the future work.

Note also that in the current approach the marine engineer designing the system is supposed to know the number of components or that he/she varies this number within a certain range to find possible and applicable network topologies. This assumption is considered plausible and it serves as the starting point of the NTG algorithm. It is also assumed that he/she has an idea for the value or range of values for hub density and/or starness. Although these steering parameters are new for marine engineers a feeling for these parameters will soon be learned as wrong values will quickly lead to unrealistic networks.

Other steering parameters can be defined as well and these will be investigated in the near future to establish which parameters can best be used for NTG.

Once the right steering parameter(s) have been found and the right constraints have been set a NTG algorithm will have developed that functionally resembles the packing algorithm as used by van Oers [1] to generate ship configurations for supporting naval architects, but in this case network topologies are generated for supporting marine engineers designing technical systems. If this has been achieved the NTG algorithm can be called upon many times by a genetic algorithm that varies input parameters like number of components and steering parameters. This was done by van Oers with the packing algorithm as well and it quickly showed the entire design space. For this it is important that the runtime of the NTG algorithm is small, which it is as was shown in the results section. With such an approach the complete design space for different kinds of energy distribution systems (including their integration) can be analysed in early ship design. If the many networks that come out of the NTG algorithm driven by a genetic algorithm are subsequently introduced in a vulnerability analysis a marine engineer might soon learn which network topologies are most promising concerning vulnerability. Next to that it should be possible to use the adjacency matrices of the many networks to analyse performance of the networks under different circumstances as well (if a component library is available).

CONCLUSION

This paper has raised the question how marine engineers design distribution systems on board naval vessels. The current approach, which quickly fixes network topologies and interdependencies between systems on basis of previous experiences has been reviewed. A disadvantage of the current approach is the fact that only a small part of the total design space is covered; many more network topologies could probably have worked just as well or even better but these designs are now not analysed as it is considered too time-consuming to analyse different topologies. The experience from different projects in industry is that this approach might lead to major design alterations during detailed design, because it is then discovered that the chosen network topology is too vulnerable or simply not functional. Exceeding of the budget is easily caused by such major design alterations. By investigating more network topologies and thereby covering a larger part of the design space the designer can be more confident about choosing the right system and risks for budget overruns are mitigated.

The paper has shown that different network topologies can be generated automatically and quickly using a NTG algorithm. This algorithm is still under development but important first steps have been made. The design space for naval technical systems can be filled using such a NTG algorithm, which uses network theory concepts in a naval engineering context. To the authors knowledge this has never been tried before.

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