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A new case study

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Design Space Exploration for on-board Energy Distribution Systems - A New Case Study

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Abstract

This paper demonstrates the usefulness of an automatic topology generator that uses genetic algorithm techniques to generate many alternative system designs and in doing so enables design space exploration for on-board energy distribution systems. This will provide better insight in the relation between design requirements (e.g. budget), system design solutions and important performance characteristics like ship survivability in early design stages. The basic idea is to apply proven techniques as used for ship configuration (i.e. hull and layout design) to the design of "ship service systems". The case study will consist of multiple, interconnected systems on board an Ocean-going Patrol Vessel that distribute electric power, chilled water and mechanical (propulsion) power.

1. Introduction

Design space exploration using Genetic Algorithm (GA) techniques is a well-known approach to map design solution spaces, *Deb (2001)*. The purpose of design space exploration is providing insight in how requirements, constraints, technical design solutions and performance characteristics relate. This is achieved by automatically generating many alternative design solutions, order of magnitude is 10^3 – 10^5 (or even above) and comparing these with respect to their scores on objective functions, see Fig.1. In case of opposing objective functions this leads to a set of Pareto-optimal design solutions. Exploring the design space and evaluating the (Pareto-optimal) design solutions helps illustrate the existing design freedom and provides insight into what is driving design requirements. This insight is vital to arrive at (ultimately) a single, balanced, well-founded design solution that can serve as input for later design stages in which the selected concept designs are worked out in more detail.

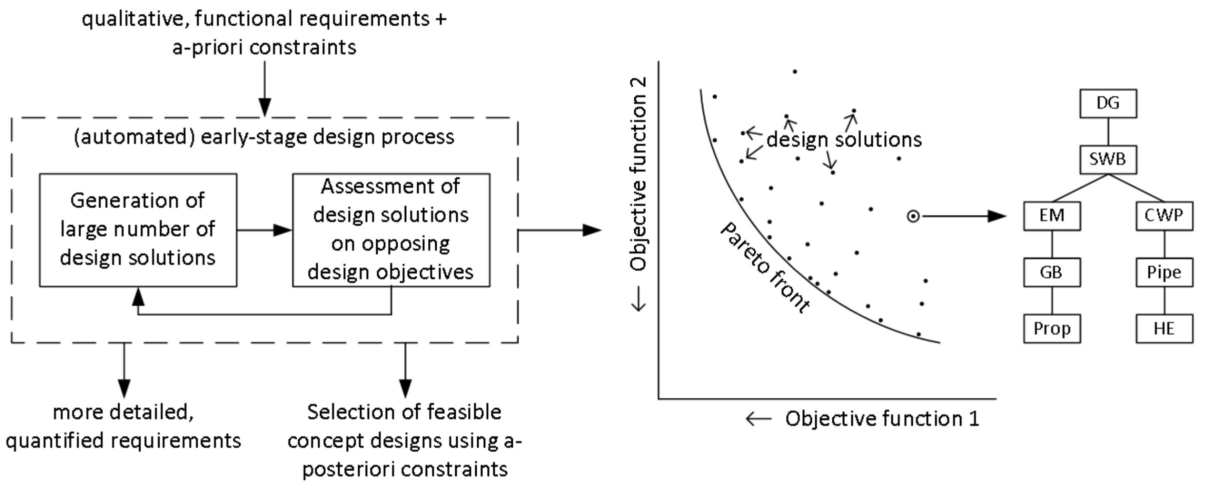

Fig.1: Principle of design space exploration using GA techniques applied to system concept design

Design space exploration using GA techniques has also been applied in the context of early stage ship design, e.g. *van Oers (2011)*. Together with *Duchateau (2016)*, he enabled (semi-)automatic generation of multiple, and varying, ship concept designs or "ship configurations". However, the way on-board energy distribution systems are incorporated in the generated ship configurations is deemed inadequate. Systems are in practice designed (with sufficient detail) in later ship design stages. This means the generated ship configurations lack concept designs of on-board energy distribution systems, thus limiting the ability to use the exploration results to provide insights in performance characteristics driven by energy distribution system design, such as warship vulnerability. It also may lead to sub-optimal system performance, vulnerable systems or high re-design costs if a major revision of the ship configuration is needed in later design stages.

To address this important issue, an Automatic Topology Generation (ATG) tool for on-board energy distribution systems was developed. In the ATG tool network theoretic descriptions, i.e. the way in which "nodes" (system components) are connected by "edges" (connections between components) as specified in an "adjacency matrix", of energy distribution system topologies are generated using GA techniques. As an example, a (very) simplistic system topology is shown at the right-hand side of Fig.1 to provide the reader with an idea of the generated design solutions. In this example, a diesel-generator set (DG) supplies electric power to a switchboard (SWB) which distributes the power to an electric motor (EM) that drives a propeller (Prop) through a gearbox (GB) and a chilled water plant (CWP) that provides chilled water to a heat exchanger (HE) through a main pipe line (Pipe). The system topologies generated by the ATG tool are larger and more difficult but can be principally understood with this simple example. The set-up and considerations of the ATG tool is extensively discussed in *de Vos et al. (2018)* but will be recapitulated in section 3 of this paper as well. The basic idea is that the design space exploration approach of *van Oers (2011)* to ship concept design can also be applied to on-board system design. This should lead to better insight into the driving system design requirements and enable a better integration of system concept designs into ship concept designs. This improved integration in turn enables better assessment of the availability of vital components and systems after a warship is hit, i.e. warship vulnerability; see *Duchateau et al. (2018)* and *Habben Jansen et al. (2018)*.

To elaborate, Fig.2 depicts the process of early stage ship design, in fact an extended version of earlier V-diagrams of the process. Distribution system design is integrated as a parallel process including the interaction with ship concept design.

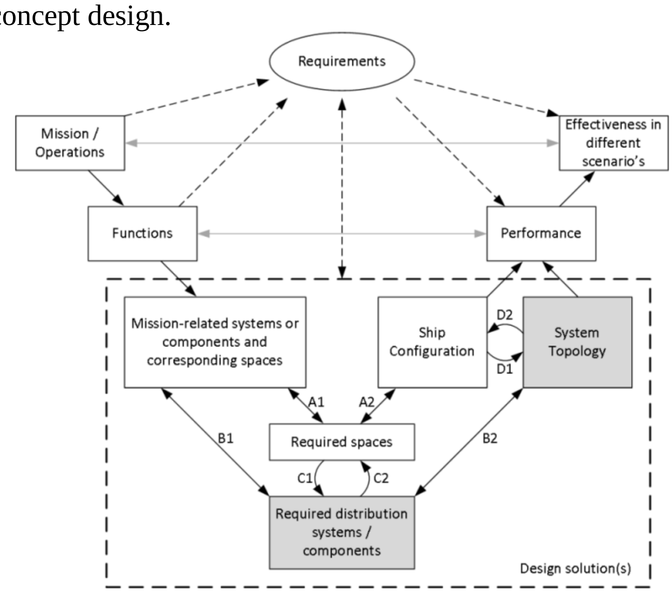

Fig.2: V-diagram representing the ship and system early stage design process

Route A (A1-A2) represents the design space exploration approach to ship concept design by *van Oers (2011)* and *Duchateau (2016)*. Route B (B1-B2) represents the design space exploration approach to system concept design enabled by the ATG tool for on-board energy distribution systems as described above.

Furthermore, in order to integrate the generated topologies in ship designs not only the connections between components (e.g. pipes, cables) must be routed but also the main components physically placed in order to size ship machinery spaces (arrow D2). To address this issue a method was developed for first-principle dimension prediction of components of energy distribution systems, see

Stapersma et al. (2015). The method first sizes the core of machines / equipment using first principles and then applies (manufacturer) data-driven correlation factors to predict the dimensions of the overall machine. This method is regarded as inherently safe and fundamentally more correct then methods relying only on manufacturer data and leaving out preliminary design of the core of system components.

Although this "sizing of components" ultimately is necessary, this paper will demonstrate only the usefulness of the first methodology: automatic topology generation, as an early stage ship design decision support tool. The ATG tool will be used for exploring the design space for distribution systems by automatically generating large numbers of system concept designs, perhaps better known as "one-line diagrams" or "energy flow diagrams", specifying the system components and connections between them. The case study will consist of a number of interconnected energy distribution systems: the electric power, chilled water and propulsion systems on board of an Ocean-going Patrol Vessel (OPV). The same OPV was used in *Duchateau (2018)* to demonstrate automatic routing of system connections through a ship concept design using similar GA techniques. He used it to visualize the trade-off between overall system connection length and warship vulnerability. In this paper, the trade-off between "system claim" (or impact) of the systems on the ship and "system robustness" will be visualized. These design objectives for systems are important aspects of total costs and ship survivability. This paper also discusses the definition of system robustness and compares two objective functions that try to capture this difficult concept in early stage ship design, which also helps in demonstrating the usefulness of the ATG tool.

2. Recapitulation Automatic Topology Generation tool

The ATG tool as a method to automatically generate many system topologies is introduced and elaborately explained in *de Vos (2018)* and is recapitulated in this section. The ATG tool uses a Genetic Algorithm (GA) to "populate" a design space with system topologies (representing system concept designs or design solutions) in turn enabling design space exploration. While generating topologies, the GA minimizes two opposing objective functions for which a number of available options will be discussed in this section as well. At the end of this section a hypothesis is formulated concerning the performance of two of the available objective functions. This hypothesis is tested in the subsequent sections in which system topologies are generated for the case study with the ATG tool to demonstrate its usefulness.

2.1. Approach and calculation procedure

The GA used in the ATG tool is a version of NSGA-II (Non-dominated Sorting Genetic Algorithm II), *Deb et al. (2002)*. Depending on the settings of NSGA-II the number of system topologies generated by the ATG tool is between 10^3 and 10^5 (or even higher). The design space and a Pareto front of non-dominated system topologies are visualized by the ATG tool as main graphical output. See Fig.1 again for the principle of automatic design solution generation using GA techniques or the appendix for examples of system topologies generated by the ATG tool. A system designer can study the generated Pareto front and its topologies to gain insight into the driving design requirements and to select one or more promising system concept designs that need further development.

System topologies are generated by the ATG tool as NSGA-II varies network theoretic descriptions of energy distribution systems. Applying network theory to on-board energy distribution systems here means system components are modelled as "nodes" and system connections are modelled as "edges". A system topology then is a network (or graph) captured mathematically in an "adjacency matrix". NSGA-II varies the element values in the adjacency matrix using functions that mimic biological cross-over and mutation processes, thus generating different networks or "individuals" from a biological perspective. Each individual generated is a system topology for the interconnected on-board energy distribution systems under consideration. Fig.3 shows the general calculation procedure in the ATG tool – an elaborate explanation can be found there. Vector **x** represent the generated system topologies, the repair function ensures that all system components are connected to the network (in case NSGA-II generates networks with unconnected components) and the objective functions are used to evaluate the generated system topologies. Steering may be applied to help NSGA-II search and populate the relevant parts of the design space.

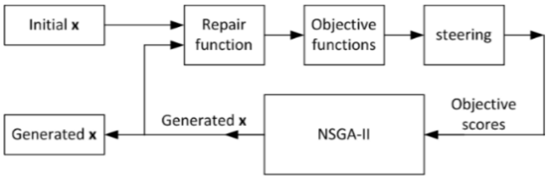

Fig.3: Calculation procedure ATG tool, *de Vos (2018)*

In contrast to conventional network theory a node in the ATG tool can have one of two functions, i.e. there are two types of nodes according to the node differentiation framework that was already introduced in *de Vos (2014)*. The role a node can have is either "converter" or "hub". Converters are suppliers and / or users of a certain type of energy flow, like engines, generators, transformers, pumps, heat exchangers, etc. Hubs are (major) junctions in the network topology; they do not supply or use energy themselves, energy simply "passes through" (although in practice a small portion of the incoming energy may be lost in the hub as heat). Hubs gather all incoming energy from suppliers and distribute it to the different connected users. Examples are switchboards, distribution panels, gearboxes, main pipe lines and valve chests. Note that edges are differentiated as well in the ATG tool according to the specified, different types of, energy distribution systems. Types of edges that may exist are e.g. 440V, CW (Chilled Water), Mech (rotating mechanical power for propulsion), etc.

Differentiating between different nodes and edges has several advantages:

1. The generated system concept designs are more realistic in comparison to using general nodes and edges as one can relate to practical system components and connections found on board ships.
2. In practice components may have different roles in different distribution systems, e.g. a switchboard is a hub in an electric power distribution system but may require chilled water for cooling in order to operate. This makes the switchboard a user in the chilled water distribution system. The developed node and edge differentiation framework is able to deal with this dual (or multiple) functionality of system components.
3. The amount of possible system topologies (i.e. the size of the design space) is drastically reduced as "non-negotiable (or a-priori) constraints" concerning the inputs and outputs of system components follow from the differentiation. To clarify, consider an Electric Motor (EM) as an example. An EM requires electric power of a certain voltage as input and supplies mechanical power to e.g. a gearbox as output; it is meaningless to connect the electric motor to e.g. a main pipe line for Chilled Water (note that the latter is valid for the output of the EM, it may require CW as an input if it is a water-cooled motor). This example shows that constraints can be set up based on physical principles. These constraints are indeed of the "non-negotiable" type.

A major disadvantage of differentiating between types of nodes and edges, which adds (marine) engineering knowledge to network theory, is that many of the general network theory concepts and metrics lose applicability.

The generated system topologies are ranked by NSGA-II with respect to two opposing objective functions: <u>system claim</u> and <u>system robustness</u>. System claim aims to capture weight and space requirements of the distribution systems, their procurement and installation costs, and system operability. The first two are important aspects of the impact systems have on the overall ship design and total investment costs. The latter, system operability, is related to Human-Machine Interaction and asserts that systems with less components and connections are easier to understand and operate for human operators (which most probably applies to control systems as well). Two versions of the system claim objective function, differing in the way system claim is measured, have been developed and implemented in the ATG tool. These are discussed in section 2.2.

System robustness is the second, opposing design objective which will require more system components and connections. System robustness is an ambiguous term with many definitions. *De Vos (2018)* defined system robustness in the context of naval ship design as "The ability of energy distribution systems on board of (war)ships to withstand perturbations in system operation to a certain extent". Seven different versions of the system robustness objective function, or its inverse: system vulnerability, have been developed and implemented in the ATG tool. They differ in the way system robustness is measured. These system robustness metrics (or indicators) are discussed in section 2.3. Two of the seven versions are for now considered best, i.e. they are more or less in line with the given definition of system robustness. These two system robustness objective functions are used and compared in later sections of this paper.

A further elaboration in section 2.2 and 2.3 of the system claim and system robustness objective functions is necessary as the fidelity of the generated system topologies highly depends on the quality of these functions. This is true in general for any optimisation algorithm, not only for genetic algorithms. Then again it is difficult, if not impossible, to have high-quality functions, i.e. accurate assessment, of system claim and robustness in (very) early design stages. Drastic simplifications of the design objectives are necessary to be useful in inherently low-detailed early stage design tools like the ATG tool. This is also the reason for having multiple options and metrics for the two opposing objective functions. In addition to a list of systems components and their functions (converter / hub), the ATG tool might require further input depending on the chosen objective functions. For example, the (approximate) location of the components in the ship or the vitality of components (i.e. does a component fulfil a vital function?). The different objective functions, their workings, and their required inputs are discussed further below.

2.2. System claim objective functions

As stated, system claim can be subdivided in to weight and space requirements of the distribution systems, their procurement and installation costs, and system operability. Combining all of these quantities in one objective function is not an easy task, especially not in early design stages. Still, one can try to do so when the aim is to enable design space exploration as then the accurateness of the functions to determine the objective is not as important as in later design stages; a qualitative design solution comparison is sufficient.

Two versions for the system claim objective function are defined in the current ATG tool. The first was introduced in *de Vos (2018)* and simply counts the number of connections and components in a generated system topology. The idea behind this metric is that system claim scales (and increases) with the number of connections and components. Since objective functions are minimised by NSGA-II, system topologies with fewer components and connections are preferred. Note that the number of components is in fact constant during a single run with the ATG tool and is added only for comparison between runs with the tool. Therefore, this first system claim objective function is briefly called "n_connections" in the remainder of this paper. Clearly n_connections represents a crude approximation of the reality of system claim but the trend of the function is assumed to be correct.

The second version for the system claim objective function is more detailed and requires an approximate or exact location of the system components inside the ship. This objective function calculates the combined length of all connections in a generated system topology and uses this length as a metric for which system is "better" from the system claim perspective: shorter overall length is preferred, i.e. topologies with few and short connections. The length of a connection, if it exists in a generated system topology, is calculated from the distance between the connected components. This distance may be calculated using different techniques: Eulerian distance, "city-block" routing distance, etc. The main difference with the length calculation of *Duchateau (2018)* is that no information on ship spaces is included in the ATG tool. This means that it is unknown whether the calculated distance can actually be applied as a routing as it might pass through tanks, blast proof bulkheads, etc. Hence, the calculated length of a connection is at this stage an approximation of the actual cable, pipe, duct or shaft length, but is again considered sufficient for comparing system topologies.

Additionally, approximate locations may also be formulated to match a rough sketch layout of the ship design. Here system components may be allocated to certain decks (above/below waterline), certain zones (fwd, midship, aft), or even PS, CL, SB. This method gives an intermediate accuracy between counting connections (version 1) and using connection length (version 2). However, using a length-based metric (as described above), whether based on a crude or more refined ship configuration, requires more detail and input than the first system claim objective function (n_connections), while it only better approximates the system installation costs part of system claim, but barely does so for procurement costs, weight and space requirements, and system operability. This is the reason the remainder of this paper will use the first system claim objective function.

2.3. System robustness objective functions

As system robustness is an ambiguous term it is even more difficult to find a suitable objective function for the second design objective than it is for the first. How should one measure system robustness? With weight and space requirements, as well as with costs, the unit in which to measure the quantity is at least known. A discussion on the applicability, accurateness or other model performance characteristic can be held when a model is available to determine these quantities, but the metric is known (e.g. kilograms, cubic meters or euros). This is not the case with system robustness.

It was argued in *de Vos (2018)* that an attempt to increase system robustness in early system design stages should focus on improving system reconfigurability by increasing the number of disjoint paths between hubs. The system robustness objective function presented in that paper does so by maximizing the flow in hub-hub sub-matrices of the generated adjacency matrix, i.e. system topologies with more connections between hubs are preferred. Moreover, not only are more connections between hubs preferred, max-flow-between-hubs even prefers ring distributions (if sufficient hub-hub connections are available to make rings) over other distribution patterns. In a practical setting, such hub-hub connections are bus-ties between switchboards, cross-connect gear transmissions, and undirected "communication" pipes between main pipe lines in a fluid distribution system, allowing reconfiguration of the system in case of system damage.

This "max-flow-between-hubs" objective function is based on the observation that in design practice system robustness of on-board energy distribution systems is increased by, *de Vos (2018)*:

1. "increasing redundancy by duplicating supplying components and supply lines to vital users,
2. introducing separate "islands" in the system topology that are able to operate as stand-alone systems in critical operations (islands should then also be physically separated; i.e. located in different zones in the ship separated by fire-resistant and watertight bulkheads),
3. increasing reconfigurability of the distribution systems by increasing the number of paths between suppliers and users. This is one of the reasons for interconnecting the afore-mentioned islands by so-called cross-overs"

The latter measure is the main reason for measuring system robustness by the potential flow between hubs in the max-flow-between-hubs objective function. A consequence of choosing this metric is that the other robustness measures are not part of the objective function and need to be introduced in the ATG tool in a different way. The number and type of system components are input (as discussed), so the measures of redundant components and (potential for) separate islands, i.e. sub-systems of suppliers, hubs and users, are captured in the input of the ATG tool. The main (topological) measure that is missed is increasing the number of direct supply lines to vital users. This is solved in the ATG tool by specifying the required number of supply lines of a certain type of energy for a (vital) component in the input for the tool. For example, if a vital user requires 440V the number of required 440V supply lines for that user may be specified as two. The vitality repair function then ensures that vital users have the required number of supply lines of a specific energy type as defined by the system designer in the input. The number of supply lines is, in other words, a "non-negotiable constraint" when max-flow-between-hubs is the applied system robustness objective function, like the connectedness of the system (also in repair function).

An alternative robustness objective function, developed by *van Leeuwen (2017)* and used by *Duchateau (2018)*, does not require the number of required supply lines as input to the ATG tool. This objective function is based on percolation theory; it employs a depth-first search of the remaining system topology after one or more random hits take out nodes or edges to determine whether "end users" are still connected to the required suppliers; i.e. whether a path exists (then percolation is possible) between vital end users and components generating the required energy. The method is fundamentally different from the max-flow-between-hubs in that it is not a deterministic a-priori objective function but the a-postiori outcome of a Monte Carlo based vulnerability analysis on the topological level.

The method is called "vulnerability connectivity" by *van Leeuwen (2017)*, but mathematically connectivity implies the number of disjoint paths between nodes. Furthermore, vulnerability is again an ambiguous term. One could define vulnerability as the inverse of robustness, but that does not help much if robustness is not well defined. More importantly vulnerability may not be exactly the inverse of robustness, *de Vos (2018)*. Here the robustness objective function of *van Leeuwen (2017)* will be called "hurt-state-percolation". This function does require end users to be defined that are considered to be vital and as such must remain operational even after damage impairment to enable the ship to perform its mission. Note that, with regards to the required input to the tool, the difference with the max-flow-between-hubs objective function is that one or more components are declared vital and not the potential consequence of this declaration: an increased number of supply lines. As a consequence, the ATG tool will determine itself which topological robustness measure is preferable: adding redundancy in supply lines (A) or increasing overall system reconfigurability by interconnecting hubs (C), when generating system topologies with hurt-state-percolation as applied robustness objective function and n_connections as system claim objective function.

The hurt-state-percolation objective function is more in line with the earlier specified definition of system robustness and the given practical robustness measures than the max-flow-between-hubs objective function. Furthermore, the function may fit better with the explorative nature of early-stage system design and the evolutionary nature of the genetic algorithm. Finally, the hurt-state-percolation function, being a topological vulnerability analysis, can also be employed to establish the validity of earlier design choices or simpler design tools like the max-flow-between-hubs function.

Regardless of one's perception of the different robustness objective functions, it is interesting to note that it was observed in earlier research, e.g. *van Leeuwen (2017)*, that the ATG tool preferred system topologies with redundant supply lines to vital users when hurt-state-percolation and n_connections were the applied opposing objective functions. Increasing overall system reconfigurability with hub-hub connections was not used as a robustness measure. This begs the question whether the max-flow-between-hubs robustness objective function "misses the point" with its focus on hub-hub connections. But the number of specified end users has in earlier research always been one, which is believed to be the reason that hurt-state-percolation (in combination with n_connections) prefers redundancy in supply lines over hub-hub connections. It is hypothesized here that the two robustness objective functions converge; i.e. show similar system topologies on the Pareto front, when the number of vital end users is increased. To test this hypothesis both the max-flow-between-hubs and the hurt-state-percolation robustness objective functions are used and compared in this paper for the case study.

Several other robustness objective functions have been implemented, but will not be discussed here as they are considered less applicable, performing poorly either in the fidelity of the generated system topologies or in the required input and calculation time.

3. Case study

With the ATG tool recapitulated and the different available objective functions discussed the case study will be introduced and discussed in this section. In the next section system topologies will be automatically generated for the case study, which will help test the hypothesis concerning the system objective functions formulated in the previous section. Note that the system topologies that are shown in this section are handmade and not generated by the ATG tool.

3.1. Ocean-going Patrol Vessel

An Ocean-going Patrol Vessel is a relatively small warship, typically designed for hostile environments that are considered to be “low in the violence spectrum”. As such they are typically well equipped for anti-drugs and anti-piracy missions and/or (sea) border control, but unfit for enemy engagement in an actual war. Still, the lifetime of these vessels is such that one cannot assume that these ships will never see an actual war environment. As a result, a fictional scenario in which the ship and its systems are extensively re-designed and engineered for a more violent environment can be thought of. This fictional scenario is the background of the present paper and case study.

Duchateau (2018) presented the OPV lay-out and a single network topology for a small number of its “distributed ship service systems”. This single network topology is subsequently automatically routed many times over through spaces inside the ship’s envelope using a k-shortest path algorithm. While doing so constraints coming from e.g. the type of space and / or bulkhead location are taken into account. For each routing the hurt-state-percolation objective function is used to determine the vulnerability of that routing to one or more random hits. Repeating the process of routing and vulnerability assessment is achieved by integrating the algorithms with NSGA-II “in an attempt to find a Pareto-set of solutions minimising both overall routing configuration length and the distributed system vulnerability”. The paper as such demonstrates the possibility to better incorporate early stage system design in early stage ship design. However, automatic routing was done for a single system concept design (one network topology) in a single ship concept design (one lay-out of spaces). This may lead to sub-optimal solutions as a good routing will hardly mitigate the flaws of sub-optimal system or ship concept designs. Ultimately an integrated approach in which different system concept designs (from the ATG tool) are routed in different ways (from the routing tool) through different ship concept designs (from the packing tool) is envisaged.

3.2. 23-node case study system on board of OPV

Fig.4 shows the handmade 23-node case study system topology of *Duchateau (2018)*. Table I was reprinted from his paper and lists the system components (nodes) and their role, i.e. supplier, hub or user (where suppliers and users are converters), in the different considered (energy) distribution systems (edge types). The number of possible connections for the 23-node case study system is 71: 8 DG-SWB connections + 1 SWB-SWB connection (bidirectional) + 4 SWB-TR connections + … and so on. The vast majority of these potential connections are supplier-to-hub (s-h) or hub-to-user (h-u) connections. In fact, there are only three (bi-directional) hub-to-hub (h-h) connections possible; one between the two switchboards, one between the two CW hubs and one between the two Computer rooms. *Duchateau (2018)* choose the 76mm Gun as the only vital end user reflecting a scenario where fighting power is considered the only vital function.

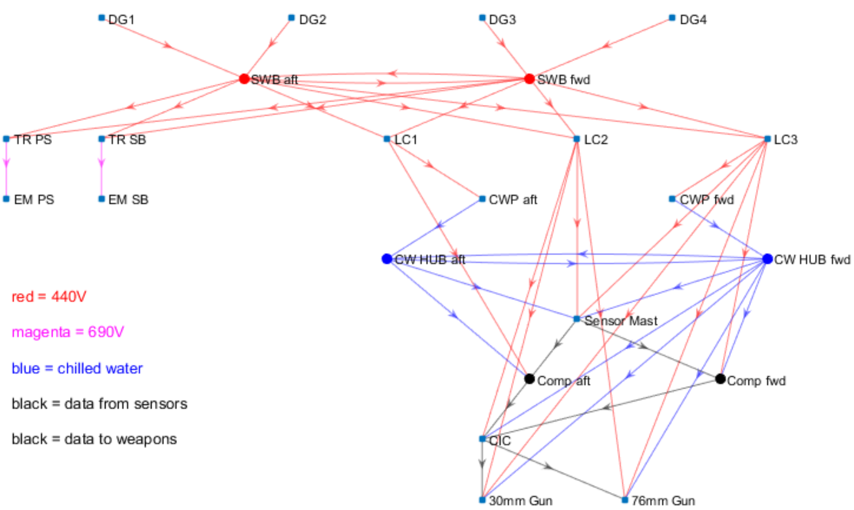

Fig.4: Graph of 23-node case study system

Table I: List of OPV system components and associated distribution systems.

System component	Distribution system in which system component is		
	user	hub	supplier
4 x Diesel-Generator set (DG1-4)	-	-	440V
2 x Main Switchboard (SWB aft & fwd)	-	440V	-
2 x Transformer (TR PS & SB)	440V	-	690V
2 x Electric Motor (EM PS & SB)	690V		
3 x Load Centre (LC1-3; aft, mid & fwd)	-	440V	-
2 x Chilled Water Plant (CWP aft & fwd)	440V	-	CW
2 x Chilled Water Main Pipe line (CW HUB aft & fwd)	-	CW	-
Sensor Mast (incl. radar)	440V; CW	-	S_data
2 x Server Room (Comp aft & fwd)	440V; CW	S_data	-
Command Centre (CIC)	440V; CW; S_data	-	W_data
2 x Gun (30mm & 76mm)	440V; CW; W_data	-	-

3.3. Necessity for scaling up the 23-node case study system to a 35-node case study system

In order to test the hypothesis of section 2.3 the 23-node case study system needs to be scaled up. Especially the number of hubs needs to be increased in order to raise the number of possible hub-hub connections. This will increase the potential for the max-flow-between-hubs objective function to improve system reconfigurability. The number of vital end users needs to be increased as well in order to see whether the two robustness functions indeed converge as was hypothesized.

It is interesting to see whether the propulsion system can be integrated in the ATG tool as well. First of all, because propulsion and manoeuvring capabilities can be considered vital for survivability, meaning that integration of more propulsion components presents a way of increasing the number of vital end users (e.g. propellers and steering machines). Furthermore, the components of propulsion systems typically are relatively large. Thus, a system designer wanting to apply the first principle dimension prediction design tool of *Stapersma (2015)* (or a different dimension prediction tool for that matter) needs to know which propulsion system components should be sized. Another reason to integrate the propulsion system here is that this is seldom done in comparable studies (also not in *de Vos (2018)*), while the propulsion system is, at this stage, just another energy distribution system (that is indeed vital to both the ship's mission capability and survivability).

Table II lists the system components that are added to the 23-node case study system in order to scale it up to a 35-node case study system that will be more fit for testing the hypothesis of section 2.3 and demonstrating the usefulness of the ATG tool. Fig.5 shows a handmade 35-node case study system topology. For sake of clarity not all potential connections are shown. The 35-node case study system has 126 potential connections. Still the vast majority of these are s-h and h-u connections, but now there is also more design freedom in h-h connections. E.g., the two switchboards have each been split in two separate segments. This will in practice always be the case when two DG-sets are providing power to a single switchboard: a bus breaker will be integrated in that switchboard. Typically, the bus breaker will be closed and the switchboard is operating as one hub. This is the reason for connecting the two segments of the two switchboards in Fig.4 as well (bi-directionally). During automatic topology generation system topologies may however be generated where these specific h-h connections do not exist, i.e. there are no bus breakers and there really are four separate switchboards. In such a case (4 hubs) the number of potential h-h connections in that specific hub layer is $nh \cdot (nh-1)/2 = 4 \cdot 3/2 = 6$. It can be seen that the propulsion system is indeed added more elaborately in the 35-node case study system (hybrid or CODELAD concept) including the steering machines (rudders). Both the rudders and the propellers will be defined as vital users, but redundant supply lines for the propellers implies each propeller being driven by two shafts, which is impractical to say the least. The redundant supply with the propulsion diesel engines as driving machines next to the electric motors of course is the crux of hybrid propulsion. Note that the propulsion diesel engines (same as the diesel generators) are “stand-alone” in the sense that their fuel supply and cooling water & lube oil systems are omitted here. Further, the ATG tool will confront a system designer with an important question concerning the mechanical power distribution system, as it may generate system topologies where the gearboxes are connected by a cross-connect transmission. After all, to the tool these are just hubs (in a mechanical power distribution system). This will be shown in the next section, where system topologies are automatically generated for the 23-node and 35-node case study system case study system.

Table II: List of additional OPV system components and associated distribution systems.

System component	Distribution system in which system component is		
	user	hub	supplier
2 x Main Switchboard (extra; so total number of SWB will be 4)	-	440V	-
2 x Diesel Engines (DE PS & SB)	-	-	Mech
2 x Transmission Gearbox (GB PS & SB)	-	Mech	-
2 x Propellers (Prop PS & SB)	Mech	-	-
1 x Bridge	-	-	HC_data
2 x Steering Machines (Rudder PS & SB)	440V; HC_data	-	-
1 x Bow Thrusters	440V; HC_data		

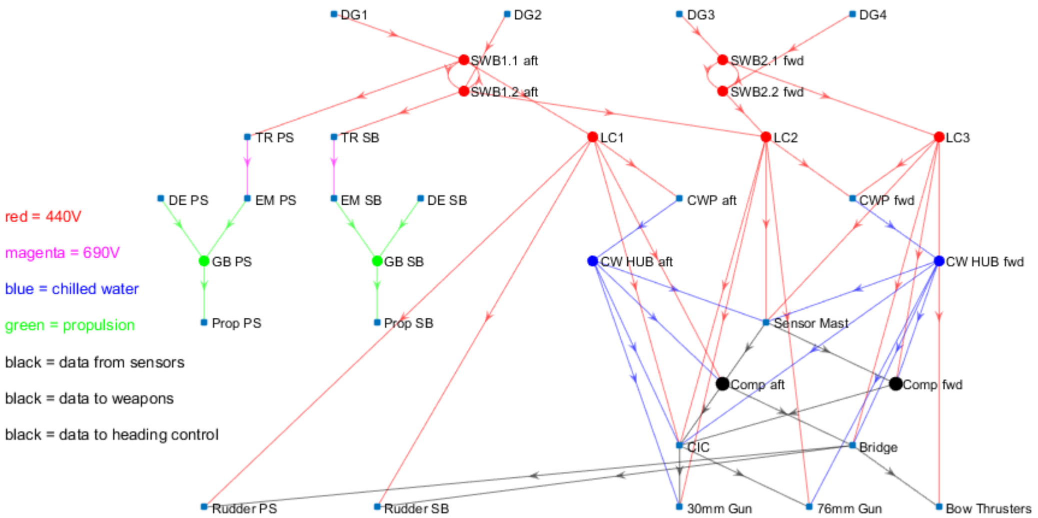

Fig.5: Graph of 35-node case study system. Note the added propulsion components and shaft connections (green) and the rudders and bow thruster.

4. Automatic Topology Generation for case study systems

Based on the previous sections and recommendations of the other, related publications; *van Leeuwen (2017), Duchateau (2018) and de Vos (2018)*, the following questions are raised with respect to automatic topology generation for the case study systems:

1. How do the two robustness objective functions (max-flow-between-hubs and hurt-state-percolation) perform in terms of finding realistic system concept designs, i.e. which is most suited to the design problem at hand? Do the metrics indeed converge when the number of end users is increased?
2. Does the ATG tool succeed in supporting a system designer who aims to find system design requirements and promising system concept designs?

These questions are the main focus of this section in which the results of the ATG tool for the OPV case study are presented and analysed.

4.1. ATG for 23-node case study system

Fig.6 shows two generated design spaces and Pareto fronts for two runs with the ATG tool for the 23-node case study system: one with max-flow-between-hubs (left) and one with hurt-state-percolation (right) as robustness objective function (on the y-axis). The system claim objective function is in both cases n_connections (on the x-axis), to which a constant number of components (23 in this case) is added. Max-flow-between-hubs is a normalised function with respect to the maximum flow that could occur per hub layer (multiplied by 100 per hub layer to mimic a percentage). A constant "hub density" multiplied by 100 is added. The mathematical function and algorithm itself is not very difficult, but the explanation and interpretation of the values is. A reader wishing to understand the function and its output is referred to *de Vos (2018)*. The output of the function is made negative as NSGA-II minimizes objective functions, while the idea behind the max flow function is that flow between hubs is maximised. Hurt-state-percolation calculates the chance that a number of vital end users do not receive the energy (or other supply) they require for operation, given a generated system topology and a pre-defined number of random hits. Note that the values on the y-axis can then best be interpreted as: the chance that energy cannot flow (percolate) towards pre-defined vital users when the system is hit (metric for system vulnerability). An elaborate explanation of this function can be found in *van Leeuwen (2017)*.

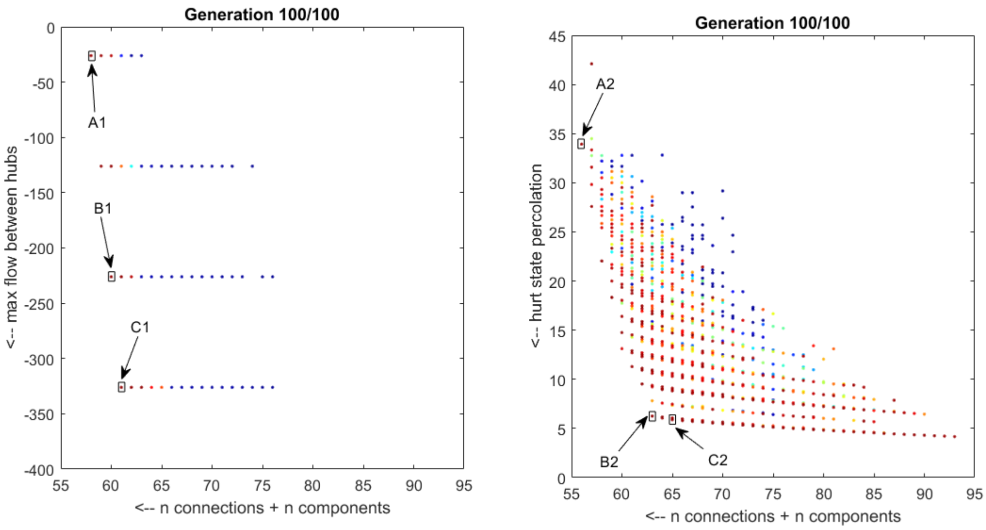

Fig.6: Design spaces for 23-node case study system with n_connections as system claim objective function and max-flow-between-hubs (left) or hurt-state-percolation (right) as robustness objective functions.

Focussing on the "Pareto front" in Fig.6 (left), there are only four "optimal" system topologies when max-flow-between-hubs is the applied system robustness objective function. All other generated topologies score equal on max-flow-between-hubs but have more connections as can be seen from the "design space". Every "dot" may represent multiple unique system topologies as different topologies may score equal on both objective functions. The difference in such a case is then in the supplier-hub (s-h) or hub-user (h-u) connections. The reason for the low number of optimal system topologies in the left-hand plot is simple: there are only three possible hub-hub (h-h) connections in the 23-node case study system (as explained before). Since the max-flow-between-hubs objective function only uses potential h-h connections to increase system reconfigurability, the design freedom for NSGA-II is very small in this case. A1, B1 and C1 are three of the four optimal system topologies on the Pareto front. These topologies are shown in the appendix. A1 has no h-h connections, B1 has two h-h connections (between the two SWB's and the two CW hubs) and C1 has three h-h connections (also between Computer rooms). Note also that each of these optimal system topologies have a minimum amount of s-h and h-u connections to make sure the system is "connected". This means no components or sub-networks are "loose". This is the work of the earlier described repair function.

The right-hand plot, with hurt-state-percolation as system robustness objective function, shows a more variable design space. The number of generated system topologies is similar (10000), but the scores of generated system topologies on the objective functions used is more variable. System topologies A2, B2 and C2 were selected to be shown in the appendix. First compare system topology A2 to A1 to see that the minimum number of connections + components that is reached is slightly lower in the right-hand plot of Fig.6 than in the left-hand plot: 56 (A2) instead of 58 (A1). The reason for this is the earlier introduced vitality repair function that ensures that vital users have multiple (redundant) supply lines. The vitality repair function is turned off when hurt-state-percolation is the applied robustness objective function (right-hand plot) to give the ATG tool the freedom to decide whether redundant supply lines should be used. The vitality repair function should however be activated when max-flow-between-hubs is used (left-hand plot) as that objective function does not consider redundant supply lines as a robustness measure. With the 76mm Gun as the only vital user (like in *Duchateau (2018)*) the difference between topologies A2 and A1 then is exactly two (58-56), namely, a redundant 440V supply line and a redundant CW supply line. Indeed, A2 has almost no components with double supply lines and no hub-hub connections (the latter was also true for A1 of course) and therefore represents the least robust system concept design with the lowest number of connections (while the repair function does still ensure a connected system).

Both of these robustness measures, redundant supply lines and hub-hub connections, are indeed used by hurt-state-percolation to make systems more robust. This can be concluded from analysing the differences between the system topologies on the Pareto front. Comparing A2 to B2 one can see that seven additional connections were made going from A2 to B2; B2 is at 63 for number of connections + components. Six of these are h-u connections (the first ones made are an extra 440V and an extra CW supply line to the 76mm Gun), while one of them is a h-h connection between the two CW hubs. Furthermore, one can see that the Pareto front in Fig.5 makes a very sharp corner at system topology B2. Robustness still increases when system topologies have more connections than B2, but the increase is a lot less than adding (the correct) connections to system topologies with a lower number of connections than B2. It is to be expected that the Pareto front will become smoother when more vital end users are defined. It may then also become more interesting for the hurt-state-percolation objective function to increase the number of hub-hub connections. This can also be expected from analysing system topology C2, where two additional hub-hub connections are made (in comparison with B2): one between the switchboards and one between the Server rooms Comp aft & fwd. Thus, these connections are for the 23-node case study system the “best-of-the-rest”.

4.2 Topology generation for 35-node case study system

For the 35-node case study system the variety in system topologies increases compared to the 23-node case study system, Fig.7. Fig.7 (left) shows that with the 35-node case study system the design freedom has now also increased for the max-flow-between-hubs robustness objective function. The freedom and resulting variety in developed system topologies remains however inherently lower than for the hurt-state-percolation robustness function as more constraints are applied and the focus remains limited to hub-hub connections. Note that the maximum value of the y-axis has increased with 100; this is a consequence of a new hub layer being part of the system: the mechanical hubs (better known as gearboxes). Their contribution to the increased design freedom is limited however, since there are only two gearboxes and the only option for max-flow-between-hubs is to add a bi-directional connection between the gearboxes or not. Nevertheless, confronting a system designer with the option of having such a “cross-connect” transmission to increase system reconfigurability fits well with the intention of the ATG tool. The real increase in design freedom is caused by the increase in number of hubs in the 440V hub layer. There are now 4 hubs, which means there is now a possibility that generated system topologies have ring distributions in that hub layer. The max-flow-between-hubs objective function is designed to value such topologies and indeed system topology D1 (see appendix) has a full ring in the 440V hub layer. The only topologies that outperform D1 according to max-flow-between-hubs have the same full ring + additional connections between the hubs in the ring. Note that this in fact just increases the number of rings present in the 440V hub layer as can be seen from topology E1.

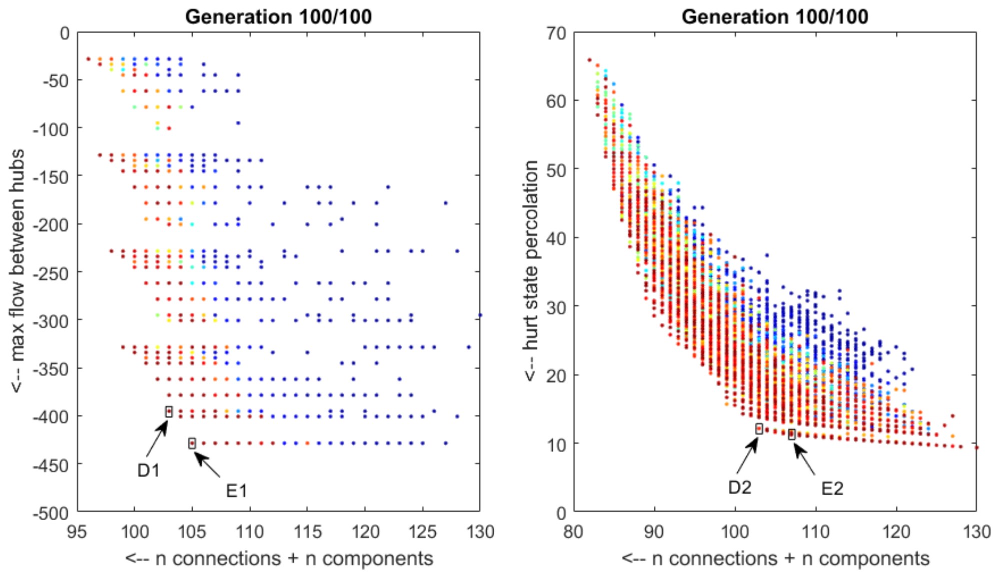

Fig.7: Design spaces for 35-node case study system with n_connections as system claim objective function and max-flow-between-hubs (left) or hurt-state-percolation (right) as robustness objective functions. Compare with Fig. 6.

The Pareto front in the right-hand plot in Fig.7 is much smoother than in Fig.6, as expected. Note that for this run with hurt-state-percolation as robustness objective function nine vital end users were specified: the 76mm Gun, 30mm Gun, CIC, Sensor Mast, Bridge, both propellers and both steering machines (rudders). System topologies with hub-hub connections start to appear more frequently in the left (steep) end of the Pareto front in this case. One should however be careful to conclude that this is because hub-hub connections are now in general valued by hurt-state-percolation. It is also possible that the ATG tool is unsuccessful in finding approximately equally robust topologies with less (hub-hub) connections as the optimization with NSGA-II may not be perfect.

To understand this, it is important to note that the sharp corner in the Pareto front is still there, although now somewhat less sharp, at system topology D2 (shown in the appendix). When following the Pareto front system topologies from the least robust (lowest number of connections + components) to more robust (i.e. from left to right), D2 is the first topology for which all vital end users have redundant supply lines. As soon as that is the case, hub-hub connections become more or less meaningless when the pre-defined number of hits in the simulation is limited to one. The reason being that, with the redundant supply lines, the only way to knock out a vital user with a single hit is by hitting it directly. If the number of pre-defined hits would be two the sharp corner would be present in the Pareto front as well: at the first system topology that has three supply lines to all vital end users.

When comparing the steep-end Pareto front system topologies (i.e. left of D2) it is clear that especially the hub-hub connection between the CW hubs is often present, while hub-hub connections in the other hub layers “seem to appear and disappear randomly”. Hurt-state-percolation, in combination with n_connections, apparently has no or little use for these h-h connections, while it does for the h-h connection in the CW hub layer. The difference between the CW distribution system and the other distribution systems stems from the ratio between the number of vital users and the number of supplying hubs. In the CW network only one h-h connection adds redundancy in the supply path to five vital users (Sensor Mast, CIC, Bridge, two Guns). The other option, making five redundant supply lines, is more “costly” in terms of n_connections. At system topology D2 these redundant supply lines are there anyway and the h-h connection between the CW hubs loses its meaning, but before that point is reached (to the left of system topology D2) the CW h-h connection is deemed a very good robustness measure. The only reason this connection is still there in topology D2 is that NSGA-II was unable to optimise further and delete it from a topology that has so many redundant supply lines. Hurt state percolation in combination with n_connections here “teaches” the user of the

ATG tool (and the main author of this paper…) that h-h connections are only good robustness measures when the ratio between the number of vital users and the number of supplying hubs (per energy type) is sufficiently high. This also means the earlier defined hypothesis of the two robustness objective functions converging is only true under the condition that the ratio N_vu / N_hubs per energy distribution system is sufficiently high.

Furthermore, it is clear that the main robustness measure that is preferred by hurt-state percolation in the other energy distribution systems (with a lower N_vu / N_hubs ratio) is to add redundant supply lines to vital end users. Only after the supply lines are there, hub-hub connections start to be preferred by hurt-state-percolation (to the right of D2) in these energy distribution systems as well. But by then they contribute very little to system robustness as they are in the mildly decreasing end of the Pareto front. System topology E2 is shown in the appendix and indeed contains all possible hub-hub connections. From the observation that redundant supply lines are "added" in the steep part of the Pareto front and hub-hub connections thereafter in case the hurt-state-percolation is the robustness objective function, it is concluded that the "non-negotiability" of this robustness measure when max-flow-between-hubs is the robustness objective function is a fair assumption (given a sufficiently low N_vu / N_hubs ratio – which typically is the case).

4.3 Topology generation for 35-node case study system with LC's promoted to SWB's

Finally, if the ratio between the number of vital end users and the number of supplying hubs is so important, an interesting question can be raised: why is it that the Load Centres are hierarchically lower than the switchboards and why can't they be interconnected? They are performing a similar function as the SWB's: a junction in the network where energy is gathered and distributed. When setting up the case study system the LC's were placed lower in the hierarchy of the 440V network topology and interconnections between them were not allowed in order to mimic practical system designs. Indeed, such a "radial distribution" is found often in marine engineering practice, especially for smaller ships with lower voltage levels. The main reason for this hierarchical approach is probably that it enables application of overcurrent protection devices in the supply lines of the lower level LC's (also known as distribution panels). In this way, only a small group of users attached to the local LC will experience power loss when a short circuit or overload occurs in that part of the system and the overcurrent protection as a result takes the local LC of the grid. The larger network is then left undisturbed. As such, the hierarchical design of "radial distribution" networks (really a combination of radial and tree distribution) in combination with overcurrent protection is an effective measure against total black-outs and so-called cascading failures as a consequence of internal or external perturbations. However, this hierarchical approach comes at the expense of reconfigurability options as it fixes the N_vu / N_hubs ratio (usually at a low value). Note that for the "real" 440V hubs (SWB's) in the case study systems up till now there have only been five users: three LC's and two transformers, none of which were specified as vital. Only users connected to the LC's were specified as vital.

Completely connected hub layers with many rings, as would surely be preferred by the max-flow-between-hubs objective function may be preferred by the hurt-state-percolation function as well when the LC's are "promoted" to the level of the SWB's. The ATG tool can cope with such a "wild idea": all that needs to be done is allowing bi-directional interconnections between the LC's themselves and between the LC's and SWB's. This promotes the LC's to 440V SWB's, of which there are suddenly seven (4 former SWB's + 3 former LC's). This increases the N_vu / N_hubs ratio for the 440 V network from 0/4 to 7/7. Note however that the ratio still does not become as high as it is for the CW network (5/2) as the number of vital users is approximately equal while the number of 440V hubs is much higher (7) than the number of CW hubs (still 2).

Fig.8 shows the design space when the run of Fig.7 is re-done (only with hurt-state-percolation) with the Load Centres at the same level as the 440V switchboards. Note that the sharp corner is again present in the Pareto front; this time at n_connections + n_components = 113. Again, these topologies, and the topologies to the right of the corner, are the topologies where all vital users have redundant supply lines. The increased availability of hub-hub connections in the 440V network is now used by hurt-state-percolation to improve robustness in the steep end of the Pareto front (to the left of the corner). System topology F, at the right-hand side of Fig.8, shows even a ring (SWB2.1 – SWB2.2 – LC1 – LC2 – SWB2.1) to which almost all vital end users are connected. This was observed in other topologies in the steep end of the Pareto front as well. This is considered sufficient proof that the two robustness functions indeed converge as long as the N_vu / N_hubs ratio is sufficiently high. It is also clear that the CW hub-hub connection is present in system topology F. Again, it is stressed that especially for this energy distribution system the N_vu / N_hubs ratio is favourable for hub-hub connections (cross-over) as robustness measure.

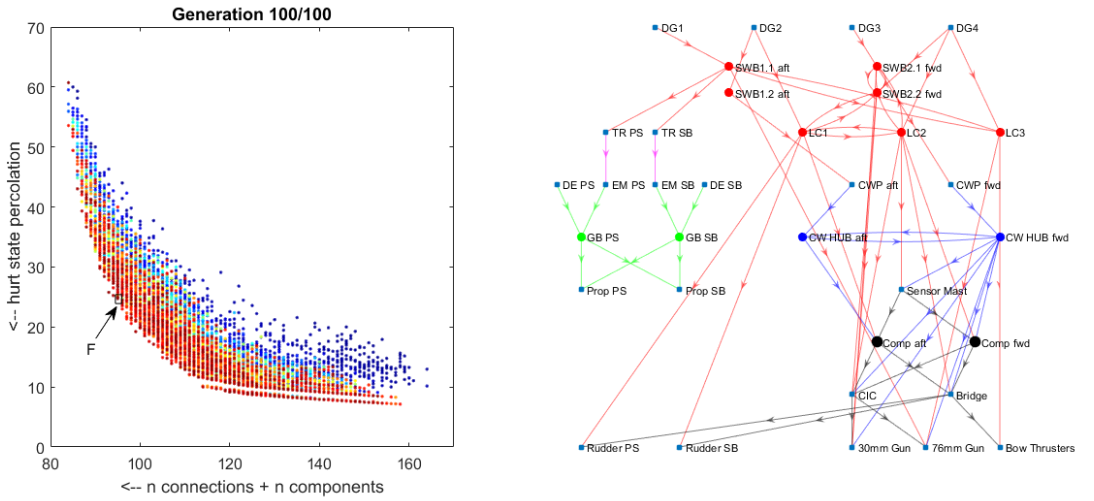

Fig.8: Design space (left) and generated system topology F (right) for 35-node case study system – Load Centres act as 440V hubs as well, together with switchboards.

The reader may observe the “propeller shafts” in system topology F. It is clear that this rather theoretical approach to distribution system design does not take into account specific details of the different energy distribution systems; like the fact that doubling mechanical connections is difficult and highly impractical (especially under water). For electric and hydraulic connections (cables and pipelines) this is somewhat easier, although doubling supply lines for these systems also means that some form of switching between or accumulation of the supply needs to take place inside the components. Here one should remember that the ATG tool is not necessarily meant to provide “the right answers”, i.e. feasible system concept designs, but rather answers that makes the designer aware of his/her preferences / biases. In the case of the propeller shafts it is clear that a designer immediately “fixes” the system topology by deleting the redundant shaft lines. Although it is interesting to note that the generated system topology is only highly impractical, not entirely impossible! With max-flow-between-hubs this strange design solution for the propulsion system would not have been generated by the way. That function is somewhat more of an engineering tool, taking some practical considerations better into account. The more important notion however is that the theoretical exercises above can be related to a classic discussion in marine engineering: radial vs. (zonal) ring distribution, see e.g. *Geertsma et al. (2009)*. In the more traditional design approaches (zonal) ring distribution is often mentioned as a more robust system topology because of its reconfigurability. The current approach cannot count as mathematical proof for this statement, but it is clear that the presented ATG tool and the focus on network design with hubs provides a much better foundation to deal with this (and other) important design question in network design. This is considered proof of the approach being able to support a system designer in finding the important system requirements and promising system concept designs.

5. Conclusions and Recommendations

The intention of this paper is to show the usefulness of the ATG tool as a designer support tool. Usefulness however is a tricky concept since, like with system robustness, a clear metric may be lacking and “it is in the eye of the observer” that the usefulness can be found. At least the paper has sharpened the author’s awareness to avoid own biases and to keep an open mind with regards to the approach.

This paper focused on design space exploration for distributed systems on board ships and utilizes methods that have already been applied for ship concept design. The validity and effectiveness of design space exploration may be different for system design and ship design. The three general robustness measures as specified in section 2.3 are widely used and may make the approach less useful to system design. Still, it is shown that the ATG tool more or less confirms these measures using two very different robustness objective functions, of which one is in fact designed to be in line with the measures and practical system designs (max-flow-between-hubs) and the other (hurt-state-percolation) is less biased towards design practice (but still confirms the measures under certain conditions). It is even clear that these conditions and the tipping point between the discussed topological robustness measures may be investigated with the ATG tool. By doing so the ATG tool succeeds in providing a much better foundation to choose certain system topologies and better explains why they adhere to existing design rules concerning system robustness.

Clearly a system designer is confronted with important questions concerning system design requirements when using the ATG tool for design space exploration. A designer may also use the tool to select promising system concept designs from the automatically generated system topologies.

Finally, it is possible to treat energy distribution systems, their components and their connections as more or less equivalent in functionality and working principle in early design. This generic perspective on on-board distribution systems may sometimes be missed in practice as many systems are designed in later ship design stages by specialised companies or organisational units. Also, the interaction between the systems of different domains are integrated into one overall topology making the designer more aware of potentially inconsequent choices. The risks for sub-optimal integration of system designs with conventional design practices should not be underestimated.

Much is still to be learned about early stage on-board system design, both from applying the current ATG tool and from developing it further. Many ways forward can be envisaged, amongst which a further development of the system claim and system robustness objective functions (e.g. include capacity calculations). The presented approach may be unique as design space exploration in early stage on-board system design is rarely undertaken and the developed node and edge differentiation framework seems to work very well in enabling system design in an integrated manner. Interested readers are invited to follow future publications from the authors on this topic (of which the dissertation of the main author will be the first).

Acknowledgements

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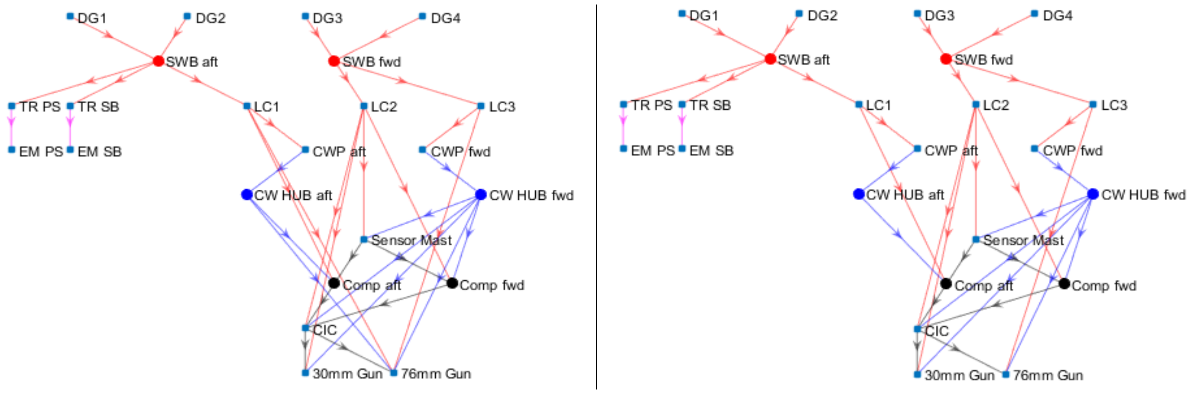
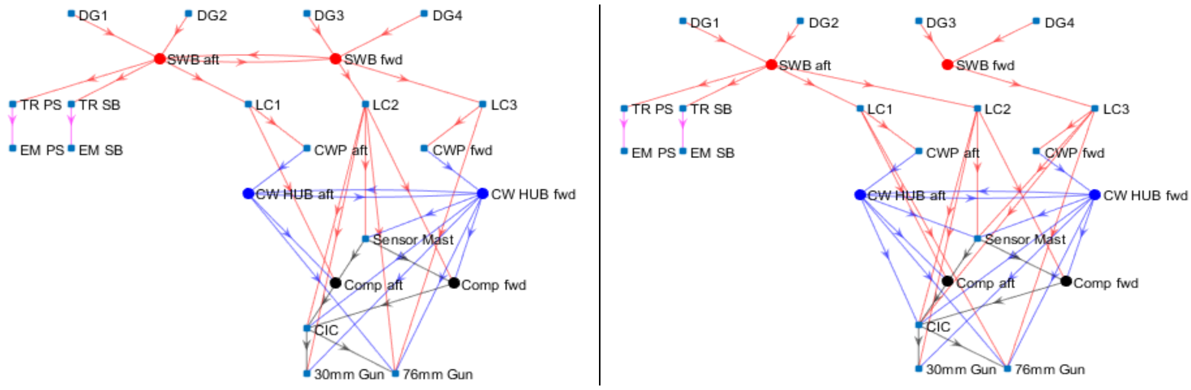
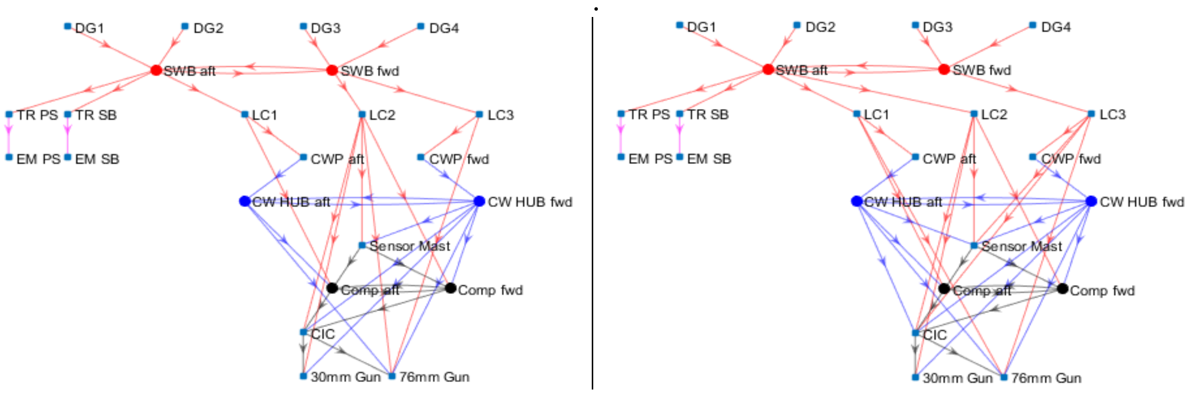
Appendix



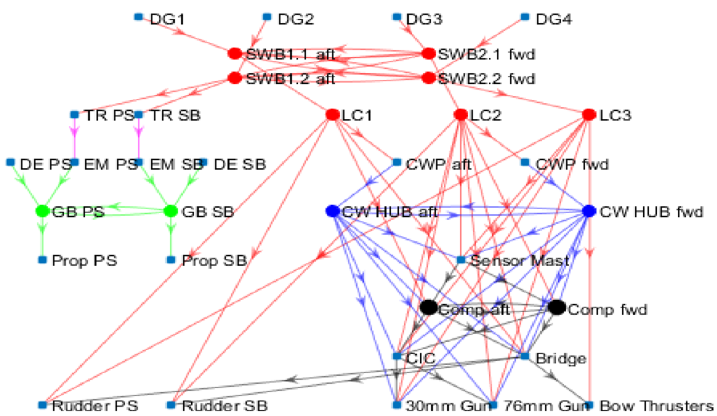
Generated system topologies of 23-node case study system: A1 (left) and A2 (right), ref. Fig.6



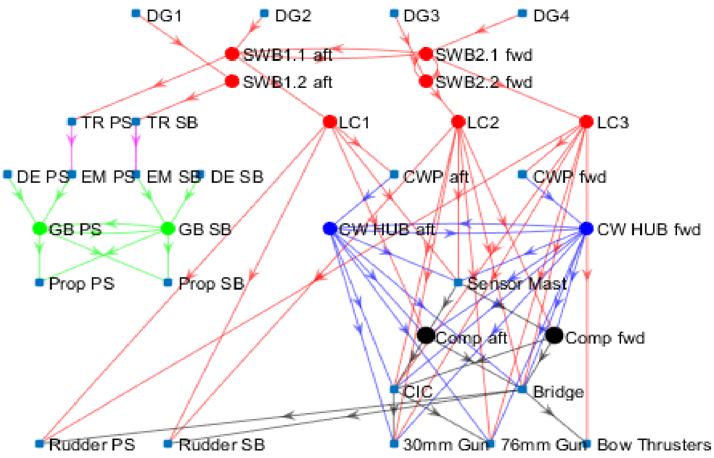
Generated system topologies of 23-node case study system: B1 (left) and B2 (right), ref. Fig.6



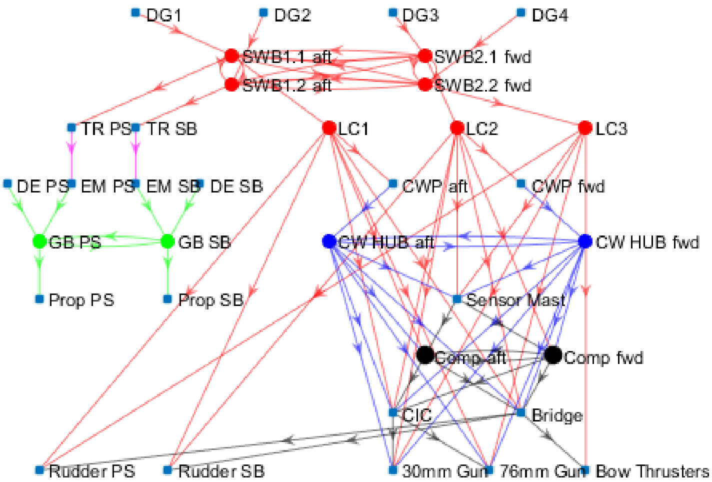
Generated system topologies of 23-node case study system: C1 (left) and C2 (right), ref. Fig.6



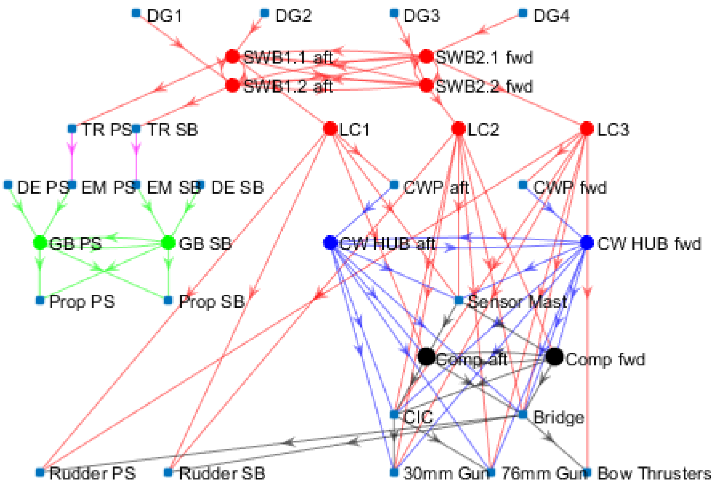
Generated system topology of 35-node case study system: D1, ref. Fig.7



Generated system topology of 35-node case study system: D2, ref. Fig.7



Generated system topology of 35-node case study system: E1, ref. Fig.7



Generated system topology of 35-node case study system: E2, ref. Fig.7