Analysis of General Arrangements created by the TU Delft Packing Approach

making use of Network Theory

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by

M.J. Roth

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Preface

The thesis you find before you should , after 8 years of studying, come as the icing on a cake and finish my time as a student. It shows some hard work that have lead to obtaining a degree of Master of Science within Marine Technology at the Delft University of Technology. I want to use this part of this thesis to thank those people that have made this possible.

First of all I would like to thank my daily supervisor, Dr. Austin Kana, for supporting me through this thesis and allowing me the freedom to work on this thesis whilst giving me guidance and feedback where I needed it. Furthermore, I would like to thank Prof. ir. Hans Hopman for being the chairman on the thesis committee and supplying me with the problem this thesis arose from and Dr. ir. Ido Akkerman for being on the committee and assessing this work.

I want to thank the MSc and PhD students from the ship design lab as well with helping me. The almost weekly updates and presentations helped me with my work and multiple brains might make work simpler sometimes. I would like to thank Dr. ir. Thomas DeNucci for allowing me to use his database of design rationale and Dr. ir. Etienne Duchateau for supplying me with this database.

Special thanks to my parents who supported me through a long time of studying. Without their support this would have never been possible. I would also like to thank my brother, sister and the rest of my family for their support.

Finally, I would like to thank my friends, roommates, football and sailing team for giving me the opportunity to relax from time to time and give me support or help where possible.

M.J. Roth
Delft, July 2017

Abstract

Constructing the general arrangement of a ship tends to be a very complex naval architectural problem. There are multiple systems that all work integrally. Some of these systems need to be placed together, others need to be separated and some systems probably need to be both at the same time for different objectives. The preliminary ship design phase is all about finding the balance between these objectives and possibilities within the arrangement. Automated general arrangement generation methods, such as the TU Delft packing approach and IECEM, have created an algorithm and methodology that are able to generate thousands of feasible ship designs corresponding to the desired requirements. These approaches combine a bin-packing and a genetic algorithm in order to create a diverse set of possible designs. Although optimisation approaches can efficiently generate and search for a set of designs, it can not automatically select a design, van Oers et al. (2008). Out of the cloud of generated designs, choosing and evaluating those designs that are of most interest seems to be a more difficult task, DeNucci et al. (2008). Human rationale deems necessary to decide what properties of an arrangement can be analysed as “good” or “bad”. Using computational force to assist with design selection based on qualitative properties needs a way of capturing this rationale, which is demonstrated by DeNucci. Subsequently, this captured knowledge needs to be applied in a methodology to actually analyse the data by this rationale.

Design selection of computer generated arrangements is currently based upon performance parameters focusing on numerical characteristics of the designs. Spatial relations within the interior layout can now only be manually analysed, which is merely possible for a singular design. This results in a lack of understanding of spatial and physical relationships, or qualitative properties, within the designed arrangement. This thesis proposes a method that is able to quantitatively compare these qualitative properties by creating a measure of effectiveness of the interior layout, or arrangement, of the designs. This is done by creating a simplified representation of the 3D arrangements using network theory.

By converting system objects and connections of these systems into nodes and edges, a mathematical network description of the arrangement is possible. Using eigenvector and betweenness centrality measures, rank and weights are given to these system objects. Design rules based upon rationale captured by DeNucci are set up and used to analyse connections between these systems. A scoring algorithm is created that is able to combine the ranks of the systems with the captured rationale to give a singular performance parameter, or measure of effectiveness of the interior layout characteristics of the designs. Application of this method to a data set of small cruise ship designs shows the capabilities of this methodology and the ability to quantitatively compare the qualitative properties of these designs.

A data set of over 20,000 cruise ship designs created by the TU Delft packing approach is analysed by the use of the method. This demonstrates that the proposed method can be used on an entire data set allowing design selection based on the quality of the provided arrangements. The proposed method can be used to filter the data set of those arrangements whose quality seems to be too poor to be taken into account in design selection. Having these arrangements in the data set is still necessary, as this allows the genetic algorithm to create enough diversity within the design space. The proposed method can find specific physical properties of the arrangements and should lead to improved design space exploration of layout features of the generated designs.

Capturing the quality of the design into a single measure of effectiveness brings problems as well. It allows the possibility of direct comparison of a large number of designs, but does not relate back to why designs score differently. Splitting design rules into different design objective scores, and possibly summing this later, could allow the designer to relate back to the design rationale and why a design scores better or worse. This would lead to more understanding of possibilities and problems within the proposed arrangements.

Contents

Glossary

COMPIT Conference on Computer Applications and Information Technology in the Maritime Industries. 2, 39

DMO Defence Material Organisation. 17

EV Eigenvector. 13

GA General Arrangement. 3

IECEM Interactive Evolutionary Concept Exploration Methodology. 5

NICOP Naval International Cooperative Opportunities in Science & Technology Project. 5

OPV Offshore Patrol Vessel. 17

SSSM Simplified Ship Synthesis Model. 7

TU Delft Delft University of Technology. 5

UCL University College London. 5

UM University of Michigan. 5

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1
Introduction

General arrangements describe the architectural layout of the vessel. A very big part of ship design, especially in early stages of the design process, is to evaluate the placement of different systems within these arrangements. One needs to find out what systems need to be incorporated and where they can be placed. The title of this thesis is "Analysis of General Arrangements created by the TU Delft Packing Approach making use of Network theory", which states that there is a necessity in the ability to quickly and directly be able to analyse computer generated general arrangements. The following chapter will introduce the personal motivation of the thesis and where the problem arrives from. Furthermore it will introduce the problem description this theses is based upon, which will be evaluated into more depth in chapter 2. In the last place it describes the structure of the thesis.

Personal Motivation

During one of the first meeting of this thesis project, where a subject still has to be decided upon, a fellow student came into the room whose green light meeting for finishing his thesis was beginning to slightly overrun. He had used the packing approach and IECEM, a concept exploration methodology which will later be introduced within this thesis, to evaluate possibilities for the design of a small cruise vessel. Having generated over 20,000 designs and getting stuck in design selection, he finally decided upon a design that came out as one of the most promising and looked like a very decent initial design. Printing the general arrangements of this vessel however, showed that there were a number of flaws within the design that with the current methodology he could have never had properly evaluated with the huge number of possible arrangements. The professor, wanting this student to succeed aimed at me looking to begin my own thesis, and said that this might be something for me to have a good starting point for this thesis and a research objective is born.

Problem Description

Being able to directly compare, or somehow score, the layouts of computer generated designs seems to be of value to design selection during design exploration. There is a necessity in creating more insight into the layout or general arrangements of these computer generated designs. The main objective is to find a method to **quantitatively** compare arrangements based on **qualitative** properties of the layout. These qualitative properties refer to physical relations and adjacencies between systems within the arrangement. In order to do this comparison, a simpler representation of these architectural layouts seems necessary. A mathematical description, hereby proposed through network theory, is necessary to allow automated comparison methods. Here the first problem arises. The packing generated arrangements needs to be converted into a network representation of this arrangement.

If the arrangement is converted into a network arrangement, it needs to be correctly analysed. Network theory knows many metrics or measures that are able to rate networks or parts of a network by its value. To allow a direct comparison between generated networks, an appropriate method needs to be chosen, or developed.

In this research, there has been chosen to develop a method that is applicable to arrangement analysis, based upon earlier research in the field of ship design.

The next problem is to define what needs to be analysed. It is hard to define what is “good” or “bad” in a design. It might well be possible that when an arrangement is presented to two different naval architects, they completely differ in their opinion on this arrangement. Creating a ship arrangement is always a trade-off between mixed or even conflicting objectives and one might value this differently. Furthermore, compressing these qualitative properties into a single value with a fitness function brings difficulties as well.

Chapter 2 tends to define this problem statement in more detail and gives detail on prior research that this thesis is based upon.

Scope definition

Since ship design is a trade-off of multiple objectives such as for example sea-keeping or redundancy, there needs to be a focus on what qualitative properties this analysis is based upon. The current methodology allows the user to give a preference to physical location of certain spaces. Chapter 5 gives a proposed design for a small cruise ship design. Issues with this design are primarily based on physical relations between systems within this design. The focus within this thesis will lay on analysis of the architectural relations within spaces.

Network theory is used as a mean of generating arrangements as well, but this thesis will only focus on the analysis of the arrangements. Chapter 6 will try to give an explanation of how this analysis method can also be used as a mean in the generation of the designs. The focus lies on being able to improve the design selection process within the approach, not improve the designs generated by the approach.

A full design data base for a small cruise ship vessel is delivered by Droste (2016) and is available for this research. This thesis will scope on analysing these designs, but tries to give a generic method or metric that should be able to analyse any computer generated arrangement.

Thesis Structure

In the following chapter, chapter 2, a more detailed problem description will be given. By analysing earlier research, in the field of ship design and further, there is tended to create more understanding of the problem and find an origin of a solution to the proposed problem. A research objective and questions will be defined in order to find this solution.

Consequently, chapter 3 gives an introduction to network theory and the mathematics applied to this research. This chapter should give enough mathematical background in able to understand the contribution of this theory to this thesis and the method introduced in the following chapter 4. This will describe how packing arrangements can be converted into a network arrangement and introduce the method to analyse these networks.

Following, chapter 5 applies the method to two designs by manual application. It will show how the method scores these networks and how certain aspects the layout of these are reflected into the score.

Being able to use the method to a single design and starting to understand the applicability of the score, chapter 6 applies the method to an entire data set of over 20,000 small cruise vessels. It will eventually describe how the metric can be used as a method to improve design selection taking into account the architectural layout within the packing approach.

Finally, conclusions and answers to research questions will be defined in chapter 7. Recommendations and possibilities of further research within the introduced method can be found in chapter 8.

Work in this thesis has been presented and published at the 16th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT). This paper can be found as a reference in appendix A.

2

Definition Study

The following chapter will give a definition study of the problem description which this thesis is based upon. First it will introduce General Arrangement (GA) optimisation or exploration tools in general. Then it will describe the packing method developed by Delft University of Technology and the issues involved in the generation of thousands of designs. Full information and background of this approach can be found in earlier published work, as in theses as Duchateau (2016) and van Oers (2011) who have actually developed this technique and where this theory is based upon. Furthermore, it will introduce the capturing of rationale as developed by DeNucci et al. (2008). Finally, it will give the research goals and objectives of the thesis.

2.1. Ship Design Process

The process of ship design is commonly divided into three successive design phases, taking place before the actual construction of the vessel, as enumerated by Duchateau (2016):

1. Preliminary design phase; Being the first step in the process, where a balance needs to be found between what the customer needs or wants and investigating the possibilities for the design.

2. Contract design phase; One design solutions is worked out in such detail that a contract and price can be established

3. Detailed (engineering) design phase; Translation from the contract towards a design definition suitable for production

During the design process, the Naval Architect is able to alter variables in order to create a design. By analysing or measuring this design, a multi-dimensional performance of the design is possible. Figure 2.1 maps the synthesis of a single design within the performance space, Devanathan and Ramani (2010) and Duchateau (2016). It shows that within the design space, there are designer's constraints that can be directly linked to performance constraints. Furthermore, there is an area that corresponds to infeasible variations within the design space. This thesis is focusing on the analysis of general arrangements and seeking the performance of a single design, or an entire design space, into a single dimension within a performance space. The alteration of variables is done within the preliminary design phase to investigate the possibilities within the design space and how these are mapped and reflected into the performance space.

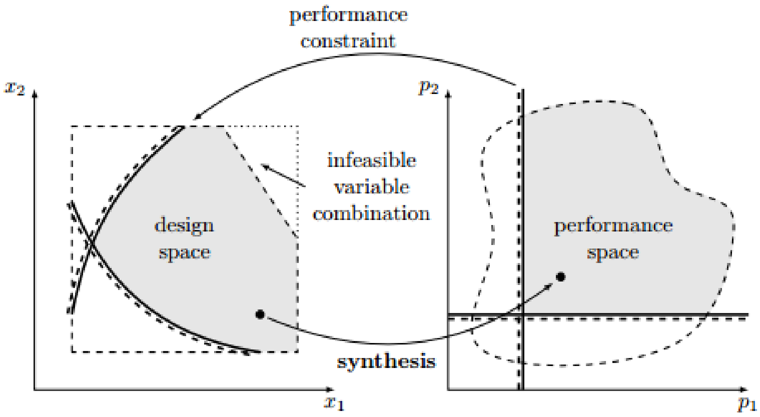


Figure 2.1: Placing design space in context with performance space Duchateau (2016) Devanathan and Ramani (2010)

There have been many attempts of describing this preliminary ship design process, most of them referring to a design spiral, first of all by Evans (1959), as show in figure 2.2. This displays a model of the stages of ship design in an iterative process, which was developed to efficiently and logically order the steps that need to be iterated to converge to a single design. This process of iterative exploration of the design space, is also known as sequential or point-based exploration. Subsequently updating and improving a design to find a balance between the performance of desired mission requirements of the ship. The first step within this design spiral model is the configuration of the general arrangement, stating the importance of this step within this design stage.

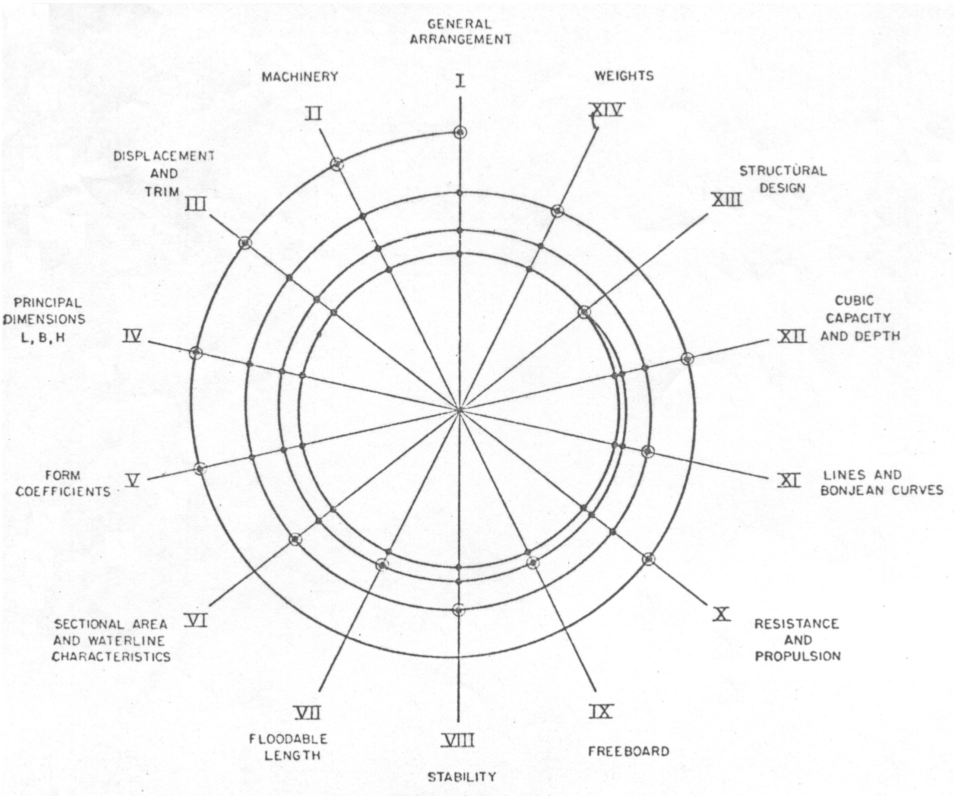
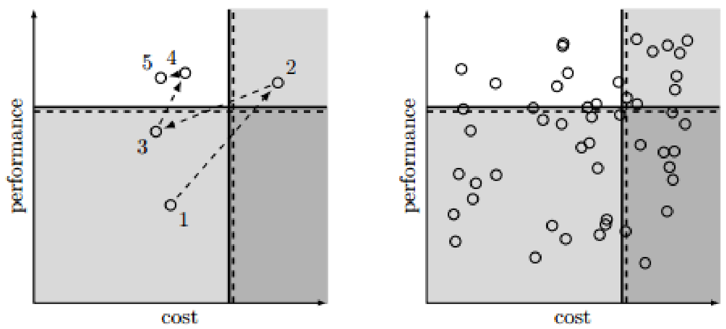


Figure 2.2: General design spiral model diagram Evans (1959)

One of the biggest issues of this sequential exploration is the number of designs, or the size of the exploration space, that can be analysed by the method. Every step has to be taken iteratively and takes considerable effort, limiting the possibilities of design exploration and possible ship performance. Efforts are being taken to introduce a concurrent, or set-based, exploration method, for example by Interactive Evolutionary Concept Exploration Methodology (IECEM) by Duchateau (2016). What this pretty much does, is performing a single iteration on this design spiral creating a single viable design. By doing this thousands of times, thousands of single viable designs are created, exploring the possibilities within the design space. Instead by optimising a single design, and finding a single (local) optimum, iteration improves on this wide variety of single designs supposing to find numerous of local optima within the exploration space giving more insight in the possibilities of the design. A visual representation of the difference between this sequential and concurrent exploration methods are shown in figure 2.3. A very detailed description of application of set-based design and decision support within this process are set out by Mckenney (2013). He sets out a decent execution method of application within a ship design process.



(a) Sequential (point-based) exploration **(b)** Concurrent (set-based) exploration

Figure 2.3: Two main design exploration methods, a) sequential and b) concurrent approach Duchateau (2016)

2.2. General Arrangements and Automation

During the preliminary ship design phase, problems concerning the overall composition of the vessel can be directly related to the arrangement of systems, compartments and components. Historically, these arrangements have been compiled into detailed drawings of the vessels where the naval architect has decided on the arrangement and connections between these compartments manually. These decisions have been traditionally built upon design rules and the experience of the designer. Furthermore, the designer can usually fall back to comparison vessels to have a decent understanding of the architectural problems and to have a starting point for the current design. A problem occurs when new vessel classes are being designed or in situations where a lack of experience is encountered, Andrews (1998).

Currently, multiple projects are being undertaken for general arrangement automation in an earlier stage of the design process, such as the packing approach, van Oers (2011), the Intelligent Ship Arrangement platform, Parsons et al. (2008) and the Design Building Block approach, Andrews and Dicks (1997). These projects all make the use of computing power to generate a concept exploration space, but may still using a sequential exploration approach. By creating a numerous amount of feasible design concepts, a solution space is created where the designer will be able to select multiple concepts for further examination.

These methods are combined into an international project, Preliminary Ship General Arrangement Design Naval International Cooperative Opportunities in Science & Technology Project (NICOP) NICOP et al. (2012), which is a collaboration between three major marine design centres, University of Michigan (UM), University College London (UCL) and Delft University of Technology (TU Delft), combining their researches addressing optimisation and modernisation in ship design methodology. Other publications include NICOP et al. (2013) and NICOP et al. (2014)

A usual visual representation of a general arrangement is a series of (commonly two-dimensional) projections, such as sections and deck views. It can illustrate placement of different spaces and components and the relationships between these spaces, for example the placement of a generator room and it's connection through a funnel to an exhaust on deck. As the ship can be a very complex configuration of many interconnected spaces with unarguably a huge number of geometrical and relational constraints, the construction of a "good" GA is not as easy as it may sound.

It is possible to describe or generate 3D arrangements by different mathematical methods. One such other representation of the arrangement of a vessel is through the use of network science or graph theory, as introduced into ship design by efforts by UM, Gillespie (2012). This composes a graph network of nodes and edges, representing the items in the design and its interactions or relations within the total system. This may give a very detailed description in possible relations and constraints within the design, but may not be useful for the actual placement of the different systems. Other descriptions may lay in the use of an agent-based approach, as introduced by Daniels and Parsons (2006). They have compared a genetic, an agent-based and an agent-genetic hybrid algorithm in order to optimise zone-deck allocation for general arrangements within the Intelligent Ship Arrangement platform. The idea is to combine the advanced search capabilities of agent-based models with the robustness of a genetic algorithm. They found that the hybrid algorithm showed superior performance behaviour to the genetic algorithm and agent-based model. It does however ask for more computational power, which might give problems for more increasing problem complexity.

The naval architectural problem concerning GA exploration can be divided into two major issues, the actual known problem of forming the general arrangement, including the placement of systems and the problems occurring when trying to implement this into a computing model. Furthermore, the exploration tool is capable of generating thousands of designs. Analysis of these thousands unique designs and using this information yields a second problem. The first problem is addressed by the TU Delft Packing approach, van Oers (2011), implemented into the IECEM by Duchateau (2016) helping the analysis of these designs. There still is a huge gap in the actual understanding of these general arrangements and thus improving the quality of the generated arrangements.

Placement of systems within the arrangement is a very complex process. Systems need to work together, need to be separated and the vessel needs to be a stable platform in order to be functional. Using computer algorithms and a system based approach to create these arrangements greatly facilitate easier ways of creating viable arrangements or layouts. However, these approaches lack a capability of human interaction and input within this preliminary design phase. A lot of information is generated by creating a large design set, which might be lost when selecting most promising designs. There is still a lot of information left within the data set, that without manual and individual analysis of designs cannot be assessed. Furthermore, the designer needs a way of interpreting the information generated by the algorithms. In the early 1970's, the perception was that computers should only be used as an aid for analysis of the designs rather than actually be used as a contribution to the design process itself, Andrews (1998). Since computer algorithms, and the understanding of these algorithms, have seen an amazing growth in the last decades, this perception has become seriously outdated. Current ship design is primarily done by using computing power, including processes as CAD, FEM and CFD. Also, ship design processes has been analysed within literature and incorporated into design methodologies. Combinations of this neoteric computer technologies and understanding of design processes seem to be very promising and ameliorate ship design methodologies. An occurring problem is that human interference within this process tends to get lost, and therefore the information gained within the preliminary ship design process actually deteriorates. It is apparent that naval staffs are struggling with increased retirement and thus a decrease of the amount of knowledge of design within these naval staffs, DeNucci et al. (2009). Concentrating on computing algorithms on creating arrangements instead of actually creating understanding of the arrangement problem for young designers does not improve design knowledge within these naval staffs. A balance should probably be found in the use of computing algorithms and human input in order to gain most information from these algorithms. Furthermore, more intelligent analysis algorithms, and more understanding of these complex algorithms, deems necessary in order to let designers learn more from data generated by computer technology within ship design processes.

2.3. TU Delft Packing Approach and IECEM

The design space exploration project created at Delft University of Technology, the packing approach, uses a bin-packing algorithm into a parametric ship description. Together with a genetic search algorithm, it creates a space where the objects are packed into a cloud of feasible ship designs. The naval architect can use these feasible ship designs by identifying and selecting a number of promising alternatives. This method has been an effort by primarily B. van Oers, van Oers (2011) at TU Delft and DMO.

This approach is a 2.5D bin packing based approach, that basically consists out of a two step method, shown in figure 2.4 taken from van Oers and Hopman (2012). The first step is a combination of a binpacking algorithm and a genetic algorithm placing objects within a positioning space. In a ship design approach, this would convert to the placement of ship systems, as generator room systems or accommodation room systems, within a parametric ship design developed by a Simplified Ship Synthesis Model (SSSM). The genetic algorithm is introduced in order to create diversity within the design set. The basics and details on the actual generation of these designs can be found in work published by van Oers, van Oers (2011)

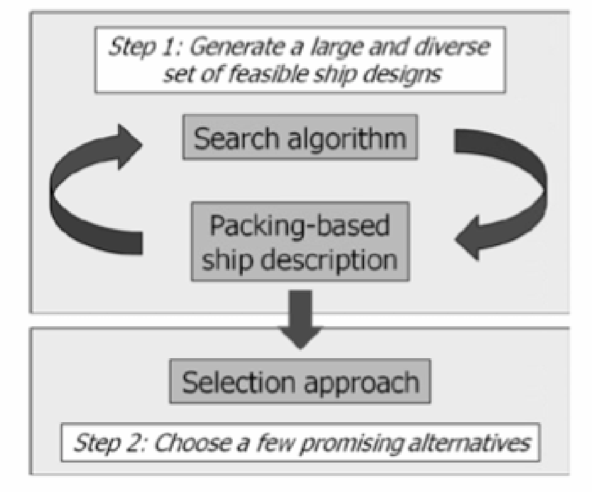
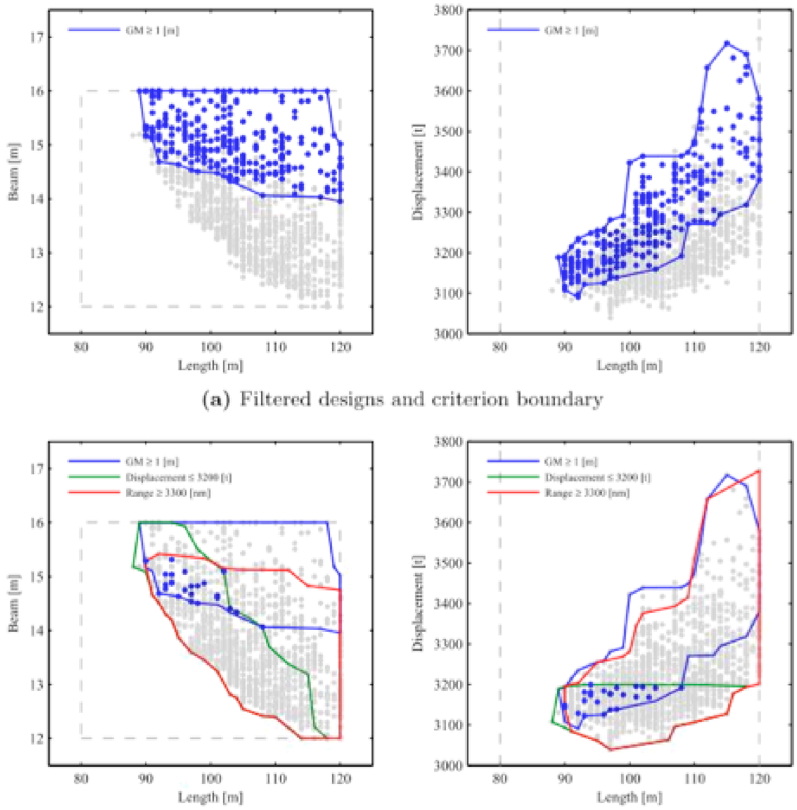


Figure 2.4: Overall process to generate and select promising feasible ship designs van Oers and Hopman (2012)

The second step in this process is the selection approach. The methodology and application of this selection approach is incorporated in the IECEM methodology by Duchateau (2016). The method is developed in order to be able to explore the results generated by the method, and to actually create insight knowledge of the generated data. Using this insight knowledge of the generated designs, specific parts of the designs space with a high interest can be evaluated into further detail and generate a denser solution for this area. This leads to selection of those solutions that seem most promising and can be taken to next stages within the design process Duchateau et al. (2015).

One of the biggest issues, as addressed before, comes by the number of designs. Since the method is easily capable of generating thousands of designs, the designs space seems to grow to proportions that a single Naval Architect is inevitably never able to manually compare. Therefore, designs can be represented by two dimensional visualisation of numerical characteristics. These can be technical characteristics such as length, beam or block coefficient, as well as financial characteristics, in the form of building or running costs. Adding criterion boundaries, the designer can identify how these boundaries are reflected in the entire data-set and represented when comparing other numerical characteristics, as shown in figure 2.5 from Duchateau (2016). Knowing the impact of certain of these characteristics, the architect allows himself to gain insight in the influence on the performance of the vessel by these certain characteristics. Using a pareto-front optimisation approach within these criterion boundaries, those designs that lay within these boundaries and seem most promising can be identified and reviewed in further detail.



(a) Filtered designs and criterion boundary

(b) Multiple criteria boundaries

Figure 2.5: Visualising numerical design characteristics and criteria Duchateau (2016)

Within the current methodology, performance parameters are focusing on numerical characteristics of the designs. Using the IECEM, the designer can interactively down-select or filter those designs through preferred system positions, as applied by van Oers (2011). However, spatial relations are highly disregarded because they can currently only be manually analysed for a single design. This results in a lack of understanding of the spatial and physical relationships within the vessel. Manual analysis of those designs that are of the highest interest to the designer is possible, but an earlier, or simpler, representation of these physical relationships could allow the designer to actually incorporate this in an earlier stage of this packing approach. Introducing a technical characteristic to the design that is able to directly relate to the quality of these physical relations might improve the solution selection in this stage.

Multiple thesis work has been developed based on or applying this packing approach and IECEM, such as Zandstra (2014), Cieraad et al. (2017) and Droste (2016). Each of these theses has applied the theory as developed by van Oers and Duchateau on different fields of study and application. This thesis relies specifically on the data-set set up by Droste (2016) on the application in cruise-ship design. As stated in section 1, the level of detail and correctness of these layouts seemed fairly poor. Therefore, further investigation in the detail of these layouts deemed necessary. The challenge is, however, to develop a method that could be applicable to data that has been developed by other applications of the methodology.

Network science focuses on describing physical relations whilst simplifying the rest of the structure of a system. By compressing subsystems, which in a ship design process could relate to spaces, into nodes and connecting these by edges the relations within a complex 3D ship design can be identified by a rather simplified network version of the 3D reality. The necessity of a method that allows a direct comparison between these physical relations seems to be promising for the packing approach methodology. Applying network theory to describe these physical relations is possible, as demonstrated to be possible by Gillespie (2012) or Rigterink (2014). This introduces a method to describe these physical connections, or adjacencies, within these generated designs. The following step is to find and implement which of these connections add value to the design or are regarded as unwanted connections.

2.4. Capturing Design Rationale

In order to do this quantitative assessment, one needs to know what qualitative properties are desired in the design. Deciding what designs are either "good" or "bad" depends on personal preference and will most certainly lead to different design decisions between different designers. Since there is no singular "wrong" or "right" solution, but more commonly a "better" or "worse" approach to the problem, it is very hard to describe the rationale behind certain decisions. DeNucci (2012) introduced a method of capturing design rationale for complex ship general arrangement design. His method interviews multiple naval architects to evaluate both desirable and undesirable features presented in one or multiple designs, accompanied by the underlying rationale and saves this in a database. For instance, a generator room should preferably not be placed adjacent to accommodation space to minimise noise levels in accommodation rooms. Using DeNucci's method and rationale database as quality metrics, one can start to define what is the motivation between certain design decisions and start to analyse which of these decisions are better or worse for the total design.

What DeNucci observed in an early stage of these arrangement optimisation approaches, is that although optimisation approaches can efficiently generate and search for a set of designs, it can not automatically select a design van Oers et al. (2008). Out of this cloud of generated designs, choosing and evaluating those designs that are of most interest seems to be a more difficult task, DeNucci et al. (2008).

Design selection is pretty much summed up in two stages. First, one must decide which design seems to be better. Second, one must decide why it is better, or different, from the other designs. DeNucci introduced a method, that is able to re-actively capture knowledge. Generating a diverse set of designs, for example by using the packing approach by van Oers (2011), and creating a human feedback loop, desirable and undesirable features of these designs can be identified.By storing the underlying rationale, this intelligence can be used as an input to create designs that should have more reasoning behind desirable features in the following diverse set of designs DeNucci et al. (2009). Because current design selection is primarily based on financial performance parameters, design selection will focus on designs that have a low building and running costs, thus those that are possible the smallest in the design set. Based on the experience of users, up-scaling of the selected design is commonly necessary in order to have an arrangement that is of a acceptable degree. Possibly, a-priori filtering of designs that are of a poor quality could allow the architect to evaluate those designs that are slightly more expensive, but have an architectural layout that is of sufficient quality.

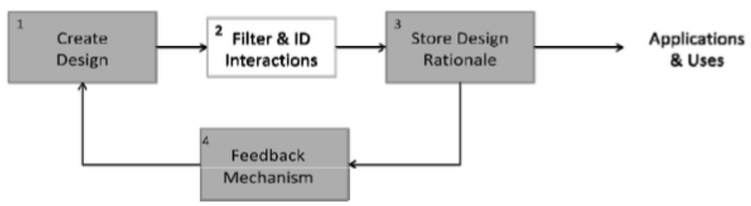


Figure 2.6: Block diagram of the prototype rationale capture tool DeNucci et al. (2009)

2.5. Measure of Effectiveness

Analysis of a large number of designs based on interior arrangements needs some sort of a performance parameter, that can be easily calculated and analysed by a designer. This performance parameter should give an indication of the quality of the low detail interior designs and allow direct comparison between these designs. Currently, a lot of human effort is necessary after selecting designs of interest from the dataset. An engineer still has a lot of work in actually transforming the packing arrangement into a workable arrangement that can be analysed and worked out in further detail for later design stages. It is beneficial to be able to take those arrangements from the dataset, that are of a higher level of quality and need less attention to transform into a workable layout. Furthermore, there is a lot of information within the dataset considering interior layout that is currently obsolete because it can not be analysed. It is impossible to view all designs and see where interesting arrangement solutions have been achieved. Being able to pick those from the dataset that are different allows the designer to learn more about possibilities within the arrangement.

In order to do a comparative analysis of the interior layouts, the performance of the interior needs to be calculated. This can be done by creating a measure of effectiveness of the interior layout or arrangement of the design. Chapter 4 describes the method that has been created to measure this performance. Prior to this, one has to develop the mission objectives that have to be measured by the metric. This might be problematic in ship design, whereas mission objectives such as costs, redundancy or seakeeping capabilities, might lead to contradicting performance measures. For seakeeping capabilities and costs, generator rooms should probably be placed close together as they have the same parameters. In the case of redundancy, a designer probably wants to place these generator rooms separated. When performing a single measure of effectiveness, this performance measure needs to be able to incorporate multiple mission objectives into a single score or separate these scores into the multiple mission objectives. The method introduced in chapter 4 introduces a single scoring measure of effectiveness allowing simple and fast comparison between the high number of designs. The mission objectives can be identified by assessing the captured rationale by DeNucci and test the arrangements on desirable and undesirable features of the designs based on this rationale.

2.6. Research Goals and Objectives

The goal of this research, backed up and introduced in chapter 1, is to able to earlier identify undesirable features considering architectural relations within a concept exploration design process. Combining earlier research on network arrangement descriptions and rationale capturing enables a method of introducing layout analysis within concept exploration methodology.

Following the motivation behind this thesis, the following main objective is defined:
"Develop a post-processing method that is able to quantitatively compare arrangements generated by the packing approach, taking into account its qualitative properties."

In order to develop this objective, combination of earlier research based on this problem will be evaluated. The method shall introduce a metric that should be able to score arrangements and allow direct comparison between these qualitative architectural properties of the designs. The following research questions have been stated to reach this objective:

- Is network theory applicable as a way of describing the architectural relations between systems in the packing arrangement?
- Is conversion of packing arrangements into a detailed network possible?
- Can earlier captured rationale be used to analyse the architectural relations withing the network arrangements?
- Can these qualitative properties be compressed to a single score for an arrangement?

3
Network Theory

The following chapter will give an introduction to network theory as applied in the method of this thesis. This chapter should give enough mathematical understanding of network theory in order to understand the developed metric and used terminology. It introduces the basics of the mathematics of network theory and describe some basic network metrics that are used to analyse behaviour of these networks and how this might be used within the method. Networks have been defined in different ways by different authors, definitions and theory in this chapter have been primarily taken from Newman (2010).

3.1. Introduction to Network Science and General Arrangements

Network modelling is a mathematical representation of reality, using a collection of points joined by sets of lines as a spiderweb, Newman (2010). They are commonly applied to represent social or economic interactions. Systems that are composed of individual components that are somehow linked together, can easily be identified as a network. Examples of networks can be the internet, multiple computers linked by a data connection, and human societies, people linked by families and friends or connected through social "networks".

Since many different forms of information can be stored in these points and links, networks are applicable to many other fields of study besides social or economic interactions. This includes architecture and engineering, such as applications in urban movement, Hillier and Iida (2005), or application in space syntax, Vasku (2013). The method required to analyse the arrangements requires a representation of the arrangement of the design that can be easily reviewed and analysed. This can be done by making use of this network theory. Since networks can be a simplified representation of such a complex system, it is a powerful tool to analyse connections or interactions within these complex systems in a simpler way.

As ships can be identified as complex systems of individual components, network theory seems very suitable for application to the design of ship arrangements. This has been demonstrated by research at the University of Michigan, identifying drivers of arrangements, Gillespie and Singer (2013), or the generation of applicable general arrangements for complex vessels, Gillespie (2012), Gillespie et al. (2013). Furthermore, Rigterink (2014) used network theory to model and analyse disparate ship design information, including general arrangements. The metric and method presented in this thesis, introduced in chapter 4, will present a similar approach to arrangement representation in network form.

The metrics developed at the University of Michigan have been primarily used as a mean in generation of general arrangements. It can identify what systems drive the generation of arrangements and how these are reflected by boundary conditions within this generation. Using this simpler description within an early design stage, allows the designer to capture a lot of information about the design without going in too much detail in an early design stage.

3.2. Network theory

A network or graph is simply put a collection of points, called nodes, which are connected by lines, called edges. It is a simplified representation of a (possibly very complex) system, where only connectivity patterns are represented. Nodes within the network can represent any sort of object or entity, with edges showing connections or relations between these objects. A network can be weighted or unweighted. In an unweighted network, edges only show that there is a connection between nodes, whereas in a weighted network edges are given a value, which can add characteristics such as length or capacity to that certain edge. Furthermore, networks can be directed or undirected. In a directed network edges have a direction pointing from one node to another, only allowing information in the direction of the edge. For undirected networks, edges only show connectivity and do not include direction of the edge. Newman (2010).

There are multiple ways of representation for a network, both mathematically and graphically. In order to do calculations with the network, a mathematical representation is necessary. A commonly used representation is using an adjacency matrix, similar to Gillespie (2012) and represented as **A**. For a simple unweighted network, the adjacency matrix **A**, is described by the elements as seen in equation 3.1. A weighted network reflects to an adjacency matrix with values of not only 1 and 0, but possibilities of any value, which may even include negative values. The adjacency matrix shows which nodes are connected and what the weight of these connections are.

$$\mathbf{A_{ij}} = \begin{cases} 1 & \text{if there is an edge between nodes } i \text{ and } j, \\ 0 & \text{otherwise} \end{cases} \tag{3.1}$$

For an undirected network, the adjacency matrix **A** in equation 3.1 is symmetric, since if there is an edge between nodes i and j, there is also an edge between j and i. For the directed network type, the direction of node is represented in the asymmetry of matrix **A**. Evaluation the adjacency matrix, node and edge lists are established displaying all information of the nodes and edges of network generated out of the adjacency matrix. More information on these nodes and edges can be added into these node and edge list, including weights and node properties. Weights of edges are represented in the adjacency matrix by adding different values for the edges into matrix **A**. Figure 3.1 shows how adjacency matrices are coupled with graph networks. These representations are interchangeable and can be translated back and forth. It shows a representation for a) undirected and unweighted, b) directed and unweighted and c) undirected and weighted networks.

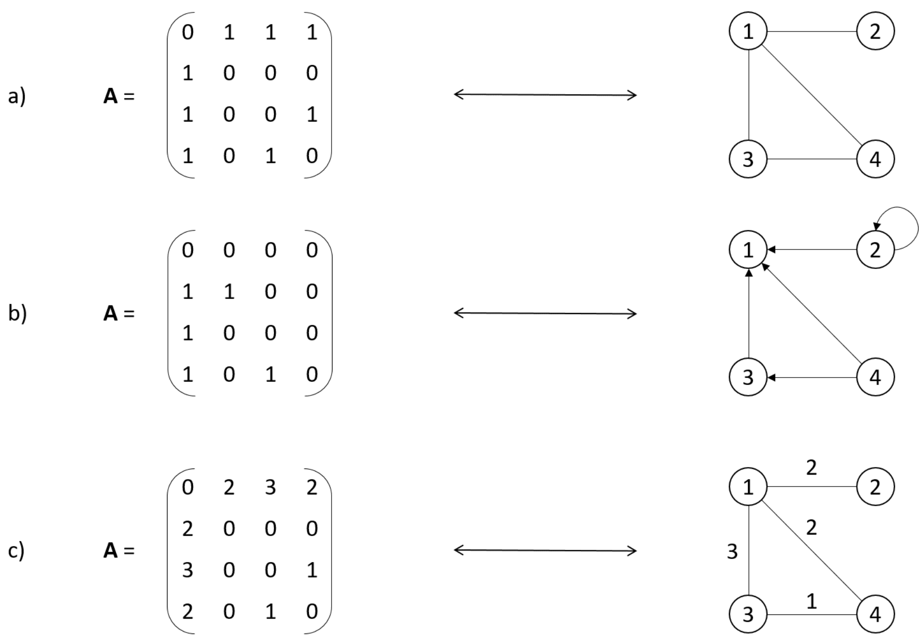


Figure 3.1: Translation between adjacency matrix A and graph network for a) undirected and unweighted, b) directed and unweighted and c) undirected and weighted networks

3.3. Centrality Measures

The method proposed in this thesis and introduced in chapter 4 needs a way of giving a weight to the importance of the adjacencies of the system in the arrangement. The nodes in the network are not of the same relevance to the total arrangement and should rank differently in the rating metric. The same would apply in a general arrangement, where for example a dry storage room systems should not rank similar to a generator room. To create a ranking factor to each node or edge, the method ranks the nodes by using centrality measures. Network centrality can be used to give an indication of the importance or influence, and thus rank, of the nodes within the network. This can be done through multiple algorithms, which differ in complexity and objectives and might give slightly different results in ranking of the nodes. Different centrality methods rate the nodes in different ways, where the “importance” of the nodes is different. “Importance” to the system can be interpreted in many different fashions, which can be compared to the trade-off of objectives in design decisions. For example, centrality based on flow of information will give a high importance to staircases where a lot of information spreads through the network. Two different centrality measures, eigenvector and betweenness centrality, will be used to compare rankings within this thesis. The following paragraphs will give a description of these centralities and their focus. More details on these centralities and corresponding algorithms can be found in *Networks, an Introduction*, Newman (2010).

3.3.1. Eigenvector Centrality

The first centrality used is the Eigenvector (EV) centrality. The eigenvector centrality is commonly used to describe the influence of a single node into the entire network. It is based on the fact that connections to other nodes with a high score are more valuable than connections to nodes with a lower score. For example, a generator room will be connected to many other important systems such as a propulsion room and fuel tanks. Therefore, a node connected to multiple nodes with a high score, will have a very high score itself. To calculate the eigenvector centrality, one needs to find the principal eigenvector $\mathbf{x}$ associated with largest eigenvalue λ as defined in equation 3.2. Furthermore, the eigenvector is normalised by dividing the scaled eigenvector by the maximum eigenvector difference to create an absolute score that can be directly compared between multiple networks as a percentage. Each element in vector $\mathbf{x}$ corresponds to one of the nodes in the network representing its relative centrality score.

$$\mathbf{Bx} = \lambda\mathbf{x} \tag{3.2}$$

3.3.2. Betweenness Centrality

The second centrality measure used is the betweenness centrality. This centrality measures the extent of which a node lies on paths between other nodes. It is commonly used to analyse the flow of information through a network, since it can easily identify the influence on control of information between other nodes. A high value means that the node will have a high influence on the total flow of information through the network model. This flow can be anything, which in ship design can be used to describe flow in people or goods through the arrangement but also water during flooding. Values for each node can be calculated by equation 3.3. For every node i, a centrality score $\mathbf{x_i}$ is introduced. n^i_{st} is 1 if the node is on the geodesic path between all nodes s and t and 0 if node i is not on this path or the path does not exist. When this is summed over all nodes s and t, one will get a number of shortest paths node i lies on. After dividing this by the total number of geodesic paths between nodes s and t, which is g_{st}, the score is normalised allowing direct comparison between networks.

$$\mathbf{x_i} = \sum_{st} \frac{n^i_{st}}{g_{st}} \tag{3.3}$$

Figure 3.2 displays a simple unweighted bow-tie network with eigenvector and betweenness centrality values for each node in table 3.1. In this bow-tie network and table, differences in the nature of the centralities can be identified and illustrates which nodes are emphasised by each centrality calculation. Looking at the central node of the network, node 1, gets a value of 0.1580 for eigenvector centrality and 0.3462 for betweenness centrality. Because the node is only connected by two edges, it gets an eigenvector centrality score that is not

Node	Eigenvector Centrality	Betweenness Centrality
1	0.1580	0.3462
2	0.2403	0.3077
3	0.1917	0
4	0.1917	0
5	0.1157	0.3472
6	0.0513	0
7	0.0514	0

Table 3.1: Centrality scores corresponding to network in figure 3.2

that high compared to other nodes, as nodes 2 or 3. Node 3 is also connected to only two edges, but since node 2 is considered to be of a higher ”importance" to the entire network, nodes 3 and 4 get a higher centrality score than node 1 or node 5, which is even connected to three nodes.

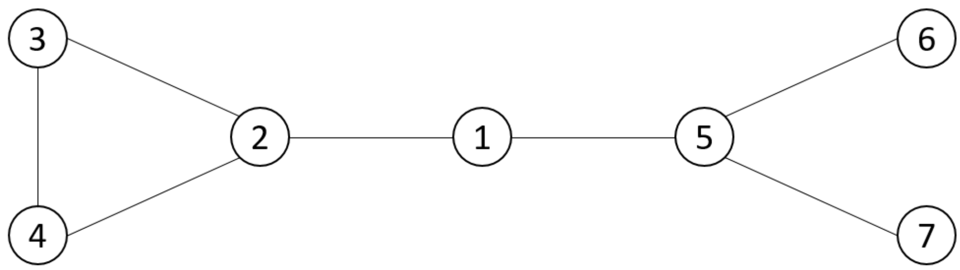


Figure 3.2: Simple unweighted bow-tie network

3.3.3. Centrality Comparison

What can be seen is the exclusion of nodes 3, 4, 6 and 7 in the betweenness centrality method, because these nodes are on no shortest paths between other nodes. Nodes 1 and 5, who do not get a very high value for Eigenvector centrality do get a high value for Betweenness centrality since they are on a high number of shortest paths between the left and right part of the bowtie. This lies a big emphasis on these nodes by this centrality calculation.

The eigenvector centrality gives a more even distribution of rank through the nodes. For the analysis of general arrangements, this means that there will be exclusion of certain spaces when using betweenness centrality, but will give peak scores on nodes in the system where a lot of information will flow through and is therefore very interesting for flow analysis. Eigenvector centrality will give a more evenly spread out score through the network and analyse the contribution of the specific node to the network.

4

Method

The following chapter will describe the method that has been developed to perform the arrangement analysis. It will introduce the translation from the 3D arrangement to a network description. Furthermore it introduced what designers rationale has been used in the method. After this, the algorithm calculating the metric is given. Concluding, the metric is used on the bow-tie network introduced in chapter 3 in combination with the introduced rationale to display the functionality of the method.

4.1. Introduction

Chapter 2 referred back to the difficulties that are encountered when generating thousands of designs. The packing approach has developed an efficient system to generate thousands of designs, but current analysis methods tend to be unable to analyse the interior arrangements of the generated designs. DeNucci has developed a method of capturing design rationale and being able to identify positive and negative aspects of different designs. This chapter introduces a method that is able to use the information captured by DeNucci and apply this information to a simplified, mathematical representation of the generated designs. This method is based on a metric, or measure of effectiveness. It tends to measure the effectiveness or performance of the generated arrangement. Coupling the network representations with the captured rationale leads to a performance metric that can be easily analysed by the designer. This allows him to take physical relations within the interior arrangement into account during design selection.

4.2. Generation and Analysis of Network Arrangements

The basis of the metric of this thesis as proposed in chapter 4 is an analysis of spatial relationships within the arrangements. This analysis is performed to analyse which of the arrangements are more promising within the design space to allow the designer to have more knowledge of the design.

The networks necessary to do this analysis, need to represent adjacencies and distances of systems within the arrangement. Therefore, weighted graph networks are necessary. As there is no interest in flow direction for this particular analysis, the networks should be undirected. Furthermore, the diagonal of the adjacency matrix will be zero, since no systems can be adjacent to themselves. These adjacency matrices have never been set up before, since there was no application for this network theory within the packing approach. Instead of generating the networks, the generated 3D arrangements need to be converted into network arrangements.

4.2.1. Matrix A

In order to create the networks, a definition of nodes and edges is necessary. As all information is stored within these entities of the network, it needs to be clear what part of the system is defined by what part of the network. Nodes will represent “system objects” or individual spaces as they are predefined into the ship synthesis model of the packing approach. Each generated design consists of the same system objects, with some design alternatives eliminating some of these objects. Edges represent adjacency of systems within the design, and will be weighted by distance of centre of gravity to centre of gravity. Whenever two system objects are on the same deck and neighbouring, allowing a small void space in between, they are considered to be adjacent. In matrix **A**, a 1 will be added for the objects that are adjacent, introducing an edge into the network. The node numbers, as presented in figure 4.1, represent these individual spaces. In order to allow transport of information through different decks, systems are connected to their corresponding staircase as they are defined by the International Maritime Organisation, (IMO, 2000), and Droste (Droste, 2016), creating matrix $\mathbf{A}'$. This explains why for example node 5 has no connections in network **A**, but is connected in network **B** as highlighted in figure 4.1.

4.2.2. Matrix W and B

A second adjacency matrix, **W**, is introduced to calculate the weight of the edges, defining the distance between spaces of adjacency matrix $\mathbf{A}'$. Matrix **W** is a connected network, with values for the Manhattan distances between all objects. The Manhattan distance is the sum of the horizontal and vertical paths between two nodes and is therefore slightly larger than the straight-line Euclidean distance. A Hadamard product, or element-wise multiplication, is taken between matrices $\mathbf{A}'$ and **W**, creating a new weighted adjacency matrix **B** as seen in equation 4.1.

What must me noticed, is that every network can have a different number of nodes and edges. The difference in number of nodes is due to small system variations within the data base, such as an extra staircase for larger vessels or number of accommodation for different luxury levels. The number of edges differs because of the number of adjacent systems differs per design.

$$\mathbf{B} = \mathbf{A}' \circ \mathbf{W}, \text{ or } \mathbf{B}_{ij} = \mathbf{A}'_{ij} * \mathbf{W}_{ij} \tag{4.1}$$

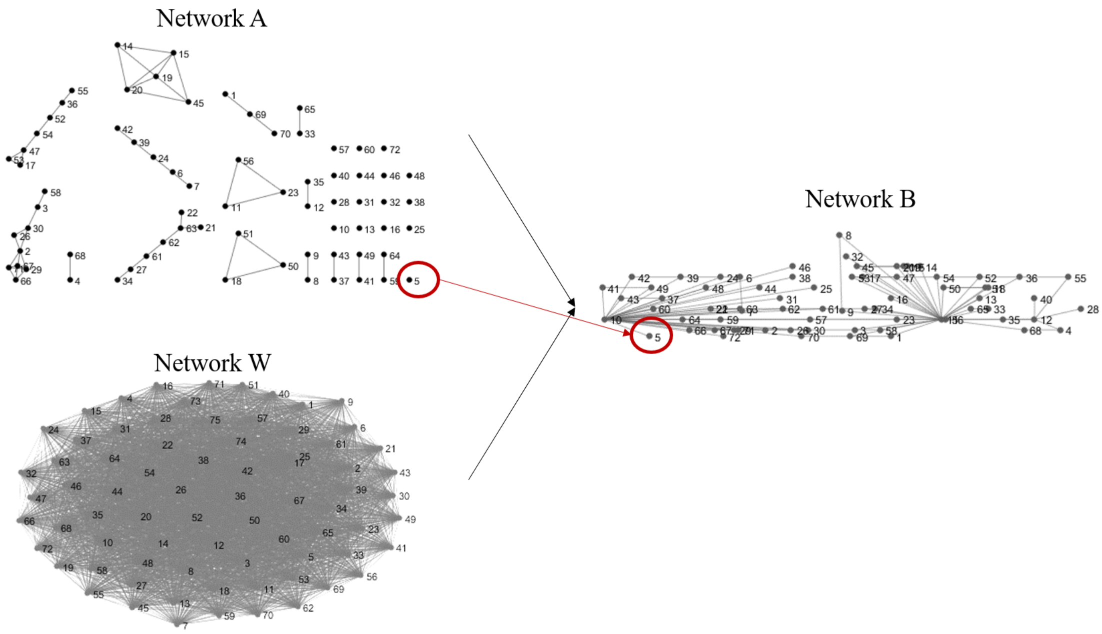


Figure 4.1: Network formation of packing design: network **A** displaying adjacent systems, network **W** a weighted connected network specifying all distances of systems and network **B** as the resulting network by Hadamard product of network $\mathbf{A}'$ and **W**

4.3. Designers Rationale used in the method

The structure of the design rationale as captured by DeNucci (2012), is directly identifiable in the network formation of the arrangements. DeNucci's rationale capturing method developed a database of design rules that describes positive and negative aspects of physical relations or locations of certain systems. Rationale used to analyse the networks is taken from the database captured by DeNucci of seven naval architects at the Dutch Defence Material Organisation (DMO) in 2010. This rationale is based on an Offshore Patrol Vessel (OPV) design.

Although the rationale lines are based on naval ship design, much of the rationale is applicable to general (complex) ship design. Rationale based solely on naval ship design has been removed from the data set to be able to setup a set of design rules that can be used for general ship design. The deleted design rules involve placement of weapon or radars systems, general ship design rules are still in this design rule set.

By analysing each edge of the system using these rationale rules, and evaluating the contribution of that connection, a complete qualitative analysis of the arrangement network is possible. The proposed method introduces a way of analysing the strong and weak connections in the network.

4.4. Scoring Metric

To rate the designs using the proposed method, a manual analysis of the edge list is done by using equation 4.2. Considering all established general arrangement rules, each edge in the list gets a score of $x_i \in -1, 0$ or 1 depending on whether it is disadvantageous, neutral or beneficial to the arrangement. The score of the edge is multiplied with the centrality scores of the connected nodes, z_{i1} and z_{i2}. This centrality score can be either the eigenvector or betweenness depending on the analysis. All edge scores are summed for all edges i to get a single score for the entire network. Thus, this metric accounts for all rationale and all spaces in the arrangement in a new quantifiable way. This is visually represented in figure 4.2, with equation 4.2 as the mathematical representation of the scoring method.

$$\begin{gathered} Score = \sum_i = (x_i * (z_{i1} + z_{i2})), \text{ with } x_i \in -1, 0, 1 \text{ for all edges } i \text{ in network} \\ z = \text{ centrality score corresponding to nodes } i_1 \text{ and } i_2 \end{gathered} \tag{4.2}$$

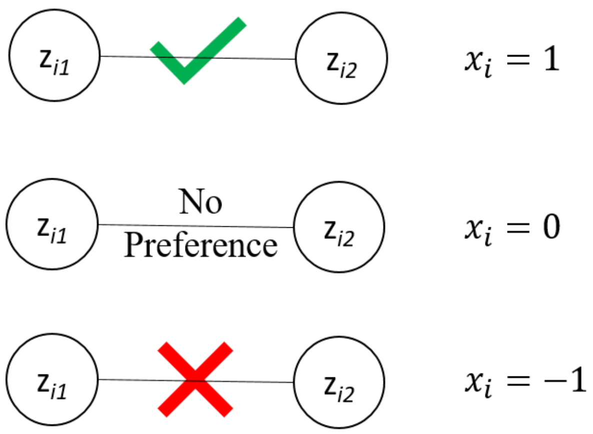


Figure 4.2: Visual representation of scoring algorithm

4.5. Application of Metric to Bow-tie Network

As the metric is introduced, it can be applied to the simple bow-tie network as introduced in chapter 3. If system types are added to the nodes, analysis with the metric is possible. Table 4.1 displays the system types for the different nodes and the corresponding centrality values. This network is merely an illustration of the method, and this network should never regarded as if it represented an actual arrangement of a ship.

Node	System Type	Eigenvector Centrality	Betweenness Centrality
1	Generator Room	0.1580	0.3462
2	Passenger Accommodation	0.2403	0.3077
3	Passenger Accommodation	0.1917	0
4	Passenger Accommodation	0.1917	0
5	Technical/Auxiliary Systems	0.1157	0.3472
6	Crew Accommodation	0.0513	0
7	General Stores Systems	0.0514	0

Table 4.1: Simple Undirected Bow-tie Network from figure 4.3 with added System types and centrality values

Using design rules from rationale captured by Denucci at DMO stating good or bad connections and the metric formulated in equation 4.2 and figure 4.2, the connections between the systems defined in table 4.1 can be analysed. This creates the analysis as shown in figure 4.3 and table 4.2. Figure 4.3 displays the bow-tie network with the analysed edges. Disadvantageous edges are displayed as red, neutral edges black and beneficial edges as green. Table 4.2 gives the edge list of the network, with the scores for each edges and the sum as calculated by equation 4.2. What is noticeable, is that the scores are now based on the edge, instead of based on the centrality of the node. Because each edge is analysed by the equation and multiplied by both centrality scores, storing the score within the edge lists is easier and can be computed faster.

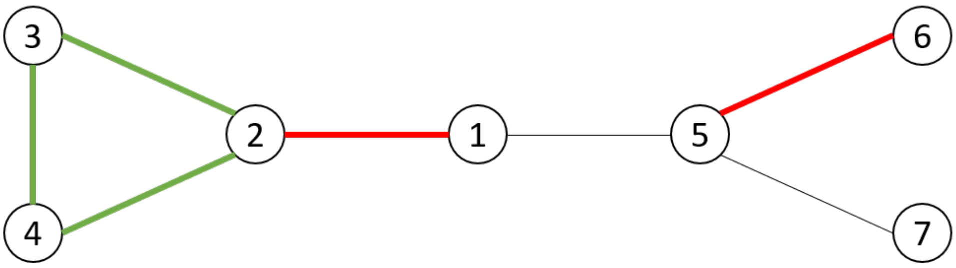


Figure 4.3: Simple unweighted bow-tie network with rated edges. Green edges are rated as beneficial, black as neutral and red edges as disadvantageous to the analysed arrangement

Edge	x_i	Eigenvector Score	Betweenness Score
1-2	-1	-0.3983	-0.6539
1-5	0	0	0
2-3	1	0.4320	0.3077
2-4	1	0.4320	0.3077
3-4	1	0.3834	0
5-6	-1	-0.1570	-0.3462
5-7	0	0	0
	SUM	0.6921	-0.3847

Table 4.2: Edge list with scores of the undirected bow-tie network

4.5.1. Analysis of Method applied to Bow-tie Network

After using the metric on the bow-tie network, a first analysis of the method is possible. The first thing that springs to mind is the difference in scores between the two centrality measures. The eigenvector score is positive, whereas the betweenness score gives a negative value for the network. Furthermore, one should know that a single score does not really say anything, but comparison of scores gives an illustration of the quality of the arrangement. It is interesting to keep evaluating both centrality scores, as they give a completely different score and focus on different parts of the arrangement.

5

Case Study with Manual Review

The following chapter will discuss a case study that is performed exploring the utility of the method and metric as introduced in chapter 4 on the design of a small cruise vessel. Two designs of the small cruise vessel database are compared and analysed by applying the metric. This chapter has been published and presented at COMPIT by the author. The presented paper can be found as a reference in appendix A.

5.1. Identification of Issues in chosen design

As stated earlier, the cruise ship arrangements showed some flaws after closer inspection. Two examples of issues in the chosen design by Droste (2016) are the placements of the emergency generator and the hospital rooms. As shown in figure 5.1, the hospital rooms are placed adjacent on deck 8 and the generator room is placed within passenger accommodation on deck 7. Hospital rooms should be placed separated from each other to fulfil redundancy and survivability requirements, DeNucci (2012). For habitability objectives, it is not desirable to have the emergency generator placed within accommodation space, especially in cruise ship passenger accommodation. The following section will look into whether these cases can be identified in the network representation of the chosen design.

For redundancy goals, hospital rooms should preferably not be placed in the same main vertical zone. Nodes representing the hospital rooms were identified in the node list to see whether they are placed in the same main vertical zone. After taking a closer look at the edge list, the edge between the two nodes representing hospital rooms exists, meaning that the hospital rooms are adjacent. Therefore, issues concerning direct adjacency or separation in main vertical zones can be identified in the network representation.

Analysing the placement of the emergency generator can be done in a similar way. Whereas an emergency generator should rather not be connected to passenger accommodation, or crew accommodation for that matter, edges between these nodes can be identified in the edge list and considered as bad connections. Figure 5.1 displays the network of 72 nodes plotted within the side view of the vessel.

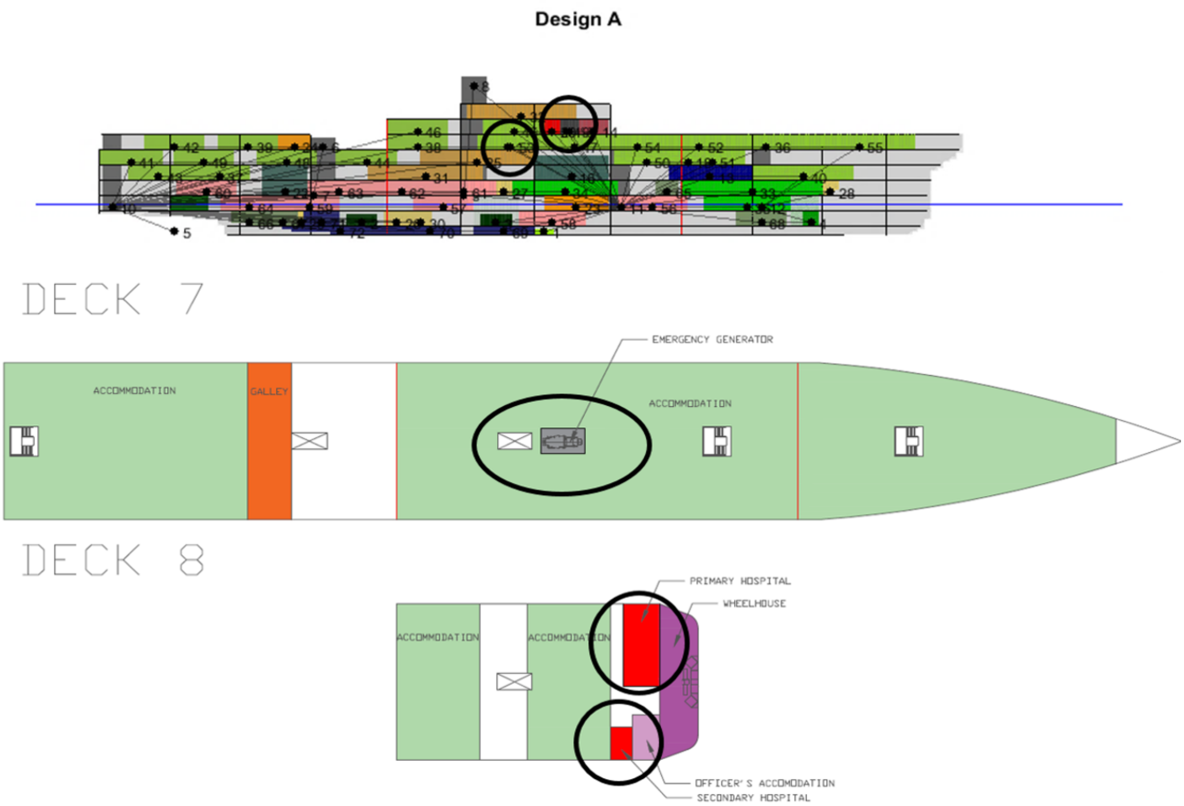


Figure 5.1: Network representation and deck views of design A, displaying the identified issues of the general arrangement

5.2. Application of Scoring Metric

However, this previous analysis requires manual inspection of the network and design to identify these problems. The proposed scoring method aims to give a quantifiable score to all arrangement rationale of the database. To test the method, two arrangements out of the cruise ship designs are analysed by the proposed metric. The first is the design as discussed in figure 5.1, referred to as design A, the second is taken from the design set, where the issues mentioned earlier considering the emergency generator and hospital rooms are not present, design B. Main parameters of the two designs are given in table 5.1 and a representation of both designs and networks in figure 5.2. As is shown, both primary dimensions and internal layouts of both arrangements vary greatly between these two designs. Manual inspection of thousands of varying designs would therefore be intractable. The difference in number of nodes is due to system variations within the designs.

Design	A	B
Length [m]	135	150
Displacement [m^2]	6907	10008
Cost [M€]	44.1	60.0
Number of nodes	72	74
Number of edges	122	125

Table 5.1: Main parameters of compared designs

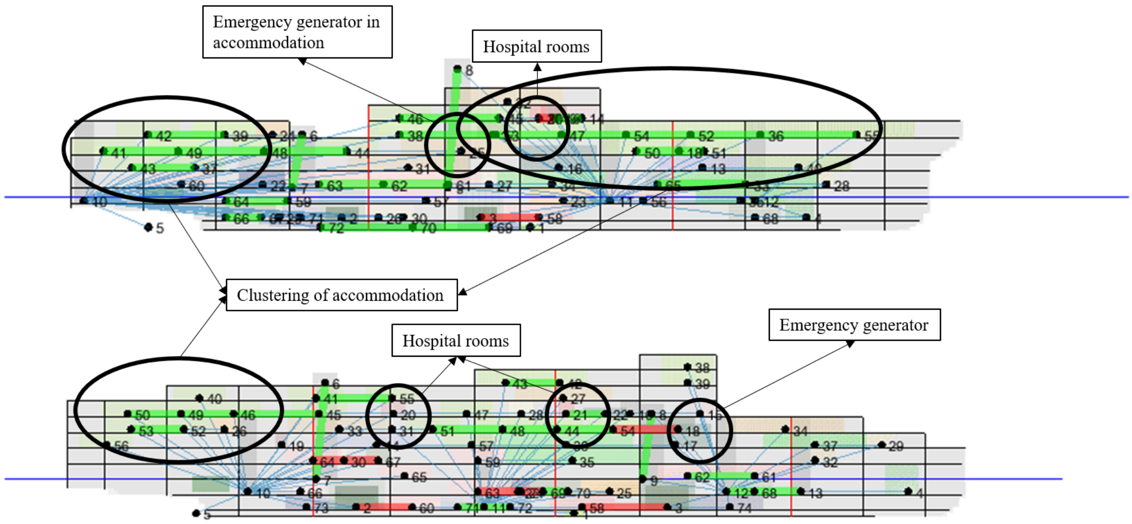


Figure 5.2: Designs A and B with different placements of hospital rooms, emergency generator and both showing clustering of passenger accommodation

5.3. Discussion of Scores

Applying the method to both designs gives the scores for the analysed designs presented in table 5.2 [1].

Design	Eigenvector Centrality	Betweenness Centrality
A	0.6542	0.4282
B	0.3514	0.0783

Table 5.2: Scores for the Designs

One sees that for the different centrality metrics, the differences in scores differ, identifying that there are differences in the type of analysis. Manually looking at the scores for each node, betweenness centrality gives a higher value for stairs than eigenvector centrality, since these are on a lot of paths because of the nature of the system type. However, there are few design rationales regarding the placement of the staircases in the database. Evaluation of the edges connected to staircases will mostly get no preference. This means that even though these nodes get a high centrality rank, they do not necessarily get a high centrality score.

Apparent is that passenger accommodation contributes a lot to the high score for design A. In the case of betweenness centrality, analysis of the node list shows that accommodation accounts for 0.29 of the total score. In design B, this value is only 0.11. This is likely due to accommodation systems being more clustered in design A, as seen in 5.2. A same trend can be found in crew accommodation, although the difference is slightly smaller. This can be explained by the fact that there is less crew accommodation than passenger accommodation present in the arrangements. Furthermore, design B has two accommodation systems that are highly penalised by the betweenness centrality because of a connection with a technical/auxiliary systems room. Looking at eigenvector centrality, the score for accommodation placement is 0.16 for both designs.

Other areas where design A scores better, especially on betweenness centrality, is the placement of the generator rooms. As generator rooms are of high importance to the vessel, there are quite some rationale rules based on the placement of generator rooms. Connections to the generator room are often regarded as positive or negative instead of neutral and are therefore highly represented in the score.

The poor placement of the emergency generator room in design A does not get penalised by betweenness centrality since it is not on any shortest paths, due to the transport through the accommodation surrounding

[1] These numbers are slightly different to the numbers presented in the COMPIT paper, due to an update to the network formation and using a different normalisation for betweenness centrality improving the direct comparison of the networks

the generator. It is therefore not visible in the betweenness centrality score. It is however penalised in the eigenvector centrality score, accounting for a subtraction of 0.01. This is rather small when comparing to accommodation scores, which lies in the fact that it only involves one node instead of twenty nodes in the case of passenger accommodation.

Because betweenness centrality can give a value of 0 for nodes on no shortest paths, the number of evaluated nodes decreases. For design A, 30 nodes get a betweenness centrality of 0, for design B this number is 38. This is about half of the total number of nodes, which is similar to the simple network in Fig.3. Since these are nodes that are on the ends of paths, these are primarily propulsion rooms and bridge or entertainment systems that are located on the ends of the vessel and are thus not reflected in the betweenness centrality score.

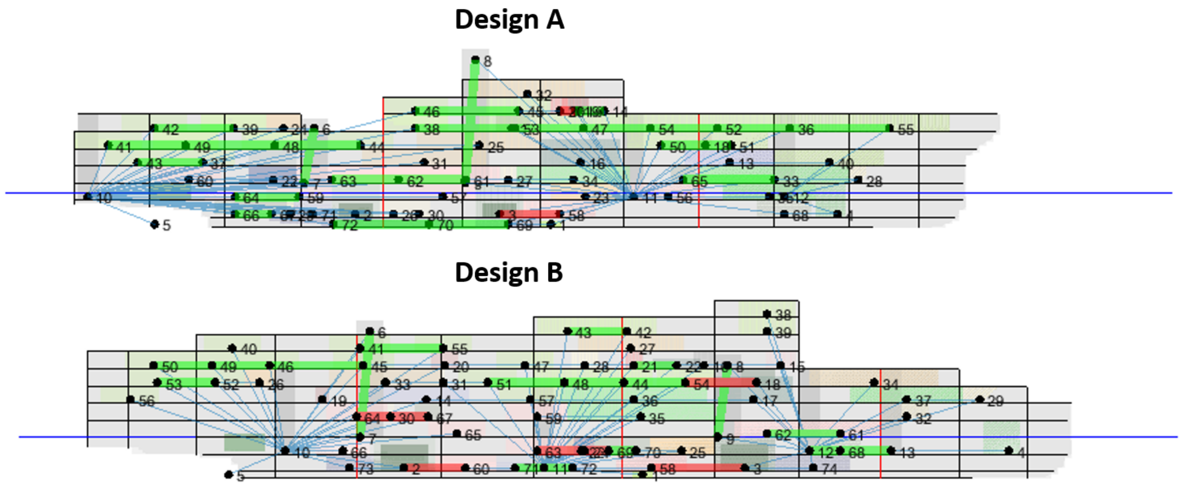


Figure 5.3: Designs A and B with highlighted edges. Green edges are positive, red edges negative and blue edges are considered neutral

Figure 5.3 focuses on displaying the positive, negative and neutral edges within design A and B, highlighting the attention points enlisted in the discussion. Both designs have a similar amount of positive and negative edges, resulting in a similar eigenvector score, but a higher penalty on the negative edges in the betweenness score for design B which is shown in the scores in table 5.2. This higher penalty is due to the fact that these bad connections are in that part where the “front” of the network is connected to the “back” part of the network. There should be a lot of flow of information through this part of the network. As this is where betweenness centrality lays it focus on, this is where this design gets heavily penalised. This can be considered as an unfair penalty, whereas not all flow of information through that edge is of importance to the design rule the consideration is based upon. Appendix B shows parts of the edge and node list of the network corresponding to Design A as a reference how the edge lists are rated.

5.4. Discussion on Manual Review

Using the scores presented in table 5.2 a quantifiable comparison of qualitative properties of the designs can be done. However, stating that design A is “better” than design B, still depends on the designer’s view and interpretation of these scores. Design A better represents designer’s overall rationale as it pertains to the layout of the general arrangements, as is shown by its eigenvector centrality score. If a specific designer is more interested in personnel flow through staircases, design A would be preferred, according to betweenness centrality score. By using this metric, one is now able to give a score to these properties of the general arrangements and compare these scores. The next stage is to apply this metric to a large set of designs, and use this to analyse the differences in designs in this entire data set which will be done in chapter 6.

Both eigenvector and betweenness can be compared by the use of the different methods. Since the rationale in the DeNucci database is solely focused on adjacency of different system types and the importance of these systems, and not based on flow between these systems, eigenvector centrality seems to be more suitable as a comparison metric in the analysis of general arrangements using this method.

6

Review of Total Cruise Ship Database

The following chapter will describe the application of the method to the entire small cruise vessel database of Droste (2016). It will introduce how the method is applied to the data set and discuss the results with the different centrality measures. Furthermore it will discuss the correlation between the centrality measure results. Concluding it will show how the method could be applied to improve design selection by the method.

6.1. Implementation of Networks and Denucci Design Rules

For the method to be applicable to the total dataset of over 20,000 designs, a few changes have to be made. The total method needs to be automated, since the initial process was done manually. The automatic review process of the dataset consists out of three steps;

1. Converting each general arrangement into a network
2. Analysis of each of the networks by the method
3. Analysis of the results

6.1.1. Network Conversion

The first step uses the same procedure as in chapter 5. Using the same method (creating matrix **A** and **W**, a Hadamard product and some added rules) and script every arrangement is converted into a network. To speed up the analysis of each designs, it has been made sure that all necessary information, such as design ID and node information, is stored in the network instead of in the design structure. The design structure holds more information that is not necessary for the analysis of the arrangement, so compressing the data into smaller files speeds up the analysis of the designs substantially.

6.1.2. Analysis of the Networks

After converting a design into a graph network, the method needs to be put into a workable script. The biggest issue is the translation from DeNucci's rule to a set of design rules in a computer aided program. Furthermore, the processed data needs to be saved in such a way, that it is easily accessible and identifiable to its corresponding design.

In order to successfully analyse the designs, programmed design rules based on the DeNucci database need to be established. In the manual approach in chapter 5, each edge in the edge list is manually evaluated and given a score from vector x_i. The automated review needs a slightly different approach. In order to analyse the edge list, the method needs to recognise the system types of the nodes connected by the edge. This can be coupled to the data in the node list, where node numbers and system types are defined. The data in the DeNucci database and the programmed design rules are based on the relation between system types similarly.

To speed up the analysis algorithm, all design rules considering a system type are combined into two longer and more complex design rules for each system type. One defines which systems are preferably adjacent and are given a score of 1. In other words, system type “A” should be adjacent to “B”, “D” and “E”. The second rule defines to which system types this space should not be adjacent and should therefore get a score of -1, or system “A” should be non-adjacent to “C” and “F”. All other edges in the edge list not described by the rules are given a score of 0. It showed that this way of defining the design rules drastically speeds up the algorithm instead of having a longer list of singular comparison rules only comparing system type “A” and “B” or “A” and “C”. Appendix B displays a small set of design rules, an edge and a node list as an illustration of the data stored within the set.

6.2. Results of Scoring Metric to Full Dataset

After running the algorithm for all designs, each design gets two scores, one based on Eigenvector Centrality and one for Betweenness Centrality. Chapter 4 has shown what the differences are between these two centrality metrics and chapter 5 has shown how this is reflected in the scores for the designs. This section will discuss the scoring results with the different centrality measures.

6.2.1. Eigenvector Centrality

Having calculated scores for all networks, we can start evaluating the division of scores. Figure 6.1 shows how the scores for Eigenvector centrality are divided, sorted by ascending score. Scores range from -0.077 to 0.9448. As already shown in chapter 4, negative scores mean that there are more heavy counting negative than positive connections within the network. It does not have to mean that there really are more negative than positive connections. Figure 6.2 shows a histogram for the eigenvector centrality scores in 100 bins. What this shows, is that the score is starting to resemble a normal distribution.

6.2.2. Normality Test

In order to see whether this distribution actually is a normal distribution, a normality test can be applied. Calculating the mean value (0.492) and standard deviation (0.114) of the design data set gives the empirical statistical values of the data set. The Kolmogorov-Smirnov test is used as a normality test. This gives a decision on whether a null hypothesis that the data within the data set comes from a standard normal distribution at a five percent significance level. Taking 2000 random values from the data set and applying a one-sample Kolmogorov-Smirnov test on the data, does not reject this null hypothesis. Normality tests can only be used to reject the null hypothesis and thus conclude that it is not a normal distribution. Because the test does not reject the hypothesis, one may assume that the data set at least resembles a normal distribution but may not conclude that it is.

6.2.3. Comparison between best and worst design in eigenvector centrality score

Figure 6.3 and 6.4 show the worst and best scoring design considering the eigenvector centrality score. The worst scores -0.0770 and the best 0.9448. The biggest difference between the two designs is the number of good and bad connections. The worst scoring eigenvector design has quite a high number of bad connections, 15 good and 7 bad. The best scoring design evidently has a lot of good and only a few bad connections, namely 30 good and only 3 bad. Of these 30 good connections, a large portion is considering the clustering around accommodation 14. Interesting to see, is that according to table 6.1 the differences in main parameters between the designs and networks aren’t that big. The best scoring is slightly more dense, with more edges within a slightly smaller vessel. Therefore, building costs are lower as well. The worst scoring design has some bad connections that are highly penalised because of the importance of the nodes for the network. For example edge 2-59 connecting a generator room to an accommodation room or 18-37 connecting accommodation to an emergency generator room. The penalties in the best scoring design however, are considered of less importance to the network, such as a 59-65 connecting crew accommodation to a fuel tank system.

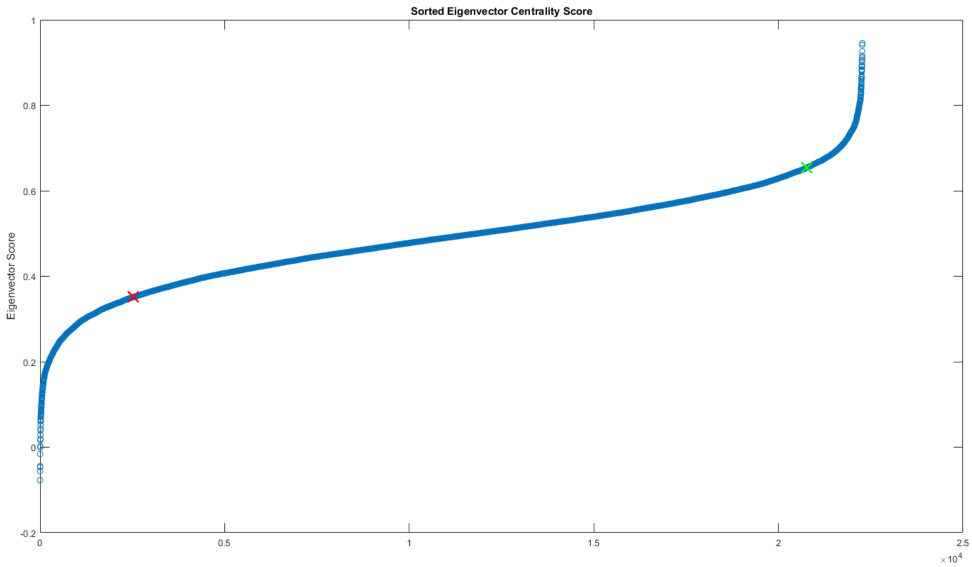


Figure 6.1: Eigenvector centrality scores for every design, sorted by ascending Eigenvector centrality scores. Design A is shown as a green cross and design B as a red cross.

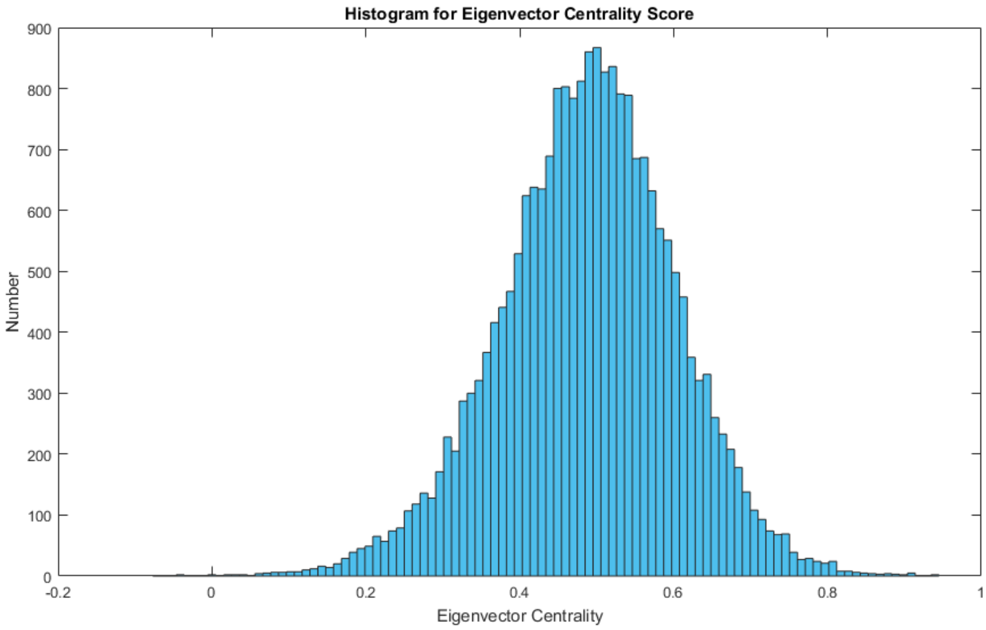


Figure 6.2: Histogram of Eigenvector centrality scores divided in 100 bins

Design	WorstEV	BestEV
Length [m]	146	143
Displacement [m^2]	8892	8174
Cost [M€]	57.1	54.2
Number of nodes	73	72
Number of edges	123	130

Table 6.1: Main parameters of Best and Worse EV centrality scoring designs

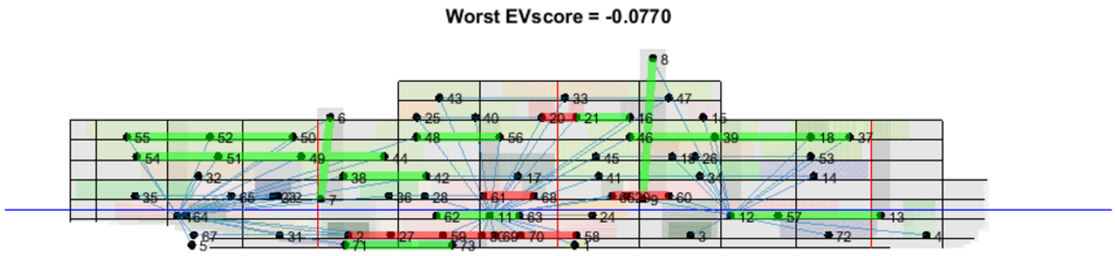


Figure 6.3: Worst scoring eigenvector centrality design with a score of -0.0770

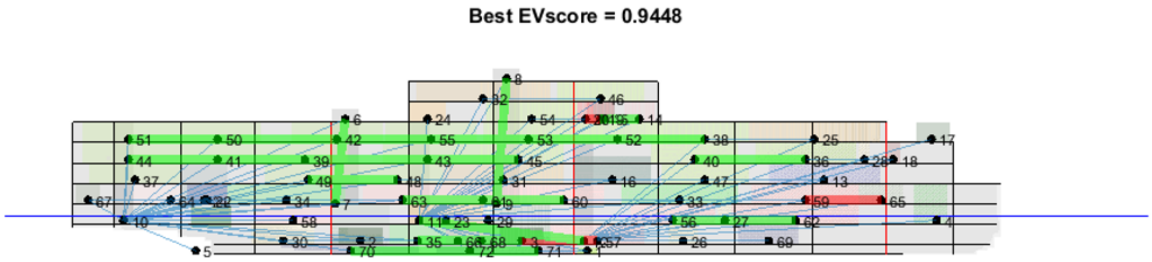


Figure 6.4: Best scoring eigenvector centrality design with a score of 0.9448

6.2.4. Betweenness Centrality

The same analysis has been run for the betweenness centrality next to the eigenvector centrality. Both calculations have been run on the same networks and same rationale, only the centrality values of the nodes differ. This does give different results for the scores however.

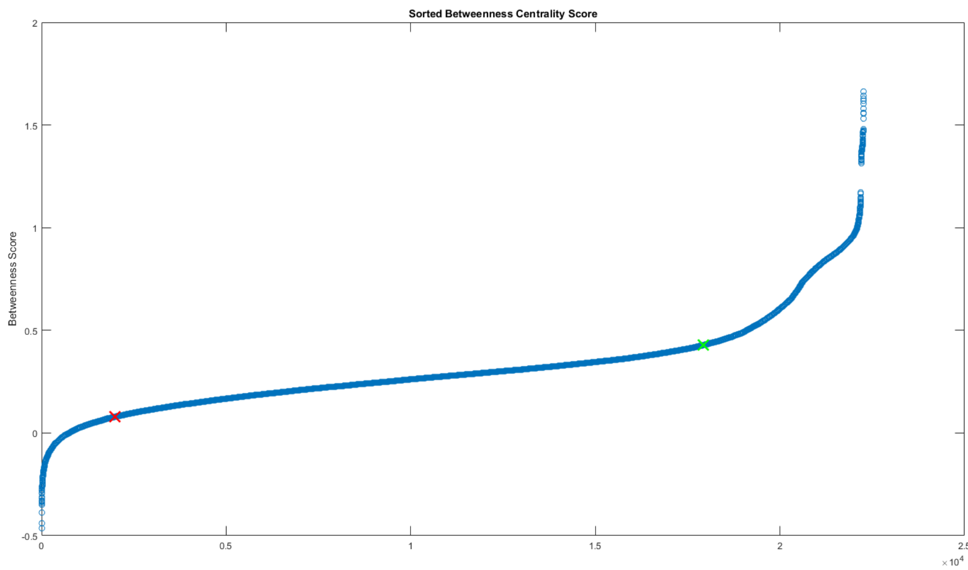


Figure 6.5: Betweenness centrality scores for every design, sorted by ascending betweenness centrality scores. Design A is shown as a green cross and design B as a red cross.

Figure 6.5 gives the betweenness centrality scored ascending and figure 6.6 gives a histogram for the betweenness centrality scores in 100 bins, similar to the eigenvector scores in figures 6.1 and 6.2. However, this resembles a completely different distribution than the scores in eigenvector centrality. Three peaks, or clusters of some sort, seem to exist within this set of scores. There are multiple steering objectives and design alternatives within the data set, for example luxury level and design speed that might have created these clusters. However, these design alternatives does not seem to reflect these three clusters in number or by individual manual analysis of these designs. Other options that have been looked at is the number of good or bad connections or number of edges within the designs. All of these do not seem to be reflected within these three clusters. There might be another reason for the occurrence of these distinct clusters that currently cannot be found yet. Chapter 8 will describe a method applied by Jaspers and Kana (2017), by making use of clustering algorithms, that could be used to analyse these groups and see whether they are reflecting in layout families. Furthermore, the betweenness score differs from -0.4633 to 1.6622, giving a larger spread than the eigenvector score. The two different scores can therefore not be directly compared, but designs can be compared using the same score type.

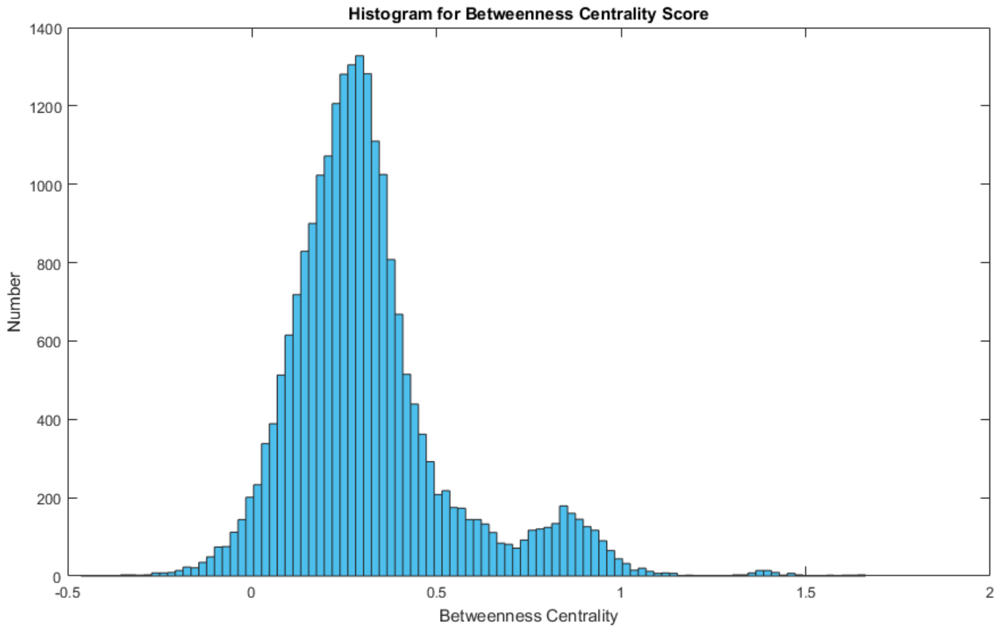


Figure 6.6: Histogram of betweenness centrality scores divided in 100 bins

6.2.5. Comparison between best and worst design in betweenness centrality score

Figures 6.7 and 6.8 show the worst and best scoring designs. Main parameters of these designs are given in table 6.2. Apparent is the number of good and bad scoring edges in the designs, 28 positive and 3 negative for the best scoring and 12 positive and 6 negative for the worst scoring designs. Furthermore, the negative edges in the worst scoring design are mostly in the lower centre part of the design, where a lot of information flows through the network. These are therefore heavily penalised by the betweenness centrality calculation. Of all connections in the best scoring designs 28 out of 127 edges are positive. Out of these 127 edges, about 70 connections are made to allow vertical travel of information, leaving about 60 edges considering the adjacency of systems. Almost half of these connections are considered positive, which allows the design to be rated as a very good layout.

Design	Worst Betweenness	Best Betweenness
Length [m]	139	150
Displacement [m^2]	8458	8613
Cost [M€]	55.3	55.7
Number of nodes	73	73
Number of edges	116	127

Table 6.2: Main parameters of Best and Worse betweenness centrality scoring designs

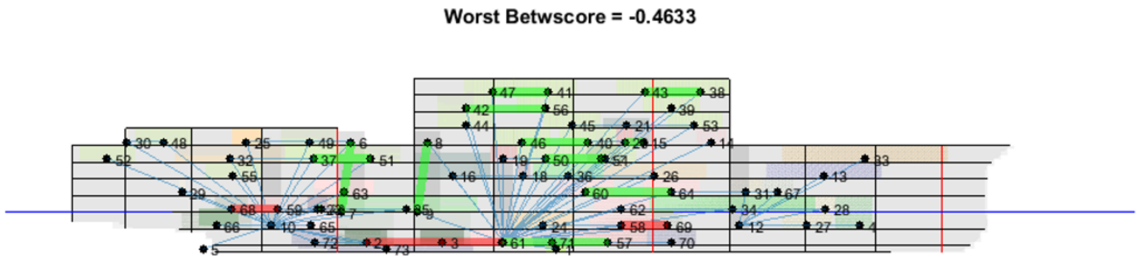


Figure 6.7: Worst scoring betweenness centrality design with a score of -0.4633

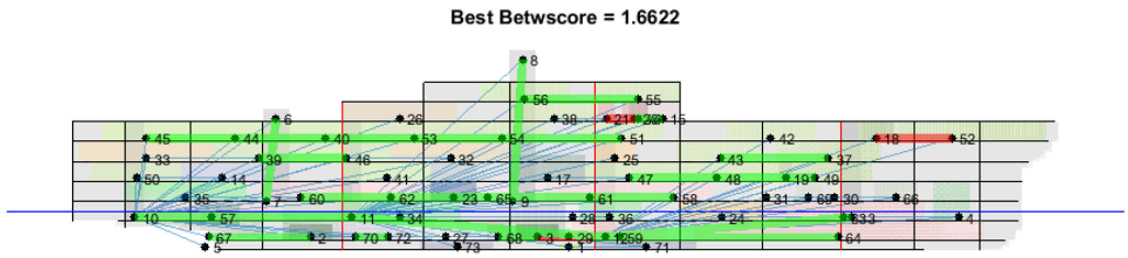


Figure 6.8: Best scoring betweenness centrality design with a score of 0.9448

6.3. Correlation of Centrality Measures

A look has been given to the best and worst scoring designs. The next step is to see whether these designs have something in common looking at these different centrality measures. Calculating the correlation coefficient between the eigenvector and betweenness centrality scores between the designs, this can be analysed. The correlation measures the amount of linear dependence between two random variables, in this case between the values for eigenvector and betweenness centrality. Scattering every design with eigenvector centrality score on the x-axis and betweenness centrality score on the y-axis gives figure 6.9. Calculating the correlation coefficient (r) gives 0.4322, meaning that there is an apparent moderate linear relation between the two variables although fairly weak. On average, a conclusion can be given that with this correlation coefficient an increasing score in one centrality measure, the other centrality measure will increase as well. This is due to the fact that both measures use the same networks and therefore the same amount of positive and negative edges. They are however given a different amount of importance to the layout by their corresponding centrality measure calculation. Design A and B are displayed within this picture as a red and green cross correspondingly to display their placement within the scatter.

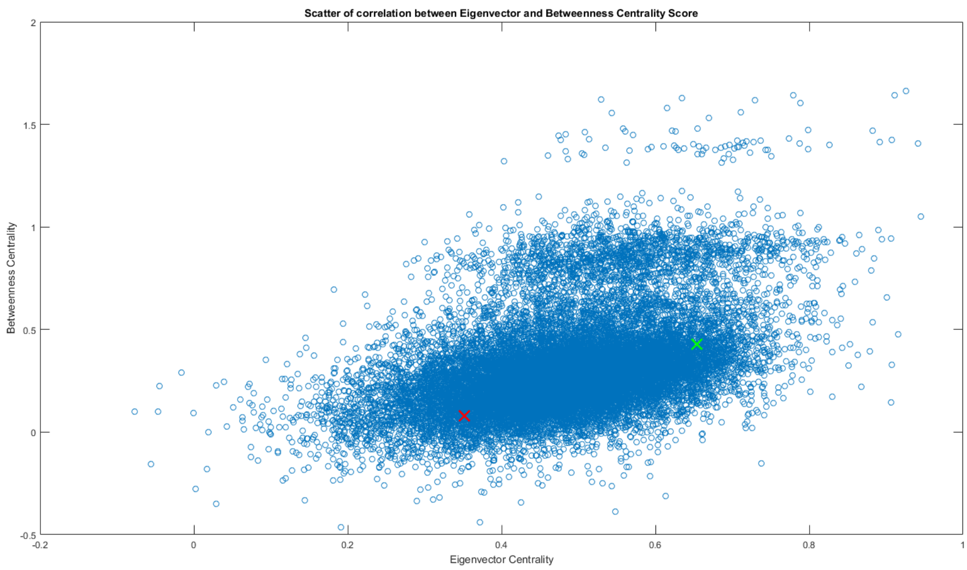


Figure 6.9: Scatter of correlation between Eigenvector and Betweenness centrality with a correlation coefficient of 0.4322, design A is plotted as a green cross and design B as a red cross

6.4. Possible improved design selection

Since there now is a possibility of giving a numeric value to the internal layout of these designs, an application of these scores deems necessary. As stated in chapter 2, there seem to be two applications of this scoring function. Giving a score to the architectural layout can be used to filter the designs according to their layout. Filtering can be done in two ways, erasing the worst or taking out the highest scoring designs. A high-pass filter will erase those designs with scores below a certain value, as shown in figure 6.10 with the red area. For the figure this area is set to a betweenness score of 0 and a eigenvector score of 0.5 Using this filter, only 10335 of 22271 will be kept in the database, about half of the total designs. This would make down-selection in a later stage easier, without having to worry about very poor layouts. Besides this, there should still be sufficient diversity in the data set in order to give the genetic algorithm of the packing approach enough space to find more local optima. Relaxing certain boundary conditions within the approach and applying this filter, might enlarge the diversity even more but still allow the methodology to find designs that full fill the requirements after filtering. It may therefore be good for set based design processes, allowing the diversity within the design set but deleting those of no interest within the selection process. This process would delete design B from the dataset, as can be seen in figure 6.10 with the placement of the red cross.

A second selection type can be done by using a high-pass filter. This allows only the best designs to pass. Setting this to 0.8 for eigenvector and 1.3 for betweenness centrality gives the green area in figure 6.10. This would leave only 10 designs for design selection out of this data set, greatly simplifying the process of design decision. Figure 6.10 shows the three of these 10 most promising designs. Apparent is the great number of positive connections, all at least 30, and the low number of negative connections, with a maximum of 3. These designs all score high for both centrality scores, which according to a high-pass filter would rate them as the best 3 designs.

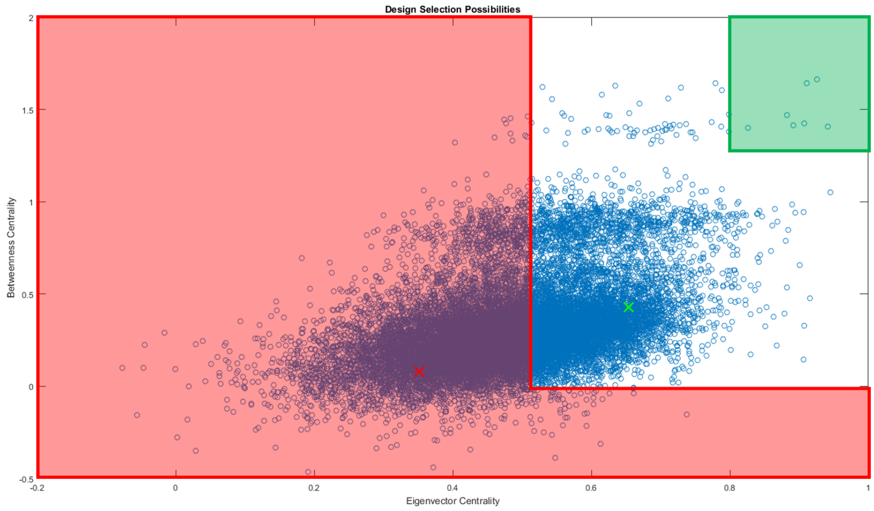


Figure 6.10: Possibilities of using these scores for design selection; filtering or deleting those with a score lower than a specific score (in red area) or selection of those with the highest scores (in green area). Design A is shown as a green cross and design B as a red cross.

Table 6.3 shows that there is some difference within the main parameters of these most promising designs . In current application of the packing methodology, it seems to focus primarily on those designs the smaller designs, since these are cheaper and have a higher packing density (DMO, personal communication 10 March 2017). In order to create a layout of sufficient quality for this part of the design process, the design needs to be scaled up or enlarged. Two of these designs however, have a higher building cost and are larger than the eventually picked design A by Droste (2016). These layouts might already be of sufficient quality and might be interesting to actually take into account when doing manual design evaluation. They would probably never be looked at with the current evaluation method, as building costs are too high compared to others.

Design	Best 1	Best 2	Best 3
Length [m]	139	150	148
Displacement [m^2]	8007	8612	8669
Cost [M€]	52.3	55.7	56.3
Number of nodes	72	73	73
Number of edges	129	127	129

Table 6.3: Main parameters of best and worse betweenness centrality scoring designs in figure 6.11

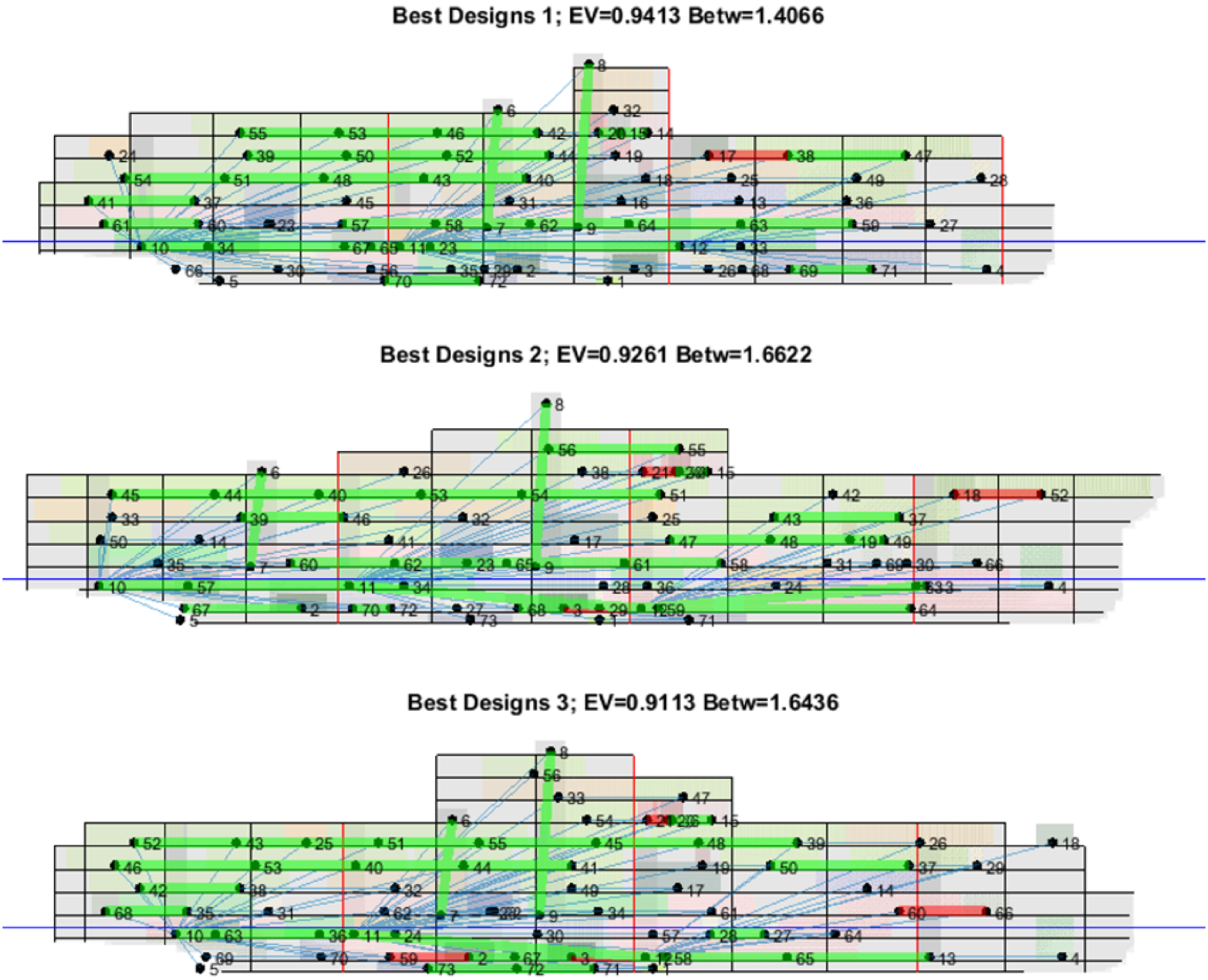


Figure 6.11: Best 3 designs when looking at EV and Betweenness centrality scores, from the green area of figure 6.10

7 Conclusions

The current TU Delft packing method by van Oers (2011) and IECEM by Duchateau (2016) have created a very intelligent methodology that is able to automatically create a design space of thousands of designs within hours of running time. The generation of designs is of a very high level, and design selection for further examination based on performance parameters is possible. However, there is a lot of information in the designs that is currently disregarded because it cannot be evaluated on a desired level.

This thesis is based on the question to create a method that is able to analyse these thousands of designs based on its architectural layout. Currently, the internal layout of the designs is somewhat disregarded. Being able to choose those designs that are of a higher level, or eliminating those that are very poor before design selection, will allow the designer to make a higher quality design selection for further examination. Analysing this problem posed the following research objective;

"Develop a post-processing method that is able to quantitatively compare arrangements generated by the packing approach, taking into account its qualitative properties."

Multiple research questions have been formed in chapter 2 to reach this objective. The previous chapters have described the background and formation of this problem and what work was performed as an attempt to full-fill this problem statement and bring possible solutions. This chapter should be able to answer the proposed research questions and conclude whether this objective has been reached or not.

Is network theory applicable as a way of describing the architectural relations between systems in the packing arrangement?

As shown in chapters 2 and 3, multiple earlier research by for example Gillespie (2012) and Rigterink et al. (2014), have shown that architectural relations within a ship general arrangement can be described by making use of network theory. A same network description, based on adjacency of systems within the arrangement, can be used to describe which systems or spaces within the arrangement are neighbouring each other. Setting this up in an adjacency matrix **A**, and adding some more rules and information to the matrix, the full architectural layout of the design can be caught with the simplified representation of the entire 3D design. Although earlier work found a different application of network theory in ship design, primarily the generation of layouts, using it as an analysis method seems to be promising.

Is conversion of packing arrangements into a detailed network possible?

As the data structure of the packing designs are set in the supplied data set, some analysis of the design structure is necessary. To convert the design into an adjacency network, an analysis of neighbouring systems or spaces on each deck is necessary. This is set into the earlier mentioned matrix **A**. Furthermore, systems are connected to their corresponding staircase within the vessel depending on their main vertical zone. This allows vertical transport of information through the network layout.

In order to properly analyse the layout, the distances from centre of gravity from each system is necessary. Therefore, a second matrix **W**, is introduced to set weight to the network. Using a Hadamard, or element-wise, product between networks **A** and **W**, matrix **B** originates. Plotting this network in the side-view of the vessel gives a network representation of the packing arrangements.

Can earlier captured rationale be used to analyse the architectural relations withing the network arrangements?

DeNucci (2012) introduced a method to capture rationale, which has been used in this thesis. This rationale is based on an MCMV design, but analysis of this rationale set gives a set of design rules applicable to general ship design, or in this case the small cruise vessel.

The method introduced in chapter 4 introduces a way of analysing edges in the network by using a set of design rules based on rationale captured by DeNucci at DMO. Stating that an edge is positive, neutral or negative gives it a score of 1, 0 or -1 respectively. Thus, this method allows rating the architectural relations based on earlier captured rationale.

Can these qualitative properties be compressed to a single score for an arrangement?

Now there is a network and a way of analysing this network. Combining these two stages, an arrangement can be analysed based on its qualitative properties considering architectural layout. Is compression of these qualitative properties to a single, qualitative and comparable score possible?

A way of rating the importance of an architectural relationship is necessary in order to give a rated score to the network. Centrality measures are a way of ranking nodes within in a network based on its mathematical properties. Using these measures, the importance or addition of this node to the entire network can be given a score. Normalising these scores over the network allows direct comparison of these scores. Combining these centrality measures with the method to describe the qualitative properties of the network, a single quantitative score can be given to each network, that because of the normalisation can be directly compared to the score of other networks.

This thesis compares two different centrality measures applied with the method; eigenvector and betweenness centrality. The origin of these measures and algorithms differ quite substantially. Eigenvector centrality describes the influence or importance of the node within the network. Connectivity to nodes that get a high score is evaluated as important and thus increases the score of that specific node. Connectivity to lower scoring nodes contribute less to the score of the first node. Therefore, important spaces in the arrangement such as a bridge or a generator room should get a high eigenvector centrality score. These spaces are commonly neighbouring or close to other important spaces in the arrangement.

Betweenness centrality measures the extent to which a node lies on the shortest paths between all other nodes. If one sees edges as a way of allowing information flow through the network, nodes that get a high betweenness centrality will have a lot of information flowing through that node and is therefore good in the analysis of flow through a system. Staircases allow vertical travel of information through the network and are on a high number of shortest paths within the arrangement. Therefore, these will get a high betweenness centrality. The same occurs for spaces that are in the centre of the vessel, possible central hall or accommodation systems.

The essence of the arrangement analysis is giving a quantitative score to the architectural layout. Since eigenvector centrality rates the influence of a node to the network, and betweenness centrality focuses on flow analysis, eigenvector centrality seems to be more applicable as a measure for arrangement analysis based on DeNucci design rationale. Analysis based on betweenness centrality is very interesting when assessing flow patterns of designs. These could be evacuation routes, for example based on Markov Decision Processes, or information or fuel flow between systems within the design. Layering of networks, which is possible by multiplex networking as demonstrated by Rigterink (2014), would allow to layer different flows of information through networks based on the same nodes and systems. Combinations of betweenness metrics based on these types of networks would allow a lot of new information about distributed systems within the general arrangement.

Conclusions on Demonstration

Chapters 5 and 6 give a demonstration of the applicability of the method. Chapter 5 shows how the method analyses a single design and how this analysis is reflected in the score of a single design. Furthermore, it demonstrates the sensitivity of some of the design rules applied and how the total score is build up. Because of the number of accommodation space nodes, a big portion of the score is based on design rules considering these accommodation spaces. Furthermore, betweenness centrality can heavily penalise edges where information flows through, although this information is not necessarily of importance of that edge itself. This confirms the conclusion that betweenness centrality might be less applicable in use of arrangement analysis using DeNucci's rationale database. Flow driven layout analysis, such as for example evacuation plans, might be better analysed using betweenness centrality.

Chapter 6 demonstrates how an entire data set of over 20,000 designs can be analysed by the method. It shows that the method can indeed be used to an entire data set allowing selection on the quality of the provided arrangements. There appears to be a correlation between eigenvector and betweenness centrality scores, but selection according to the different centrality scores differs a little bit. Eigenvector centrality depends more on the number of good or bad connections, whereas betweenness centrality focuses more on the position of these good or bad connections. Depending on the preference of the naval architect, or where he is interested in, should help the selection of a centrality method. The IECEM does however already allow position preference of systems and distances, which might make the betweenness centrality a little obsolete. Combination of the two centralities however, should focus on those designs that are of most interest to the designer. There is an amount of correlation observed between the two centrality calculation, making this combination of centralities stronger.

Using the method on the entire a data-set allows the designer to perform a design selection, now taking into account the qualitative properties of the design without manually analysing those arrangements that he seems interesting for further evaluation. It can also be used to filter those arrangements that are of a poor quality out of the data set. These arrangements are still necessary within this set, to allow diversity within the design space created by the approach and allowing the genetic algorithm to improve the quality of the design space.

8 Discussion and Possible Future Work

The method has introduced a beginning in the possibility of analysing 3D packing arrangements by using network theory and tends to improve the design selection. It does however raise questions how this can be further applied and investigated.

The metric applied creates a measure of effectiveness. It tends to capture the entire effectiveness or performance of the general arrangement into a single score. This allows the possibility of direct comparison of a large number of designs. It is very simple to compare the scores for the entire data set and compare what designs have a better performance according to the metric. It does however not relate back to why the designs score differently. The naval architect still has to manually look at the designs to see the differences in the designs and manually evaluate for what objectives the design scores better. Multiple different type of sums might create a similar measure of effectiveness, although the performance for different design objectives would be different. Think about $(2+2+2) = (3+3+0) = (6+0+0)$ etc. These all add up to the same sum or effectiveness, but the performance of the individual design objectives is completely different. For these examples, all scores are positive, for negative digits the difference becomes even bigger. Does one allow a design to score bad on a single design objective, as long as it scores really high other objectives? This does apply to single edges as well. An edge might be rated positive for one objective and negative for another, leading to a neutral edge within this system. But how does one really want to evaluate this edge? The current metric does not differentiate between these different objectives since it compresses the performance into a single score. This means that for following steps in design selection, the designer still needs to evaluate a lot by hand in order to learn a lot from the data set.

A solution for this would be to split the design rules into different design objectives. Calculating the performance in different design objectives and storing it in a vector or matrix formation, instead of in a single score or scalar, allows the designer to relate back to different design objectives. It can scan the data set for those designs that score best at for example sea-keeping, economics or redundancy. The designer can learn what design decisions lead to higher scores within the different design objectives and use this information in manual generation of the eventual general arrangement in later design stages. It does however need more time during the analysis of the data set, as well in computing as in analysis. As this creates information that can be used in later design stages the extra work might be worth.

One of the questions is how to actually apply this method in the packing method. An application could be found in using it as an input into a steering run for the Packing Algorithm. Using the centrality score for the network as a objective function within the genetic algorithm besides the packing density, would allow the algorithm to look for those arrangements that get a higher performance score. Using multiple criteria decision analysis on multiple objective functions should probably lead to more diversity in the design data set with multiple local optima.

It would be interesting to use clustering algorithms applied by Jaspers and Kana (2017) to the set of network. This could lead to distinguish clusters, or families, of general arrangements within the data set. This might lead to identify those designs that are very similar, but are still evaluated as different by current design selection tools. These clustering algorithms could also be used to identify the clusters in the betweenness centrality score, as shown in figure 6.6. Using a combination of networks, scoring and clustering might lead to a leap of understanding of the differences and similarities of the designs within the data set and find true families of layouts. Applying different objective scores as well would allow this as well. It might be interesting to use more big data analysis tools on these data sets, although one must not forget the "why" in applying these methods to design selection. One can manipulate clustering algorithms (or other big data analysis) to find those clusters that one is looking for. The architect should therefore be careful how to interpret and use this information, but it can definitely be used to gain more information from the design data set.

An improvement to the scoring algorithm would be the use of a continuous score instead of the trinomial x_i. Edges are now given a score of $x_i \in -1, 0$ or 1 depending on its performance. Using a continuous score, for example between -1 and 1, would allow the designer to manually give a weight to that specific edge or design rule. The scores, especially based on eigenvector centrality, are now highly dependent on the number of edges that are subjected to that design rule. Design rules covering a lot of edges, for example those based on accommodation spaces, influence the resulting score a lot. Using a continuous score would also allow the use of fuzzy logic. In contrary to Boolean logic, where something is either good or bad, fuzzy logic can identify something as being somewhat good or bad. Using fuzzy logic functions an identification of these fuzzy rules can be de-fuzzified into defined output functions. A well-known example is the difference between cold, warm and hot water.

The metric applied to the networks can also be used a search algorithm. Instead of using it as a measure of effectiveness of the arrangement, it can be used to find (or filter) those designs that have or lack specific connections one is looking for. For example, erase those designs that have no connection between passenger accommodations and generator rooms. With IECEM, one would have to evaluate all passenger accommodations and generator rooms, with the metric one would only have to scan all edge lists for those edges between these two systems.

The developed methodology allows the designer to start looking at physical relations within the 3D packing arrangements. Further research and application to different data sets would be interesting to see where and how it can truly be applied within the packing methodology and IECEM.

A

Appendix A - COMPIT paper

Appendix A contains a paper, published at the 16th International Conference on Computer Applications and Information Technology in the Maritime Industries (COMPIT). It was written by the same author as this MSc. thesis, in collaboration with Koen Droste, who also supplied the cruise ship data set in his MSc. thesis, Droste (2016), and Austin A. Kana, assistant professor Ship Design at Delft University of Technology and daily supervisor of this project. It was published May 2017, Roth et al. (2017) Parts of this paper have been used and/or adapted into this thesis.

Analysis of General Arrangements Created by the TU Delft Packing Approach

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Abstract

This paper applies network theory to understand the physical relationships in the general arrangements generated by TU Delft packing approach. The generated arrangements are converted into weighted graph networks. The authors have developed a new scoring metric using this network and have applied this to quantitatively assess qualitative properties of the different arrangements, enabling direct comparison between concept designs. Finding and understanding these specific physical properties of the arrangements should lead to improved design space exploration of layout features of the designs generated by the TU Delft packing approach.

1. Introduction

During the conceptual ship design phase, problems concerning the overall composition of the vessel can be directly related to the arrangement of systems, compartments and components. Historically, these arrangements have been compiled into detailed drawings of the vessels where the naval architect has decided on the arrangement and connections between these compartments manually. These decisions have been traditionally built upon design rules and the experience of the designer. Furthermore, the designer can usually fall back to comparison vessels to have a decent understanding of the architectural problems and to have a starting point for the current design. A problem occurs when new vessel classes are being designed or in situations where a lack of experience is encountered, *Andrews (1998).*

Currently, projects are being undertaken for general arrangement optimization in an earlier stage of the design process, such as the packing approach, *Van Oers (2011)* and *Duchateau (2016),* the Intelligent Ship Arrangement platform, *Parsons et al. (2008),* and the Design Building Block approach, *Andrews and Dicks (1997).* These projects all make the use of computing power to generate a concept exploration space. By creating numerous design concepts, a solution space is created where the designer is able to explore trade-offs and eventually select multiple concepts for further examination. This paper is focusing specifically on the layouts generated by packing.

In the packing approach, the actual internal layout of the generated designs is mostly ignored, because the overall quality of the generated arrangement has been considered to be fairly poor. Manual redesign of the most promising design is deemed necessary to create a complete functional layout in later stages of design. This paper seeks to create more insight and understanding into these generated arrangements, facilitating the opportunity to transfer the generated designs into later design phases. To do this, an assessment of physical locations and relationships as well as fundamental interactions between elements of systems in the designs is necessary. One might be able to improve the arrangements out of the packing algorithm by increasing the number of constraints in the model, but this will greatly limit the number of feasible designs and so the explored design space. By allowing the model to have more freedom, the design space should lead to more diversity in the set of designs. Developing a method that would be able to directly compare the generated arrangements without ove rconstraining and the model would be beneficial.

1.1 Introduction to the TU Delft Packing approach

The TU Delft packing approach is a method which uses a parametric model called the Ship Synthesis Model (SSM) composed of 'system objects' describing the spaces and systems of the design. A packing algorithm generates ship designs based on this SSM and calculates their performances. These performances such as speed, weight or costs can be used to quantify how good a design is in terms of those specific metrics. These performances are fed to a genetic search algorithm which uses them to explore the design and performance space belonging to the SSM. Specific details of the SSM can be found in *van Oers (2011)*. This highly automated search process enables fast and extensive exploration of the design space in an early design stage, *Wagner (2009), Wagner et al. (2010), Zandstra (2014). Duchateau (2016)* extended the SSM method to the Interactive Evolutionary Concept Exploration Method (IECEM) which allowed for a more interactive exploration of the design space by including the designer in a feedback loop to the search process. Each of the designs exists of a set of performance metrics, dimensions and a description of the layout of the design. Until recently the results were mainly used to find the approximate dimensions of a vessel and to study the feasibility of a set of design requirements. This work will present a method that aims to understand the layout features of designs.

The packing design is based on a parametric 2.5D ship-design, *Van Oers and Hopman (2012).* The 2.5D design describes a set of multiple 2D configurations which include a centreline, a port and a starboard slice. Objects in the vessels are placed mostly in the side-view, or x-z plane, of the design. The 2.5D approach introduces a variable width for objects and an available width for every position in the side-view of the design. This enables the packing-approach to fill a 2.5D space, instead of the necessity to describe the entire 3D space. This 2.5D approach is introduced to speed up the packing algorithm, where improvements in speed of a factor up to seven have been attainable, *Van Oers and Hopman (2012).* This enables the packing algorithm to explore a wider design space by using a simpler model.

This study uses a design set generated for a small exploration cruise ship. The design set originates from *Droste (2016)*. As is discussed in detail in the following case study, the current set of designs showed several flaws in the arrangement and raised the question of whether it would be possible to improve our understanding of the relations between the systems and spaces within the packing approach.

1.2 Analysis of General Arrangements and Rationale Capturing

One of the biggest problems in generating general arrangements, is the analysis of the generated arrangement, *Hope (1981)*. When analysing multiple arrangements by hand, one might find a number of mistakes or aberrations in the physical allocation in the arrangement that are either unhandy or non-compliant to design prospects. For an experienced designer, it should be quite easy to disclose these issues in the design by hand; however, integrating this into computer interactive methods might be quite hard. Furthermore, analysing thousands of designs as generated by the packing approach is also difficult. There may several conflicting interests within the design specifications that algorithms might not be able to analyse in a coherent way. An automated way of general arrangement analysis would need a scoring metric for the algorithm to evaluate the arrangement and to allow direct comparison. The use of a comparative score improves the solutions in a spatial or topological model, as demonstrated by *Gillespie et al. (2013).* They showed that analysis of a graph model of the design by partitioning and spatial community preferences can give guidance to the arrangement process of the allocation algorithms. To create a comparative score, quantitative assessment of qualitative properties of the designs is necessary.

In order to do this quantitative assessment, one needs to know what qualitative properties are desired in the design. Deciding what designs are either “good” or “bad” depends on personal preference and will most certainly lead to different design decisions between different designers. Since there is no singular “wrong” or “right” solution, but more commonly a “better” or “worse” approach to the problem, it is very hard to describe the rationale behind certain decisions. *DeNucci (2012)* introduced a method of capturing design rationale for complex ship general arrangement design. His method allows multiple naval architects to evaluate both desirable and undesirable features presented in one or multiple designs, accompanied by the underlying rationale. For instance, a generator room should not be placed adjacent to accommodation space to minimise noise levels in accommodation rooms. Using DeNucci’s method and rationale database as quality metrics, one can start to define what is the motivation between certain design decisions and start to analyse which of these decisions are better or worse for the total design.

To analyse these general arrangement rationales for large sets of packing generated ship designs, network modelling is used Network modelling is a mathematical representation of reality, using a collection of points joined by sets of lines, *Newman (2010)*. They are commonly applied to represent social or economic interactions. Since many different forms of information can be stored in these points and links, networks are applicable to many other fields of study including architecture and engineering. Since networks can be a simplified representation of complex systems, it is very suitable for application to the design of ship arrangements. This has been demonstrated by research at the University of Michigan, identifying drivers of arrangements, *Gillespie and Singer (2013),* or the generation of applicable general arrangements for complex vessels, *Gillespie (2012), Gillespie et al. (2013).* Furthermore, *Rigterink et al. (2014)* used network theory to model and analyse disparate ship design information, including general arrangements. This paper will present a similar approach to arrangement representation in network form, and will propose a new scoring metric to analyse the generated networks.

2. Method

The method proposed in this paper will transform the designs as generated by the TU Delft packing approach into networks and apply a new scoring metric. This scoring metric will include DeNucci's rationale capturing method and uses this captured rationale to analyse the generated network arrangements.

2.1 Network science

A network or graph is a collection of points, called nodes, which are connected by lines, called edges. It is a simplified representation of a (complex) system, where only connectivity patterns are represented. Nodes within the network can represent any sort of object or entity, with edges showing connections or relations between these objects. A network can be weighted or unweighted. In an unweighted network, edges only show that there is a connection between nodes, whereas in a weighted network edges are given a value, which can add characteristics such as length or capacity to that certain edge, *Newman (2010).*

This paper represents the layout of the design using an adjacency matrix, similar to *Gillespie (2012)*. For a simple unweighted network, the adjacency matrix **A** is described by the elements as seen in Eq.1.

$$\boldsymbol{A}_{ij} = \begin{cases} 1 \text{ if there is an edge between nodes i and j,} \\ 0 \text{ otherwise} \end{cases} \quad \text{(Eq. 1)}$$

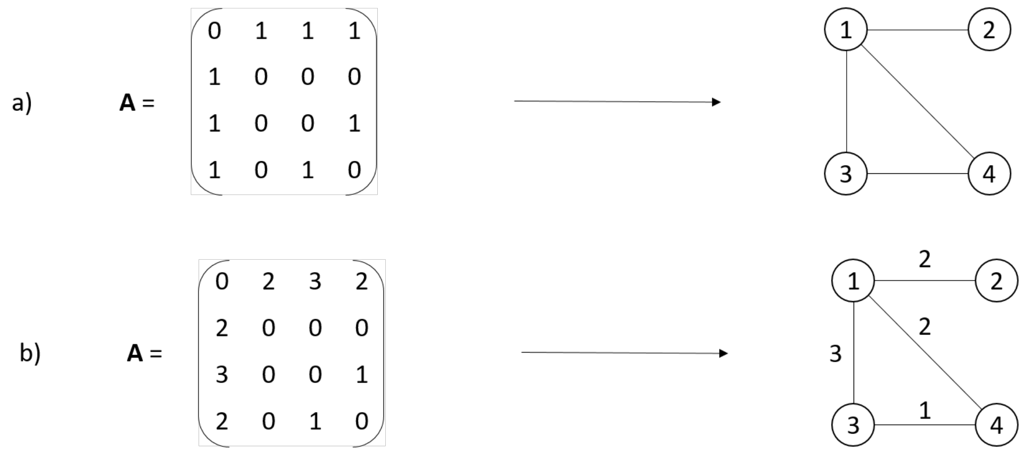

Fig.1: Translation from adjacency matrix **A** to graph network for a) unweighted and b) weighted networks

Adjacency matrices as defined in equation 1 are symmetric, since if there is an edge between i and j, there is also an edge between j and i. Evaluating the adjacency matrix, node and edge lists are established displaying all information of the nodes and edges of the generated network. More information on these nodes and edges can be added into the node and edge list, including weights and node properties. Fig.1 displays the differences in adjacency matrices and corresponding graphs for bot unweighted and weighted networks.

2.2 Generation and analysis of network arrangements

An analysis of spatial relationships is done to analyse which of the arrangements are more promising. Since the networks representing the general arrangements need to represent adjacencies and distances within the arrangement, weighted graph networks are used. Furthermore, the diagonal of the adjacency matrix will be zero, since no systems can be adjacent to themselves.

Nodes represent the "system objects" or individual spaces as pre-defined into the SSM of the packing approach. Whenever two system objects are on the same deck and neighbouring, they are considered to be adjacent. In matrix **A,** a 1 will be added for the objects that are adjacent, introducing an edge into the network. The node numbers, as presented in Fig.2, represent individual spaces.

A second adjacency matrix, **W**, is introduced to calculate the weight of the edges, defining the distance between spaces, of adjacency matrix **A**. Matrix **W** displays a connected weighted network, with values for the Manhattan distances between all objects. The Manhattan distance is the sum of the horizontal and vertical paths between two nodes and is therefore slightly larger than the direct Euclidian, distance. A Hadamard product, or element-wise multiplication, is taken between matrices **A** and **W**, creating a new weighted adjacency matrix **B** as seen in Eq.2. This matrix displays which systems within the design are adjacent and includes the distances between all connected systems. In order to allow transport of information through different decks, systems are connected to their corresponding staircase as they are defined by the International Maritime Organisation, *IMO (2000),* and *Droste (2016)*. This explains why for example node 5 is not connected in network **A**, but is connected in network **B** in Fig.2.

$$\boldsymbol{B} = \boldsymbol{A} \circ \boldsymbol{W}, or\ \boldsymbol{B_{ij}} = \boldsymbol{A_{ij}} * \boldsymbol{W_{ij}} \qquad \text{(Eq. 2)}$$

Fig.2 gives a visual representation of the generation of these networks.

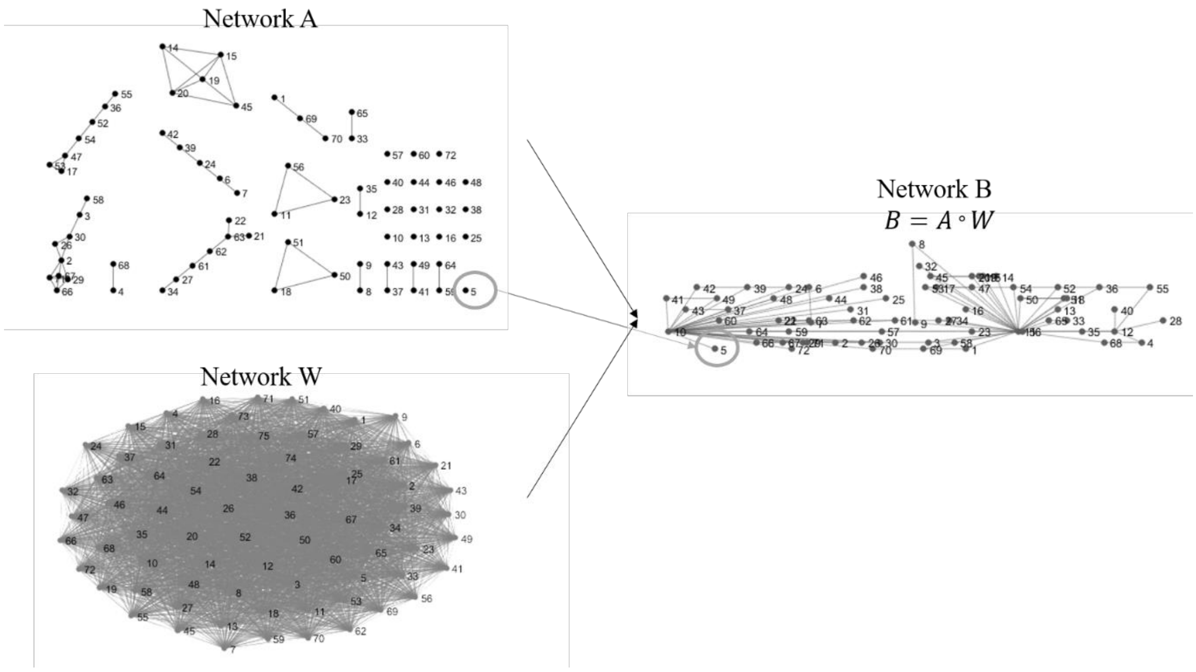

Fig.2: Network formation of packing design: network **A** displaying adjacent systems, network **W** a weighted connected network specifying all distances of systems and network **B** as the resulting network

2.3 Centrality measures

The method needs a way of ranking the adjacencies since the nodes in the network are not of the same relevance to the total arrangement. To create a ranking factor to each node or edge, this paper ranks the nodes by using centrality measures. Centrality can be used to give an indication of the importance or influence, and thus rank, of the nodes in the network. This can be done through multiple algorithms, which differ in complexity and objectives and might give slightly different results. Different centrality methods rate the nodes in different ways, where the "importance" of the nodes is different. "Importance" can be interpreted in many different fashions, similar to the trade-off of objectives in design decisions. For example, centrality based on flow of information will give a high importance to staircases where a lot of information spreads through the network. Two different centrality measures, eigenvector and betweenness centrality, are compared in this paper. More details on these centralities and corresponding algorithms can be found in *Newman (2010).*

The first centrality used is the eigenvector centrality. The eigenvector centrality is commonly used to describe the influence of a single node into the entire network. It is based on the fact that connections to other nodes with a high score are more valuable than connections to nodes with a lower score. For example, a generator room will be connected to many other important systems such as a propulsion room and fuel tanks. Therefore, a node connected to multiple nodes with a high score, will have a very high score itself. To calculate the eigenvector centrality, one needs to find the principal eigenvector $\boldsymbol{x}$ associated with largest eigenvalue λ as defined in Eq.3. Furthermore, the eigenvector is normalised to create an absolute score that can be directly compared between multiple networks. Each element in vector **x** corresponds to one of the nodes in the network representing its relative centrality score.

$$\boldsymbol{Bx} = \lambda \boldsymbol{x} \qquad \text{(Eq. 3)}$$

The second centrality measure used is the betweenness centrality. This centrality measures the extent of which a node lies on paths between other nodes. It is commonly used to analyse the flow of information through a network, since it can easily identify the influence on control of information between other nodes. A high value means that the node will have a high influence on the total flow of information through the network model. This flow can be anything, which in ship design can be used to describe flow in people or goods through the arrangement but also water during flooding. Values for each node can be calculated by Eq.4. For every node i, a centrality score x_i is introduced. n_{st}^i is 1 if the node is on the geodesic path between all nodes s and t and 0 if node i is not on this path or the path does not exist. When this is summed over all nodes s and t, one will get a number of shortest paths node i lies on. After dividing this by the total number of geodesic paths between nodes **s** and **t**, g_{st}, the score is normalized allowing direct comparison between networks.

$$\boldsymbol{x_i} = \sum_{st} \frac{n_{st}^i}{g_{st}} \qquad \text{(Eq. 4)}$$

Fig.3 displays a simple unweighted network with eigenvector and betweenness centrality values for each node in Table I.

Table 1 – Centrality scores corresponding to network in figure 4

Node	Eigenvector Centrality	Betweenness Centrality
1	0.1580	0.3462
2	0.2403	0.3077
3	0.1917	0
4	0.1917	0
5	0.1157	0.3472
6	0.0513	0
7	0.0513	0

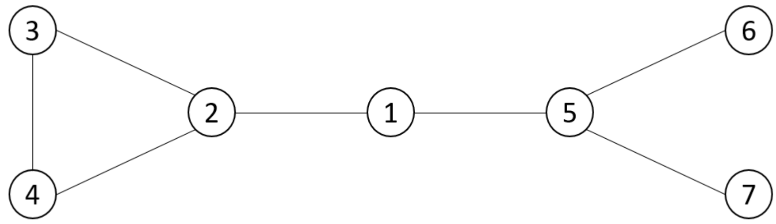

Fig.3: Simple unweighted network

This illustrates which nodes are emphasized by each centrality calculation. What can be seen is the exclusion of nodes 3, 4, 6 and 7 in the betweenness centrality method, because these nodes are on no shortest paths between other nodes. The eigenvector centrality gives a more even distribution of rank through the nodes. For the analysis of general arrangements, this means that there will be exclusion of certain spaces when using betweenness centrality, but will give peak scores on nodes in the system where a lot of information will flow through. Eigenvector centrality will give a more evenly spread out score through the network.

2.4 Capturing Design Rationale

The structure of the design rationale as captured by *DeNucci (2012)* is directly identifiable in the network formation of the arrangements. DeNucci's rationale capturing method developed a database of design rules that describes positive and negative aspects of physical relations or locations of certain systems. Rationale used to analyse the networks is taken from the database captured by DeNucci of seven naval architects at the Dutch Defence Material Organisation (DMO) in 2010. By analysing each edge of the system using these rationale rules, and evaluating the contribution of that connection, a complete qualitative analysis of the arrangement network is possible. Although the rationale lines are based on naval ship design, much of the rationale is applicable to general (complex) ship design. Rationale based solely on naval ship design has been removed from the data set to be able to setup a set of design rules that can be used for general ship design. The deleted design rules involve placement of weapon or radars systems. The proposed method introduces a way of analysing the strong and weak connections in the network.

2.5 Scoring metric

To rate the designs using the proposed method, a manual analysis of the edge list is done by using equation 5. Considering all established general arrangement rules, each edge in the list gets a score of x_i = [-1, 0 or 1] depending on whether it is disadvantageous, neutral or beneficial to the arrangement. The score of the edge is multiplied with the centrality scores of the connected nodes, z_{i1} and z_{i2}. This centrality score can be either the eigenvector or betweenness depending on the analysis. All edge scores are summed for all edges *i* to get a single score for the entire network. Thus, this metric accounts for all rationale and all spaces in the arrangement in a new quantifiable way. This is visually represented in Fig.4, with Eq.5 as the mathematical representation of the scoring method.

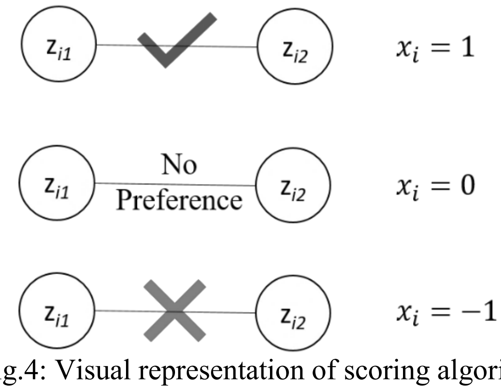

Fig.4: Visual representation of scoring algorithm

$Score = \sum_i \left(x_i * (z_{i1} + z_{i2}) \right)$, with $x = [-1,0,1]$ for all edges i in network (Eq. 5)
z = centrality score corresponding to nodes *i1* and *i2*

3. Case Study

The case study explores the utility of this method and metric on the design of a small cruise vessel.

3.1 Identification of issues in chosen design

The cruise ship arrangements showed some flaws after closer inspection. Two examples of issues in the chosen design by *Droste (2016)* are the placements of the emergency generator and the hospital rooms. As shown in figure 5, the hospital rooms are placed adjacent on deck 8 and the generator room is placed within passenger accommodation on deck 7. Hospital rooms should be placed separated from each other to fulfil redundancy and survivability requirements, *DeNucci (2012).* For habitability objectives, it is not desirable to have the emergency generator placed within accommodation space, especially in cruise ship passenger accommodation. The following section will look into whether these cases can be identified in the network representation of the chosen design.

For redundancy goals, hospital rooms should not be placed in the same main vertical zone. Nodes representing the hospital rooms were identified in the node list to see whether they are placed in the same main vertical zone. After taking a closer look at the edge list, the edge between the two nodes representing hospital rooms exists, meaning that the hospital rooms are adjacent. Therefore, issues concerning direct adjacency or separation in main vertical zones can be identified in the network representation.

Analysing the placement of the emergency generator can be done in a similar way. Whereas an emergency generator should rather not be connected to passenger accommodation, or crew accommodation for that matter, edges between these nodes can be identified in the edge list and considered as bad connections. Fig.5 displays the network of 72 nodes plotted within the side view of the vessel.

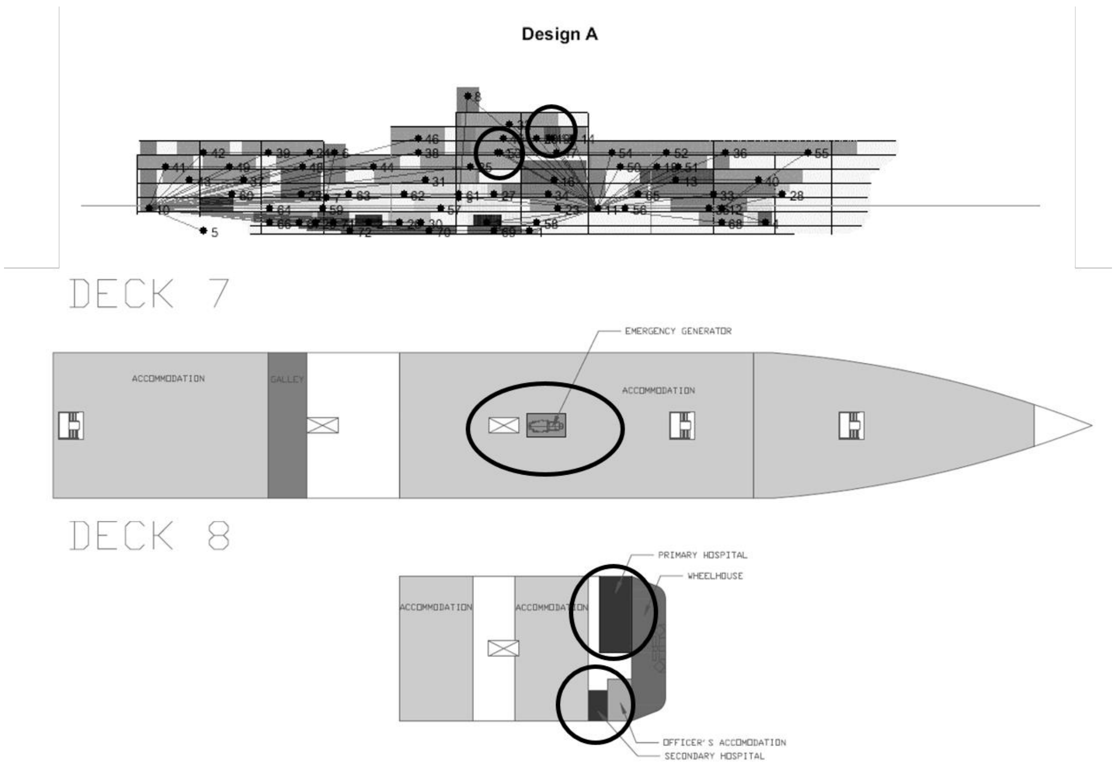

Fig.5: Network representation and deck views of design A, displaying the identified issues of the general arrangement

3.2 Application of scoring metric

However, this previous analysis requires manual inspection of the network and design to identify these problems. The proposed scoring method aims to give a quantifiable score to all arrangement rationale of the database. To test the method, two arrangements out of the cruise ship designs are analysed by the proposed metric. The first is the design as discussed in Fig.5, referred to as design A, the second is taken from the design set, where the issues mentioned earlier considering the emergency generator and hospital rooms are not present, design B. Main parameters of the two designs are given in Table II and a representation of both designs and networks in Fig.6. As is shown, both primary dimensions and internal layouts of both arrangements vary greatly between these two designs. Manual inspection of thousands of varying designs would therefore be intractable. The difference in number of nodes is due to system variations within the designs. Using the method, considering all rationale and systems, gives the scores for the analysed designs as presented in Table III

Table II: Main parameters of compared designs

Design	A	B
Length [m]	135	150
Displacement [m^2]	6907	10008
Cost [M€]	44.1	60.0
Number of nodes	72	74
Number of edges	122	125

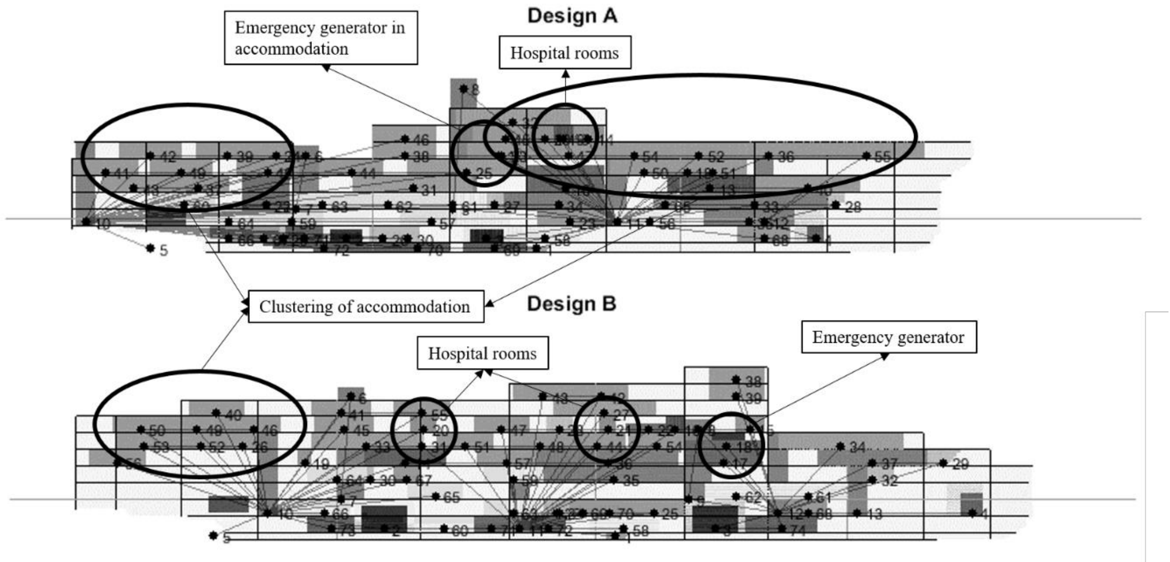

Fig. 6: Designs A and B with different placements of hospital rooms, emergency generator and both showing clustering of passenger accommodation

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Table III: Scores for the designs

Design	Eigenvector Centrality	Betweenness Centrality
A	0.4606	0.5693
B	0.4952	0.3416

One sees that for the different centrality metrics, the highest scoring design differs, identifying that there are differences in the type of analysis. Manually looking at the scores for each node, betweenness centrality gives a higher value for stairs than eigenvector centrality, since these are on a lot of paths because of the nature of the system type. However, there are few design rationales regarding the placement of the staircases in the database. Evaluation of the edges connected to staircases will mostly get no preference. This means that even though these nodes get a high centrality rank, they do not necessarily get a high centrality score.

Apparent is that passenger accommodation contributes a lot to the high score for design A. In the case of betweenness centrality, analysis of the node list shows that accommodation accounts for 0.29 of the total score. In design B, this value is only 0.11. This is likely due to accommodation systems being more clustered in design A, as seen in Fig.6. A same trend can be found in crew accommodation, although the difference is slightly smaller. This can be explained by the fact that there is less crew accommodation than passenger accommodation present in the arrangements. Furthermore, design B has two accommodation systems that are highly penalized by the betweenness centrality because of a connection with a technical/auxiliary systems room. Looking at eigenvector centrality, the score for accommodation placement is 0.16 for both designs. An overview of the breakdown of these scores can be found in Table IV.

Other areas where design A scores better, especially on betweenness centrality, is the placement of the generator rooms. As generator rooms are of high importance to the vessel, there are quite some rationale rules based on the placement of generator rooms. Connections to the generator room are often regarded as positive or negative instead of neutral and are therefore highly represented in the score.

The poor placement of the emergency generator room in design A does not get penalized by betweenness centrality since it is not on any shortest paths, due to the transport through the accommodation surrounding the generator. It is therefore not visible in the betweenness centrality score. It is however penalized in the eigenvector centrality score, accounting for a subtraction of 0.01. This is rather small when comparing to accommodation scores, which lies in the fact that it only involves one node instead of twenty nodes in the case of passenger accommodation.

Because betweenness centrality can give a value of 0 for nodes on no shortest paths, the number of evaluated nodes decreases. For design A, 30 nodes get a betweenness centrality of 0, for design B this number is 38. This is about half of the total number of nodes, which is similar to the simple network in Fig.3. Since these are nodes that are on the ends of paths, these are primarily propulsion rooms and bridge or entertainment systems that are located on the ends of the vessel and are thus not reflected in the betweenness centrality score.

Stating that design A is "better" than design B, depends on the designer's view. Design B better represents designer's overall rationale as it pertains to the layout of the general arrangements, as is shown by its eigenvector centrality score. However, if a specific designer is more interested in personnel flow through staircases, design A would be preferred, according to betweenness centrality score. By using this metric, one is now able to give a score to these properties of the general arrangements.

4. Discussion

The first question to be asked is whether quantitative assessment of qualitative properties of the arrangement is possible. The answer to this is yes, using network analysis it is possible to give a score to a general arrangement generated by the packing approach. In order to do this, general arrangement design rationale has been applied, which can be captured in methods as described by *DeNucci (2012).* This is an improvement in the current design decision process of the IECEM, as it now includes analysis of interior design arrangement of the vessel. However, using a single score for the total analysis of the design enables direct comparison, but makes traceability of high or low scores in different objectives difficult without the use of sensitivity studies.

The second question is which of the compared centrality measures would be more promising. Comparing eigenvector and betweenness centrality measures, eigenvector seems to be more applicable for this type of arrangement analysis. This originates from the fact that it is commonly used as a normalized rank and takes all nodes into account in a more similar value in comparison to the betweenness centrality analysis. The betweenness centrality excludes nodes that are on no paths and easily overrates certain nodes in the system that carry a lot of information, such as staircases. Furthermore, the analysis is completely based on the user's (in this case the authors') interpretation of the rationale database and implementation of the design rules. Overrating of nodes by betweenness centrality does not seem to be a big problem, since nodes as staircases do not have a lot of beneficial edges within the design rationale. It does however give a bigger penalty on poorly placed accommodation due to the normalization of the betweenness centrality score. Betweenness centrality analysis is applicable in other types of analysis, such as flow analysis in evacuation cases.

What makes concept design complicated, especially applied to complex ship design, is the fact that it cannot directly be validated by existing ship design. Analysis is done in a preliminary ship design phase, where there are still a lot of unknowns and uncertainties in the design and a lot of design decisions are still to be taken. The new method allows the use of captured rationale and shows how certain decisions score in the design trade-off.

5. Conclusion

The authors have developed a scoring metric, that is able to quantitatively identify qualitative properties of designs generated by TU Delft packing approach or IECEM. By converting the designs into weighted networks, a new representation of the packing generated designs is acquired. Using rationale captured by DeNucci, edges in these networks are analysed and identified based on their influence on the arrangement. This gives an overall score of the general arrangement of the packed design allowing the designer to make decisions not merely on costs or primary parameters, but also take the interior design of the vessel into account and allow direct comparison.

6. Recommendation for future work

The method proposes a beginning in the semi-automated analysis of the arrangements of packing generated designs. Future work includes a higher level of understanding of the results of the scoring metric. Understanding differences in scores between different networks should give more insight in how this score can be used, for example as a filtering measure for lower quality arrangements. By filtering, the designer would be able to improve awareness of the quality of the arrangement during design decisions. The networks could be generated in different ways, implementing directed networks or layered multiplex networking. It will be interesting to see if the method is also applicable to different datasets of arrangements generated by the packing approach or other concept exploration methods. Furthermore, the networks could be used together with a search tool algorithm as a filter to look for those designs that either include or lack certain edges.

The biggest next step is the application of this method to an entire dataset. In order to do so, the design rules need to be incorporated into the programming of the network generation. Being applied to the entire dataset, one can use it as an extra objective function for Pareto optimization, or even as a performance input in the genetic search algorithm in the packing approach. Furthermore, it can be used to assess the quality of the layout and filter the dataset of poor quality arrangements.

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B

Appendix B - Example of a rated edge list and corresponding node list

The following appendix will give an overview of some of the used design rules and how this shows in a rated edge and node list. Table B.1 gives some of these rules as an overview how they are built up. The biggest difference with these rules and the DeNucci database is that these rules are always comparing two system types. Furthermore, the DeNucci database includes rationale behind these decisions that can not be stored within the single score metric. What can be noticed within the rules is that some rules apply to multiple system types, such as all accommodation, where others only apply to certain system types, such as cruise officers accommodation. For some rules, the order of the rules is of importance as well. For example, clustering of same system types is good, except for certain system types such as generator rooms. In those cases, the score needs to be changed with the new score.

Design Rules

Design Rule	Score
System Type A = System Type B	$x_i = 1$
System Type A = Accommodation and System Type B = Generator room	$x_i = -1$
System Type A = Galley and System Type B = Restaurant	$x_i = 1$
System Type A = Cruise Officers Accommodation and System Type B = Restaurant	$x_i = -1$
System Type A = Cruise Officers Accommodation and System Type B = Bridge	$x_i = 1$
System Type A = Crew Accommodation and System Type B = Crew Dayroom	$x_i = 1$
System Type A = Fuel Tank and System Type B = Generator Room	$x_i = 1$
System Type A = Fuel Tank and System Type B = Accommodation	$x_i = -1$
System Type A = Generator Room and System Type B = Generator Room	$x_i = -1$
etc	etc

Table B.1: Table of Design Rules

Node List

Table B.2 shows part of the node list and what information is stored within this node list of design A. It shows the node identification number, its x- and z coordinate, the node name and its centrality values.

Edge List

Table B.3 gives part of the rated edge list of Design A. This shows the end node number identifications, the weight of the edge and it corresponding score x_i.

#	x coordinate	z coordinate	Node Name	Eigenvector Centrality	Betweenness Centrality
1	69.5	0.5	Stabilizer System	0.0071	0.0000
2	41	2	Generator Room	0.0217	1.7455e-04
11	81.5	4.5	Stairs 2	0.0398	0.2517
19	73	17	Hospital Primary System	0.0145	0.0000
20	70.75	17	Secondary Hospital Solution	0.0145	0.0000
52	93.75	14.5	Accommodation Block 17	0.0810	2.0946e-04

Table B.2: Part of the node list of Design A

Endnode 1	Endnode 2	Weight	Score x_i
11	54	7.6249	0
11	56	10.0378	0
11	58	18.2936	0
11	65	9.7500	0
11	68	29.0644	0
11	69	27.8229	0
12	28	12.9736	0
12	40	5.9397	0
12	55	19.0497	0
13	40	14.1146	0
14	15	3.7504	1
14	19	4.2504	1
14	20	6.5004	1
14	45	12.4641	0
15	19	0.5000	1
15	20	2.7500	1
15	45	8.7137	0
17	47	11.2506	-1
17	53	1.3577	-1
18	50	6.3439	0
18	51	3.8777	0
19	20	2.2500	-1
36	52	10.3359	1
36	55	13.4957	1
37	43	9.5000	1
38	53	14.6077	1
39	42	11.5000	1
41	49	11.0992	1
44	48	12.5481	1
45	46	15.0363	1
47	53	9.8929	1
47	54	9.8742	1
48	49	12.9519	1
50	51	10.2212	1
52	54	9.5932	1
59	64	9.2429	1

Table B.3: Part of the rated edge list of Design A

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