

Integration of aboard logistic processes in the design of logistic driven ships during concept exploration

Applied to a Landing Platform Dock design case

J.J. le Poole

SDPO.18.030.m



Integration of aboard logistic processes in the design of logistic driven ships during concept exploration

Applied to a Landing Platform Dock design case

by

J.J. le Poole

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Thursday September 20, 2018 at 10:00 AM.

Student number	4288173	
Thesis number	SDPO.18.030.m	
Project duration	December 7, 2017 - September 20, 2018	
Thesis committee	Prof. Ir. J.J. Hopman	TU Delft
	Ir. K. Droste	TU Delft
	Dr. A.A. Kana	TU Delft
	Dr. Ir. H.J. de Koning Gans	TU Delft
	Dr. Ir. E.A.E. Duchateau	Defence Materiel Organisation

Preface

My five years and one month during journey as a student at the Delft University of Technology is concluded with this thesis. This document represents the work I carried out to obtain my degree as Master of Science in the field of Ship Design. Ships are amongst the most complex structures created by human. Although ships are already being used for thousands of years, mastering the design of these crafts itself is a competence that relies heavily on experience. To increase design knowledge a naval architect uses various tools. This thesis describes a novel approach to the design of logistic driven ships in the first phase of design. This work would not have been possible without the help of many people, who I want thank for their support.

First, I want to thank my daily supervisors, Dr. Ir. Etienne Duchateau and Ir. Koen Droste. Your thoughts, experience and knowledge on the subject left me puzzled from time to time, but proved essential to keep me improving my work. Etienne, with your help the use of the Packing approach in the way I demonstrated would have been impossible. Koen, our frequent meetings influenced the content of this thesis. On the other hand, you both gave me the freedom to shape the model to my own insight.

Furthermore, I want to thank Dr. Ir. Bart van Oers, who, with Etienne, provided me with the subject of my thesis and set the bar high from the start. I want to thank Prof. Ir. Hans Hopman for being the chairman of my graduation committee. During our regular meetings my attention was drawn to the philosophical questions behind ship design. I want to thank both Dr. Austin Kana and Dr. Ir. Henk de Koning Gans for being graduation committee members.

Since I was interested in the Dutch navy from my youth, I want to thank everyone at the Defence Materiel Organisation for providing me insight in naval ship design in general and Landing Platform Dock in particular and for providing me with a working place in an organisation I have dreamed of working in.

Finally I want to thank all the students and friends who have helped me in the past years. My very special thanks go to my soon to be wife: Jacoline, thank you for staying along my side all the time, for allowing and forcing me to relax on a weekly basis, and for being patient when I was focused on my study way too much.

Joan le Poole
Delft, September 2018

Image on the cover is derived from (Damen, n.d.).

Disclaimer

The content of this thesis is the personal opinion of the author. Specifically, it does not represent any official policy of The Netherlands Ministry of Defence, the Defence Materiel Organisation, or the Royal Netherlands Navy. Furthermore, the results presented here are for the sole purpose of illustration and do not have an actual relation with any past, current, or future warship procurement project at the Defence Materiel Organisation.

Abstract

The research described in this thesis has been carried out at the Defence Materiel Organisation (DMO) and focuses on the design of logistic driven ships, like cruise ships and Landing Platform Docks (LPDs), during the concept exploration phase. These vessels are characterised by large and/or frequent amount of internal movement of entities. The operational processes involving this movement are called logistic processes. To accommodate these logistic processes sufficiently sized logistic systems, e.g. staircases and hallways, have to be included in the design. Currently the required space is estimated using a design margin. Using such margin proves insufficient and impractical. Since redesign is a costly and time consuming process, a more educated approach to estimate required space for logistic systems during concept exploration was asked for. At the DMO the TU Packing approach is used during concept exploration with the aim to increase design insight. The Packing approach is used to generate thousands of low detail feasible concept designs,

The performance of logistic driven ships is driven by aboard logistic processes. It appears that careful optimisation of the configuration of the ship's functional systems can improve the performance of these vessels. Required connection between functional systems is provided by logistic systems. In order to correctly estimate the size of logistic driven ships, the space required for logistic systems need to be included at the right place in concept designs. Therefore logistic systems need to be defined prior to the configuration. To do so the functional systems as well as the logistic relation between the functional systems (i.e. logistic system relations) need to be known. Finally also the location of the functional systems need to be known. Combining this information the location and size of logistic systems can be determined. The functional systems and the logistic system relations can be defined before making configurations. Since the locations of functional systems are obtained from the configuration, a gap in information is identified. Indeed, to define logistic systems before configuration, the configuration needs to be present already.

To solve this problem, the Packing approach is used, which configures systems and explores the design space, and integrated with a novel method, which defines logistic systems based on initial locations of functional systems provided by the Packing approach. This Logistic Model creates a network representation of the ship's structural subdivision and combines this network with the predefined logistic system relations to define a list of compartments which need to be logistically connected. Using a new path finding and selection method, based on an adapted Yen's k-shortest path algorithm, the locations of logistic systems in the ship are determined. The sizing of the logistic systems is based on the number of paths in each logistic system and the characteristics of the entities involved in the logistic processes. The defined logistic and functional systems are then configured in a low detail concept design. The performance of this design is subsequently used to initiate a new, possibly improved, concept design.

The logistic performance of low detail concept designs is calculated by a Logistic Performance Measure (LPM), developed in this research. The LPM distinguishes between design in which logistic processes cannot take place and designs in which all logistic processes can take place. The latter are scored, based on the travelling distance between functional systems, taking into account available functional systems, and weights defined by the naval architect.

Small test cases were developed to successfully validate the Logistic Model. Further the design of a LPD was used to illustrate how the Logistic Model could be used during concept exploration. The Logistic Model is able to provide information on the location and size of logistic systems in each design by an educated estimation based on initial locations of systems. Therefore it can be concluded that the Logistic Model contributes to the concept exploration of logistic driven ships. The LPM can be used to find improved logistic driven ship concepts, but is unable to provide insight in the relation between the configuration of systems and the logistic performance. Individual and manual assessment of created designs is required to obtain this information. Further research is therefore required in that field.

Contents

List of Figures	ix
List of Tables	xiii
Glossary	xv
1 Introduction	1
1.1 Problem background	1
1.2 Research motivation	2
1.3 Current ways to solve the problem	4
1.4 The research problem and goal	7
1.4.1 Research problem summary	7
1.4.2 Research objective	7
1.4.3 Research questions	7
1.5 Proposed solution outline.	8
1.6 Report structure.	9
2 Method: requirements, concept and challenges	11
2.1 Requirements for the Logistic Model	11
2.2 Finding paths in concept designs	12
2.2.1 Network theory	12
2.2.2 Path finding and selection	12
2.2.3 Summary	17
2.3 Complement Logistic Model to Packing approach	19
2.3.1 Complementing the Logistic Model with the Packing approach	19
2.3.2 Challenges	20
2.4 Conclusion	20
3 Logistic Model	23
3.1 Overview of the Logistic Model	23
3.2 Step 1. Input	23
3.3 Step 2. Physical architecture	24
3.3.1 Level of detail of processes.	24
3.3.2 Generic LPD layout	25
3.3.3 The LPD physical architecture	28
3.4 Step 3. Initial positions of systems	29
3.5 Step 4. Logical architecture	30
3.6 Step 5. Creating a physical solution	30
3.6.1 Initial position translation	30
3.6.2 Allocating systems to compartments.	31
3.7 Step 6. Path finding and selection.	31
3.8 Step 7. Define logistically required connections.	36
3.9 Step 8. Check whole ship connectivity	41
3.10 Step 9. Compile full list of connections	43
3.11 Step 10. Hull form correction	43
3.12 Step 11. Output	43
3.13 Implementation in the Packing approach.	44
3.13.1 Logistic systems as objects in the Packing approach	44
3.13.2 Bulkhead positioning routine	44
3.13.3 Packing order	45
3.13.4 Limitations of level of detail	47

3.14	Objective functions	49
3.14.1	Assessing logistic performance.	49
3.14.2	Impact of overlap management	51
3.14.3	Additional objective functions and constraints.	52
3.15	Proof of concept	54
3.16	Conclusion	56
4	Test case development – Design of a LPD	57
4.1	Primary functions.	57
4.2	Requirements	57
4.3	Operational processes	59
4.3.1	Logistic processes	59
4.3.2	Selection of suited moving units	59
4.4	Support functions.	62
4.5	Systems – The ship description	63
4.5.1	Functional systems	63
4.5.2	Logistic system relations	65
4.5.3	Logistic systems	66
4.6	Summary	71
5	The usefulness of the Logistic Model	73
5.1	The effectiveness of the Logistic Model	73
5.1.1	Small number of logistic system relations	74
5.1.2	Large number of logistic system relations	79
5.1.3	Conclusion.	80
5.2	The efficiency of the Logistic Model.	80
5.3	Further assessment of the LM's usefulness during concept exploration	82
5.3.1	LPD concept exploration.	82
5.3.2	Impact of logistic systems on ship size and logistic performance.	82
5.3.3	Impact of LPM on ship size	85
5.3.4	LPD concept selection	87
5.3.5	Conclusion.	89
6	Conclusions	91
7	Discussion and future work	93
7.1	Improve the quality of the Logistic Model.	93
7.1.1	Path finding and selection	93
7.1.2	Temporal aspects	94
7.1.3	Additional logistic systems.	94
7.1.4	Level of detail of the Packing approach	94
7.1.5	Storage of data in the Packing approach	95
7.1.6	Improve LPM calculation	95
7.2	Concept design arrangement assessment.	96
7.3	Style choices and physical architectures	96
7.4	The LPD ship description	98
7.4.1	System definition	98
7.4.2	Ballasting for well dock operations.	99
	Bibliography	101
A	Functional systems in a LPD	105

List of Figures

1.1	A logistic process consists of different classes of activities.	1
1.2	Location and size of systems drive a ship's size and performance	3
1.3	Space required for logistic connections is dependent of the positions of the systems to be connected. Indeed $\sum AreaA < \sum AreaB$	4
1.4	Iterative nature of ship arrangement design in logistic driven ships	4
1.5	Systems engineering V-diagram, (Droste et al., 2018)	5
1.6	A comparison between the level of detail used by Casarosa (2011) and in the Packing approach	6
1.7	Outline of the relation between Packing approach and Logistic Model	8
1.8	Report structure	9
2.1	Visualisation of the relation between the three primary architectures applicable to distributed systems in ships, (Brefort et al., 2018). Highlighted in grey is the area of focus for this thesis.	13
2.2	Continuous (left) and discrete (right) positions of a vertical connection. Continuous positions offer many (infinite) possible positions, while discrete positions offer only five positions in this case. Using discrete positions will therefore simplify of choosing positions for logistical systems.	13
2.3	System A and B positioned in a simplified side view of a ship. Also four out of 132 possible paths between these systems are shown.	14
2.4	Two different vertical connection designs. Way finding is straightforward in design B, while way finding in design A is difficult due to the lack of consistent visual reference.	16
2.5	Three shortest paths between system A and B, two shortest paths between system C and D.	18
2.6	Six shortest path combinations, showing different number of required vertical connections.	18
2.7	Outline of the TU Delft Packing approach	19
2.8	An outline of the Packing approach extended by the Logistic Model	20
3.1	A schematic overview of the Logistic Model.	24
3.2	A visualisation of the logistic processes in a LPD. Generally, logistic processes take place in the longitudinal and vertical direction. Courtesy of J.J. Hopman and (Damen, n.d.)	25
3.3	Four possible deck layouts, regarding hallways and vertical connections.	26
3.4	Distribution of processes over a ship, visualised by different sized, red, edges in a 2D physical architecture. Note, this figure has been specifically created for justification of the 2D approach to processes. See chapter 7 for recommendations regarding the use of graphs in analysis of concept designs.	26
3.5	The generic division of a ship, applied to a LPD.	27
3.6	A detail of a ship's compartments and possible vertical connections, as well as the related physical architecture.	28
3.7	A ship's physical architecture before detailing features are added.	28
3.8	Discrepancy between actual hull form and the physical architecture	29
3.9	Initial positions of systems before and after translation by eq. (3.2). Note that only systems above the helicopter deck are shifted. In this case an accommodation object is moved inside the superstructure.	32
3.10	Example used for explanation of directional switch calculation. Clearly this route changes direction four times, hence the directional switch is four.	33
3.11	Example of paths with different number of directional switch. Path 1a and 1c have directional switch = 1, while path 1b has directional switch = 2. Path 1b is therefore eliminated from further selection.	35
3.12	Two path combinations. A holistic path selection approach requires the consideration of temporal aspects, which is outside the scope of this thesis.	36
3.13	Example to illustrate the required connections based on chosen paths.	36

3.14	A small example case with nine compartments enclosed by decks and bulkheads. Nodes 10 till 15 represent vertical connections.	40
3.15	Determination of the size of logistic systems 1 and 2 based upon the required minimal size by activities in nodes 10 till 13.	40
3.16	A comparison between three solutions for missing connection in watertight compartments . . .	42
3.17	Varying size in staircase can be a source of congestion, (BuildingCodeNYC.com, n.d.)	42
3.18	Solution 3 can cause congestion due to changes in size of the connection	43
3.19	An example of a hull form and its deck discretisation.	44
3.20	Subdivision by bulkheads to limit flooding (Van Oers and Hopman, 2012)	45
3.21	Visualisation of the bulkhead distance parameters as used in this research.	45
3.22	Difference between packing a soft (blue) object after (left) or before (right) a hard (grey) object. This also influences the size of the envelope required.	46
3.23	Histogram of the number of unpacked systems if the logistic systems are packed earlier (dark) or later (light) in the design. If the number of of unpacked designs is larger than the value indicated by the vertical line with the corresponding colour, the logistic systems can not be packed.	47
3.24	Top view of a well dock aboard a Landing Platform Dock with three transverse slices, (Van Oers and Hopman, 2012). The centreline slice contains the well dock itself, while the port and starboard side slices contain ballast tanks.	48
3.25	Example design for the LPM network generation shown in fig. 3.26.	51
3.26	Generating networks to calculate d_i in order to find the LPM value of a design.	51
3.27	Initial versus final LPM, showing results of the fourth test case of the LPD exploration run in chapter 5	52
3.28	There is a strong relation between the packing density and the enclosed volume of the hull. The three distinct groups visible in this figure are formed due to some systems which are not necessary enclosed by the hull. An example is the hangar, which might be separated from the superstructure in the model used.	53
3.29	Matrix plot showing the enclosed volume, LPM and PD scores for the LPD exploration run. . . .	54
3.30	Convergence of the objective functions for the LPD exploration presented in section 5.3	55
3.31	Proof of concept	56
4.1	Main dimension comparison between sixteen active LPDs. The Dutch <i>HNLMS Rotterdam</i> and <i>HNLMS Johan de Witt</i> are encircled in red.	59
4.2	Value adding activities in logistic processes are divided into two categories, namely: activities during transit towards the theatre and activities during an amphibious assault in the theatre. Further activities during re-embarkation are partly shown. A value activity consists of an action and entities involved in that action. Arrows represent possible non-value adding activities, which are required depending on the configuration of functional systems.	60
4.3	An update of fig. 4.2, encompassing the selected moving units.	63
4.4	LPD's support functions, including the mapping from primary functions, requirements and logistic processes. The relation between steps is visualised by arrows.	64
4.5	Reduced level of detail of systems versus increased level of detail of the Packing approach	66
4.6	Top view of a well dock aboard Landing Platform Dock with three transverse slices, (Van Oers and Hopman, 2012). The centreline slice contains the well dock itself, while the port and starboard side slices contain ballast tanks. Revisited fig. 3.24	67
4.7	The well dock is modelled as two objects to improve the development of require logistic systems involved in processes connected to the well dock. The forward end is encircled in red.	67
4.8	Two different vehicle deck styles.	68
4.9	Example of a vehicle deck as modelled in the Packing approach.	68
4.10	Functional systems involved in the different logistic activities in a LPD.	70
4.11	Decks three and six connected by a staircase, left, and a lift, right. The lift is driven by an engine in an engine room situated below the lift.	70
4.12	Dimensions of the NH90 maritime helicopter with folded rotor and tail, (Shulgin, 2015).	71
5.1	Side view of the design with lowest LPM score found for test case 1a, in which the galley is placed aft of the mess.	74
5.2	Example to illustrate the effect of system locations on optimisation to distance.	75

5.3	The relative longitudinal position of the mess to the galley, illustrating the effect described in fig. 5.2 can be observed in a whole data set as well.	75
5.4	Side view of the design with lowest LPM score found for test case 1a, in which the galley is placed aft of the mess.	76
5.5	Side view of forward part of the design with lowest LPM score found for test case 1b.	77
5.6	The initial (top) and final (bottom) positions of the four systems in consideration in test case 1b.	77
5.7	Side view of the design with lowest LPM score found in test case 2.	78
5.8	Side view of the design with lowest LPM score found in test case 2, with overlaying physical architecture visualising the watertight subdivision.	79
5.9	Design with lowest LPM score found in test case 3.	80
5.10	Convergence plot of the LPM for test case 3 for both exploration runs. Designs with disconnections have been filtered from this data set.	80
5.11	Most promising design found in test case 4.	81
5.12	The number of design with disconnection over the number of packed designs per generation. On average 23% of the packed designs has at least one disconnection.	81
5.13	Range of main dimensions found in the exploration run performed	83
5.14	Average CD for whole data set (in red) as well as CD related to PD, enclosed volume and LPM scores of designs	84
5.15	Investigation of the area occupied by logistic systems on one deck	85
5.16	Logistic performance versus the number and volume of logistic systems in each design. Given the assumptions made, logistic performance is not driven by the amount of logistic systems.	85
5.17	Down selection based on LPM to find a relation between LPM length and width	86
5.18	Objective scores for each design. The regression line indicates a larger ship is generally required to accommodate a logistically more promising configuration of systems.	87
5.19	A comparison of system locations in design 19181 (top) and 11217 (bottom)	88
5.20	The design with minimum volume, 19996. The logistic performance of this design is bad, relative to the other designs in the data set. Also the route between the galley and the food store is visualised.	89
5.21	A randomly drawn design with ID 4280. The logistic performance of this design is bad, relative to the other designs in the data set. Also the route between the galley and the food store is visualised.	90
7.1	A fuzzy approach to path selection, similar to Nick (2008)'s Minimum Segment Width Fuzzy Utility.	93
7.2	An example of a logistic systems network as one object to be packed a concept design.	95
7.3	The current LPM calculation does not take the actual top size shape into account. This leads to infeasible paths through open space, as encircled in red.	96
7.4	Distribution of processes over a ship, visualised by different sized, red, edges in a 2D physical architecture. Busy areas can be recognised by thick edges in this graph. Revisited fig. 3.4	96
7.5	Two LPD classes with a different topside style.	97
7.6	Two new proposed physical architectures for higher detail designs.	98
7.7	Various measures used in the calculation of the required ballast capacity.	100

List of Tables

1.1	Overview of ways existing design tools deal with vertical and horizontal connections.	6
2.1	Route enumeration, corresponding computation time and route combinations to choose from, given for small grids	17
2.2	Status of requirements for the Logistic Model	21
3.1	An example of a logistic system relation	24
3.2	Layout of the structure containing initial locations of systems	30
3.3	An example of mapping systems and system category relations to logistic system relations . . .	31
3.4	Fulfilling path finding rules by taking shortest paths into account only.	32
3.5	For each node the number of activities for each moving unit is captured in a table. Vertical movement is allocated to the corresponding nodes representing vertical connections, while horizontal movement is allocated to the corresponding nodes representing compartments. . . .	37
3.6	Example of compatibility of function sharing between logistic systems for different moving units.	38
3.7	Example of definition of connections in step 7.	41
3.8	Layout of the structure containing required logistic systems	43
3.9	Status of requirements for the Logistic Model	56
4.1	Range of LPD sizes based on (Wikipedia, n.d.) and used to constrain the design space.	58
4.2	An example of a logistic system relation	65
4.3	Weighing for the moving units involved in the LPD	69
4.4	The full list of logistic system relations based on the functional systems and logistic processes in a LPD.	69
4.5	An overview of the sizing parameters for logistic systems in a LPD.	71
5.1	The efficiency of the LM in the test cases	82
A.1	List with functional and logistic systems in the ship description of a LPD.	105

Glossary

B	Beam, [m]
CD	Connection density
DBB	Design Building Block Approach, developed at University College London
DMO	Defence Material Organisation
GMt	Distance between CoG and the transverse metacentre height, which is a metric for intact stability of a ship, [m]
HVAC	Heating, ventilation, and air conditioning
ISA	Intelligent Ship Arrangement, an approach developed at the University of Michigan
LHD	Landing Helicopter Dock
LM	Logistic Model, developed in this thesis
LOA	Length overall, [m]
LPD	Landing Platform Dock
LPM	Logistic Performance Measure, developed in this thesis
MU	Moving Unit
CBRN-attacks	Chemical, biological, radiological and nuclear attacks
PD	Packing density
RNLN	Royal Netherlands Navy
T	Draft, [m]
TEU	Twenty Feet Equivalent Unit, standard size of a container
TU Delft	Delft University of Technology
US Navy	Navy of the United States of America

Introduction

1.1. Problem background

A ship's performance is defined as the ability to perform its mission. Performance measures can differ for different ship types. For instance, the performance of a container ship could be measured in ship speed and TEU capacity. On the other hand the performance of so called *logistic driven vessels* is hard to measure. Logistic driven ships are characterised by frequent and large amounts of internal movement of entities or moving units, like people and goods. This internal movement of moving units is an essential part of the operational process of these vessels. Examples of logistic driven ships are cruise ships, aircraft carriers or Landing Platform Docks (LPDs). The layout of systems in these ships can cause logistic bottlenecks. As a result, logistic processes can be delayed or even totally be obstructed. On the other hand, a carefully optimised configuration of systems can enable smooth logistic processes. Therefore, a logistic driven ship's performance is driven by operational processes of a logistical nature (Droste et al., 2018).

An operational process is often considered to be an organised set of activities or tasks that produces a specific service or product (Weske, 2012; Kirchmer, 2017; Von Rosing et al., 2014). In terms of ship design one could describe production of a specific service or product as fulfilling a specific function, for instance deployment of marines during an amphibious assault. This leads to a more specific definition: an operational process of a logistical nature is an organised set of activities that fulfils a specific function of a logistical nature. An activity is a function in itself, but can also be described as an action, according to Gortney (2010). In the remainder of this thesis the expression *logistic process* is used instead of *operational processes of a logistical nature*.

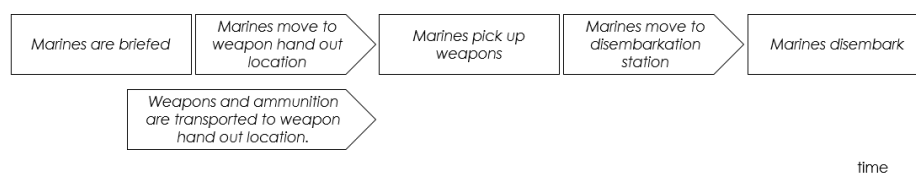


Figure 1.1: A logistic process consists of different classes of activities.

An example of an logistic process as a set of activities in a LPD is given in fig. 1.1. This example points out two things. First, activities can be divided into two classes, based upon lean production principles (Liker, 2005).

1. *Value adding activities* change the state of moving units, which includes both physical as nonphysical changes. For example, marines get information (nonphysical change) during the briefing, or get their weapons (physical change). Both changes increase the 'value' of the moving unit.
2. *Non value adding activities* don't add any value to the product or to the moving unit. In logistic processes movement does not contribute to the value of the moving units. In lean production theory

movement is seen as waste, (Liker, 2005), and therefore non-value adding movement needs to be reduced from a logistic point of view. Although movement of marines and equipment from the ship to shore can span many kilometres, aboard movement does not add value. One could argue that marines need physical training and therefore require movement, but it is believed that the relatively small distances aboard a LPD are not sufficient to provide much fitness gain. Furthermore wandering around of (foreign) marines aboard a LPD is considered to be an unwanted situation (W.H.F Burger, personal communication, April 6, 2018). Note that these activities can be reduced or even removed by carefully optimising the configuration of systems.

Second, there is a time dependency between activities. Some activities are carried out in sequence while others happen in parallel. This touches the area of logistics. Indeed, logistics is defined by NATO (2017) as the science of planning and carrying out the movement and maintenance of forces. And Gortney (2010) describes logistics as the planning and executing the movement and support of forces.

- *Planning* solves the temporal aspect of activities. Undesired effects like congestion can be reduced by carefully planning activities. The temporal relation between activities is not only dependent on key moments, when activities have to be finished, but is also dependent on the layout of the ship. Indeed, the duration of the non-value adding activities is dependent on the length of the route between functional systems, amongst others. The backward search schedule-based path finding algorithm developed by Huang and Peng (2002) could be applicable to find routes based on temporal relations between logistic processes. Since the layout is not known, the temporal relations between logistic processes are not known neither. Therefore the temporal aspect of operational processes is not taken into account in this thesis, but logistic processes are assumed to take place at the same time instead.
- *Support of forces* is, amongst others, the action of a force (or functional system) that aids, protects, complements, or sustains another force [...] requiring such action (Gortney, 2010), and can therefore be clearly linked to the value adding class of activities.
- *Movement of forces* or other moving units requires a suited connection between functional systems where value adding activities take place.

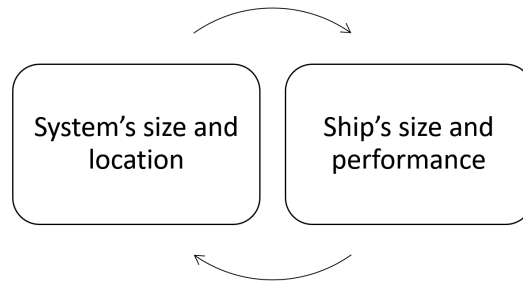
Logistic processes require connection between functional systems. Systems that need to be connected are called *logistically connected systems*. *Logistic systems*, like staircases and hallways, provide connection between logistically connected systems. The connection between logistically connected systems and spaces is described by a pairwise relation between a source and a sink system. For instance, the example above provides information that the briefing room (source system) has to be logistically connected to the weapon hand out location (sink system). This pairwise logistic relation is called a 'logistic systems relation' in the remainder of this thesis.

In logistic driven ships the space required for logistic systems is generally larger than in non-logistic driven ships. An educated estimation of this required space proves to be a challenge during concept exploration. Since logistic processes drive the performance of logistic driven vessels, these processes need to be taken into account in the concept design of these vessels. Indeed, taking logistic processes as a starting point introduces the assessment of logistic systems at the front-end of the design process, enables the informing the design and enabling improved operability while the design is still amenable to changes, according to Casarosa (2011). To find an educated estimation of space required for logistic systems in logistic driven ships during concept exploration this thesis was initiated. The next section elaborates further on the research motivation.

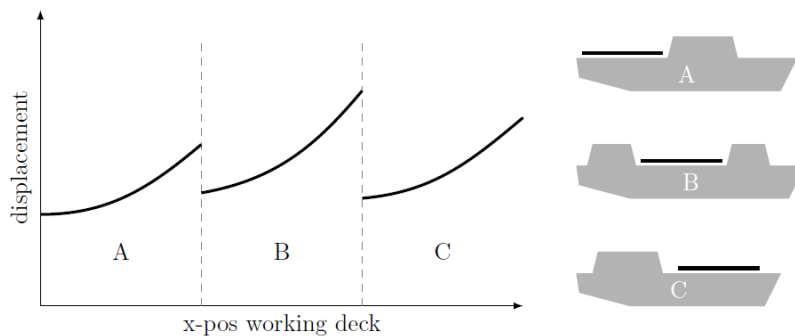
1.2. Research motivation

The design of logistic driven ships is a complex task for various reasons. First ships itself are complex structures, but other issues like an ill-defined problem and the large degree of preliminary design freedom also increase the complexity of ship design. Ship design itself is covered in various research, for an overview see (Andrews et al., 2012). Ship design starts with an exploring phase in which a balance between requirements, available budget and possible solution is sought. Different solution concepts with varying requirements and/or performance are created and investigated during this phase. This set of possible design solutions is used to support the naval architect and consumer in their search for the required design solution.

Duchateau (2016) describes a list of design options which are usually varied during concept exploration, amongst which is the arrangement of functional systems. Arrangement of relevant systems in an coherent ship configuration is one of the key features that determine the feasibility of complex ships, according to Van Oers (2011). The ship design process is characterised by an iterative nature, first described by Evans (1959) in the well known ship design spiral but later also acknowledged by Duchateau (2016); Van Oers (2011) amongst others. In addition, Pawling et al. (2017) provide a discussion on the validity of the design spiral as description of the ship design process. This iterative nature appears in different areas during design, for instance an increased range requirement might lead to an increased required fuel capacity, which in turn requires more displacement, which increases ship resistance, requiring more power and therefore even more fuel. With regards to arrangement, fig. 1.2a summarises that the location and size of systems drive the ship's size and performance, while fig. 1.2b shows an example.



(a) Iterative nature of ship arrangement design



(b) Discrete and continuous response of ship displacement caused by a large change in top-deck layout due to a continuous change of working deck position (Duchateau, 2016)

Figure 1.2: Location and size of systems drive a ship's size and performance

However the complexity of ship design is further increased when on board logistic processes need to be included in the preliminary design phase, as is the case for logistic driven ships. Logistic processes require functional systems to be connected by logistic systems. However, the size of the required connection is strongly related to the locations of the systems to be connected. A basic example is given in fig. 1.3, in which two systems are to be connected. The more the systems are separated the bigger the connection needs to be. The location of the functional systems might vary a lot during concept exploration. This makes it hard to make an educated estimation of the space required for logistic systems in an early design phase. As pointed out earlier, a logistically promising layout is important for the performance of logistic driven vessels. The logistic performance of concept designs can be used to improve the layout of future concepts as well as the routing of logistic systems between functional systems in these concepts. Figure 1.4 provides an overview of the iterative nature of general arrangement design for logistic driven vessels. Although logistic processes need to be taken into account during concept exploration, the Dutch Defence Materiel Organisation (DMO) encountered challenges regarding the estimation of required space for logistic connections.

Concept exploration for vessels for the Dutch navy is carried out by the DMO, which is responsible for the technical specification and procurement (Van Oers et al., 2017). Currently space required for logistic systems

is estimated by a design margin. Logistic systems are added as objects in later design stages. However, the DMO found that using a margin proved to be a problem in later design stages, when available area was not sufficient to accommodate logistic system because the margin was partly used by functional systems and spaces. This required a partly redesign of the ship. Redesigning a ship is a costly endeavour, and can lead to larger ships. This could lead to a budget overrun in the end. As a result, insufficient defined concept designs during concept exploration provide less reliable results for further design definition. Therefore the DMO would like to see a more detailed and educated estimation of the required space for logistic systems and their position in the ship during concept exploration of future vessels. A simple solution for an insufficient margin is to enlarge the current space estimation for required space. However, this might lead to an overestimation and therefore oversized designs, which in turn might lead to a bad cost estimate. The challenge identified by the DMO showed up in the design of a non-logistic driven ship. Its therefore likely that the design of a logistic driven ship, like a LPD, will pose even larger challenges in later design phases if the space estimation for logistic systems is insufficient.

At the DMO no tool is available to assess logistic performance of concept designs. Since the logistic performance of logistic driven ship concepts has to be known to differentiate between concept designs, and eventually configure increasingly promising concept designs, a method to assess logistic performance was also asked for.

The challenges related to the design of logistic driven ships during concept exploration and personal interest form the motivation for this research. The LPD will be used as a test case for the solution developed. The next section will cover the ship design process used in the current research, as well as some lessons learned from existing tools and approaches to the problem.

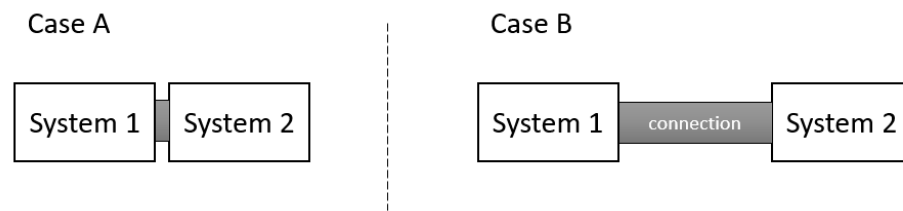


Figure 1.3: Space required for logistic connections is dependent of the positions of the systems to be connected. Indeed $\sum AreaA << \sum AreaB$

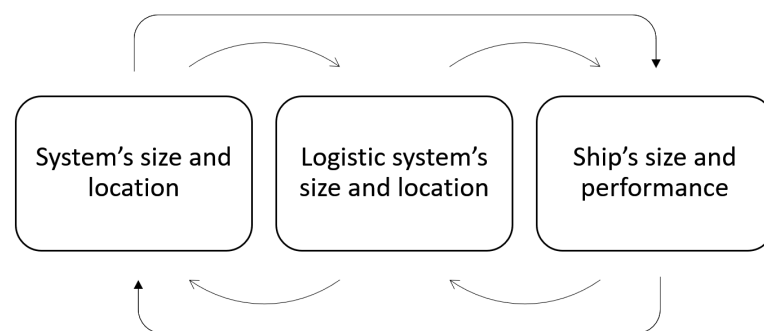


Figure 1.4: Iterative nature of ship arrangement design in logistic driven ships

1.3. Current ways to solve the problem

In addition to the design spiral mentioned in section 1.2, the systems engineering V-diagram is commonly used by naval architects to guide the ship design process to feasible and suitable designs, (Van Oers, 2011;

Droste et al., 2018). The focus of this V-diagram is on how the primary function relates to the effectiveness of the design by looking into the operational processes and subsequent support functions. Again, a logistic process can be seen as a set of activities. The activities require support functions such as hotel functions or general ship platform functions. Functions are fulfilled by systems. Systems are divided into two classes: logistical systems and functional systems. Logistic systems provide aboard connectivity between functional systems, while functional systems fulfil the other functions of the ship. See chapter 4 for an extensive example of the application of the systems engineering V-diagram in the design case of a LPD.

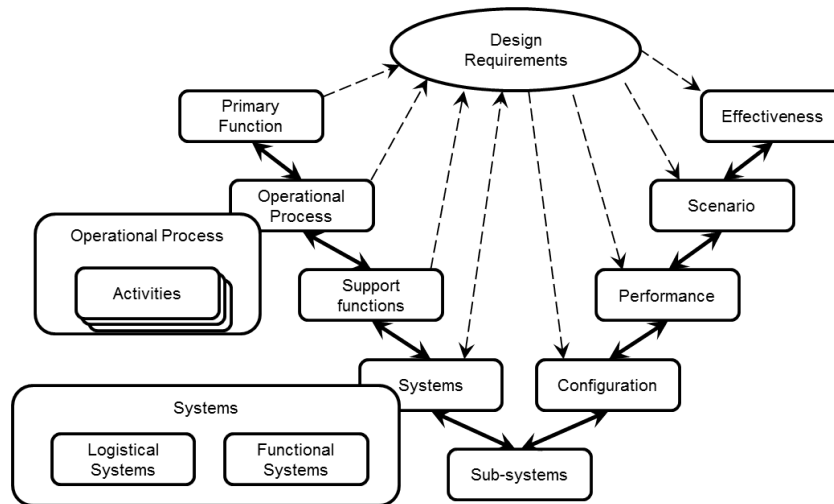


Figure 1.5: Systems engineering V-diagram, (Droste et al., 2018)

Increased computer power enabled a move from point based ship design to set based ship design. Also more tools became available to support the naval architect to solve the design of increasingly complex ships. The issue of computer-aided preliminary design has been addressed frequently, and will therefore not be further detailed in this thesis. Refer to (Nick, 2008; Duchateau, 2016; Van Oers, 2011; Andrews et al., 2012) for overviews of available design tools. With regards to the logistic performance, table 1.1 provides an overview of existing ship design tools and how these tools deal with logistic systems. Only the Design Building Block (DBB) by Andrews and Dicks (1997) is able, by designer's choice, to implement required, and sufficiently sized, logistic systems based upon the layout.

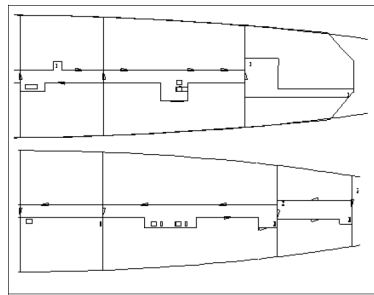
However, within the DMO the TU Delft Packing approach is used during concept exploration, and is therefore used in this thesis. The Packing approach will be explained in some detail in section 2.3, but for extensive detail refer to (Van Oers, 2011) and for an overview of the approach see for instance (Zandstra et al., 2015; Wagner et al., 2010; Van Oers and Hopman, 2012; Van Oers et al., 2017; Duchateau, 2016). In each concept design created by the Packing approach sufficient space for logistic systems has to be included as explained in section 1.2, because the logistic processes require sufficiently sized logistic systems. On the other hand the logistic performance of concept designs might be used to improve configurations of systems.

The routing of logistic connections in a ship is very similar to path finding problems presented in literature. These path finding problems are often based upon networks. A network or graph is a set of nodes and edges, describing pairwise relations. Networks are commonly used in multiple disciplines, for instance in social and biological fields, (Girvan and Newman, 2002), in the field of transportation, (Cui et al., 2010) or in general network flow problems (Jensen and Bard, 2003). Networks are used in ship design as well. Laverghetta and Brown (1999) applied networks to the ship design process but in recent years networks are often used to create insight in ship designs during the preliminary design phase (Gillespie et al., 2013; Shields et al., 2018; Roth et al., 2017; Goodrum et al., 2018). Duchateau et al. (2018) route distributed systems based upon a network and a k-shortest path algorithm (Yen, 1971). Since networks seem to be applicable to find paths between systems and to successfully represent a ship in a mathematical way, networks will be used in this thesis for the routing of logistic systems, see section 2.2.1 and section 3.3.

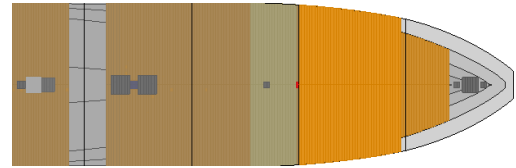
Vertical connections	ISA (Nick, 2008)	DBB (Andrews and Dicks, 1997)	Packing (Van Oers, 2011)*
number	fixed	designer's choice	designer's choice
size	fixed	designer's choice	designer's choice
location	automated	manual	semi-automatic
Horizontal connections			
number	fixed	designer's choice	none
size	fixed width	designer's choice	none
location	automated	manual	none

* In the original version of the Packing approach connections between systems existed, see (Van Oers, 2011). However, the routing of these connections proved not needed for the aim of the tool and therefore were left out in later versions. Further routing was only automated to a low extend. In the current Packing version, vertical connections are present to represent the connection between the engine room and the exhaust. Logistic systems are not modelled currently, but taken into account by a margin, section 1.2.

Table 1.1: Overview of ways existing design tools deal with vertical and horizontal connections.



(a) Design with low level of detail (Casarosa, 2011).



(b) Low level of detail of a Packing design including logistic systems. This example shows vertical connections only. Note that the transverse detail can be increased by dividing systems over starboard and port sides of the ship.

Figure 1.6: A comparison between the level of detail used by Casarosa (2011) and in the Packing approach

Analysis of concept designs is done to gather design knowledge, which in turn is used to set design requirements. In the Packing approach a quick analysis of each created design is required. The performance of each design is used to search for more promising designs. In this thesis the exploration of the design space is aimed to find logistically promising designs. Therefore a fast analysis of each design is required in order to find its logistic performance. Therefore a limited number of measures has to be selected from literature or needs to be developed in this thesis.

Analysis of concept designs can be done using various methods. DeNucci (2012) captured design rationale, while Van Oers (2011); Duchateau (2016) explore characteristics of designs. Network theory has been applied to ship design analysis as well, see for instance (Roth et al., 2017; Shields et al., 2018; Rigterink et al., 2014; Gillespie and Singer, 2013). These methods can all be applied to low detail designs, like these generated by the Packing approach. However, they are unable to assess the logistic performance of a design regarding logistic processes. Prajapat et al. (2016) presents the use of discrete event simulation to optimise the layout of a factory. However, this requires information on temporal relationships between logistic system relations. This information is not available as discussed in section 1.1. Casarosa (2011) integrated human factors, operability and personnel movement simulation in the preliminary design of ships, using multi-agent simulation. Therefore he developed a Human Performance Matrix. However, he had to use designs with significant level of detail. This included full definition of the logistic systems. In fig. 1.6 a comparison between the detail level of a Packing concept and the concept used by Casarosa is made. Due to the low detail of Packing designs multi-agent simulation can not be used. To the best of the author's knowledge, no computationally efficient measure to assess logistic performance for the level of detail aimed for has been developed in the past.

Now the background of the issues in concept exploration of logistic driven ship is given, a summary of the problem as well as the objective and research questions will be given in the next section.

1.4. The research problem and goal

First the problem described in the preceding sections is summarised. Subsequently the research objective and research question for this thesis will be given.

1.4.1. Research problem summary

In the design of logistic driven ships, the aboard logistic processes need to be taken into account. The connection needed between logistically connected systems is provided by logistic systems. Since using a design margin for the estimation of required space for connectivity appears to be insufficient and impractical, a more educated estimation is required. To determine the location of logistic systems the following three items need to be available at minimum.

1. *Systems.* Systems drive ship size and performance. Logistically connected functional systems have to be connected by logistic systems, which complicates the iterative problem. The systems have to be defined by the naval architect upfront, so this information is known.
2. *Logistic system relations.* Based on the logistic processes the naval architect has to decide which systems have to be logistically connected. This analysis is independent of the ship's configuration and can therefore be carried out by the naval architect upfront.
3. *Locations of systems.* To determine the routing of the logistic systems, and thus the locations and number of logistic systems, the locations of the logistically connected systems are required. Only if the ship is configured the locations of the systems are known. Therefore the design of logistic systems is an iterative problem in itself.

Thus the design of logistic driven ships is a double iterative design problem. Complicating the matter is the required size of the logistic systems which is dependent on e.g. the size of the moving units involved in the process. Further the logistic performance of concept designs needs to be analysed to distinguish between designs and to steer the exploration of the design space by the Packing approach.

1.4.2. Research objective

Given the problem outlined above, the aim of this research is twofold:

1. To improve the estimate of space required for logistic systems and to allocate these logistic systems to low detail concept designs.
2. To assess the logistic performance of low detail concept designs of logistic driven ships.

Both objectives aim to increase the knowledge on the impact of the configuration of systems on the logistic performance of logistic driven ships. This design knowledge enables naval architects to make more informed decisions in the design of this type of vessels. Note, since the research aims to attribute to the concept exploration phase, so the aim is not to do detailed design of logistic systems.

1.4.3. Research questions

Given the research goals stated above, the following two research questions have been developed to meet these goals. The first research question aims to provide a solution for the first objective.

1. How to include sufficient space for logistic systems at the right location in a logistic driven ship concept design?

This research question consists of different elements which are further clarified below.

1. *Sufficient space:* All required functional and logistic systems should fit in the design.
2. *At the right location:* Logistic systems have to be placed such that the ship has good logistic performance.
3. *Logistic systems:* Logistic systems are systems that provide logistic connection, like hallways, stairs, lifts and ramps.

4. *Logistic driven ship*: A logistic driven ship is characterised by frequent and large amounts of internal movement of moving units and which performance is, therefore, driven by logistic processes. The configuration of functional and logistic systems have to result in a logistically promising design.
5. *A concept design*: A concept design is a low detail design, used to study feasibility of design solutions and to set requirements. Therefore, concept designs should provide reliable information on the balance of operational performance (needs) for a given budget while safeguarding technical feasibility (e.g., a cost-effective design) (Duchateau, 2016).

To meet the second research objective the following research question has been formulated. In addition this question aims to support the first research question. Indeed, sufficient space for and right location of logistic systems should attribute to logistic performance of concept designs. On the other hand the configuration of functional systems also impacts the logistic performance. Therefore it is required to know:

2. How to assess the logistic performance of logistic driven ship concept designs?

The following section will give an outline of the proposed solution to this problem.

1.5. Proposed solution outline

Now the problem and research questions are clear, this section will outline the proposed solution. The Packing approach (Van Oers, 2011; Van Oers and Hopman, 2012) is used since the DMO uses this tool during concept exploration.

The definition of suitable low level of detail logistic systems requires a new method to be developed, since no suitable method has been found in literature. As the logistic systems need to be included in the concept designs generated by the Packing approach, this novel method needs to be connected to the Packing approach. The novel method developed in this thesis is called the Logistic Model (LM). The Packing approach provides information on system locations to the LM. The LM will then develop the required logistic systems using network theory and a path finding algorithm, and provides the required logistic systems as input for the Packing approach. Further the LM has to quickly assess the logistic performance of the concept designs found by the Packing approach, for which a new measure will be developed. The relation between the Packing approach and the Logistic Model is outlined in fig. 1.7.

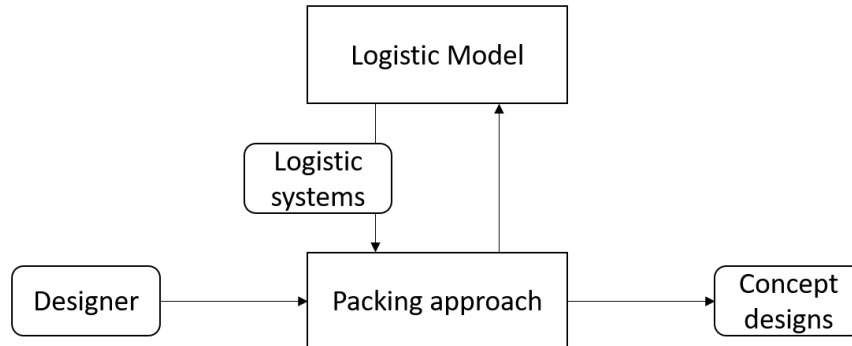


Figure 1.7: Outline of the relation between Packing approach and Logistic Model

1.6. Report structure

Now the research problem has been explained in this chapter, the remainder of this report is structured as follows. In chapter 2 some challenges regarding the proposed solution are highlighted and requirements for the further development of the LM are given. Subsequently, the LM is developed in detail in chapter 3. To validate the LM and to determine if the LM is useful during concept exploration a test case is developed in chapter 4. Subsequently the test case results and validation of the LM are discussed in chapter 5. Lastly, the report ends in a conclusion in chapter 6 and a discussion and recommendations in chapter 7. The report structure is summarised in fig. 1.8

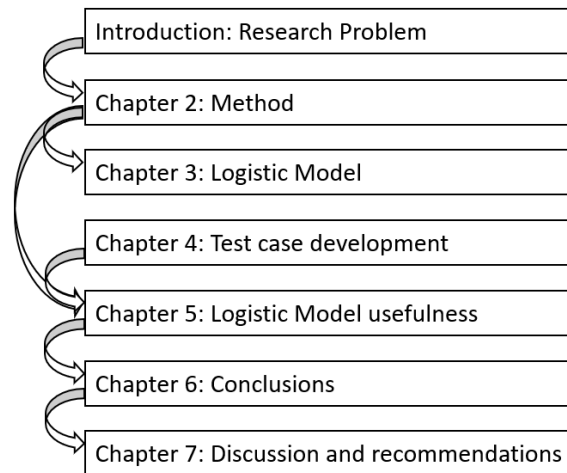


Figure 1.8: Report structure

2

Method: requirements, concept and challenges

The introduction has described the necessity to take logistic processes into account from the start of the design process of logistic driven ships. It was also clarified that no suitable methods are known to solve this part of the complex ship design problem. Therefore a novel method was proposed, called the *Logistic Model (LM)*. The current chapter elaborates on the model requirements first, and subsequently describes the concept of the model and some general associated challenges.

2.1. Requirements for the Logistic Model

Now the need for a novel method is clear this section elaborates on the requirements for the LM, in order to answer the research question posed in section 1.4.3. The LM should be:

1. **Based on known systems and logistic system relations:** In section 1.3 the systems engineering V-diagram used in this thesis is introduced. Not only the systems are known before configuration, also the logistic system relations can be defined upfront by analysing the operational processes the ship should carry out. Using system relations in ship design is not new, see for example (Gillespie et al., 2013; Nick, 2008). These researches use system relations to globally allocate systems to compartments, taking into account both adjacency and separation relations. However, these researches did not take into account the routing of logistic systems and more importantly the space required for those logistic systems, (Gillespie et al., 2013), or assumed fixed sizes for logistic systems, (Nick, 2008). The latter is no issue if only one moving unit, for instance crew, uses the ship. Standardisation of logistic systems is a defensible design choice in that case. However, if different types of moving units use the ship different types of logistic systems might be required. For instance, vehicles need ramps or lifts, while marines need big staircases.
2. **Able to determine positions and size of required logistic systems:** Determination of positions and size of logistic systems are both required to allocate sufficient space for these systems in the concept design. The need for a good estimation of the required space is described in section 1.2. Further sufficient sized logistic systems are necessary to accommodate the logistic processes aboard.
3. **Able to take the structural subdivision of ships into account in the determination of the size and position of logistic systems:** The structural subdivision of a ship puts additional requirements for connectivity of certain compartments. For instance, watertight compartments require connection to the damage control deck, as watertight bulkheads can block horizontal connection to other watertight compartments. Furthermore naval vessels are divided into zones, which can be fully secluded from other zones in the case of NCB-attacks for instance. Therefore each zone has an own HVAC installation for instance. With regards to aboard logistics each compartment needs to be connected to the other compartments in each zone. This connection should be independent from logistic systems in other zones. Therefore full connectivity between the lowest and highest decks has to be assured in each zone.

4. **Able to add the logistic systems to the concept designs:** Applying a margin to account for required space for logistic systems proved to be insufficient. Therefore, the LM should be able to add the required space at the right location in the concept designs. In the first place, this provides the naval architect with sufficient space to work with when detailing the concept designs. Secondly the naval architect is provided with information on the required positions of logistic systems as well as possible design challenges with regards to aboard logistic processes. The latter might be the case where multiple logistic activities take place in the same area, e.g. compartment, vertical connection or deck. This might be caused by the layout of related functional systems as well as by the chosen routing between those functional systems.
5. **Complement to the Packing approach:** As explained in the previous requirement, required logistic systems should be added to the concept designs as separate systems besides the functional systems. Within DMO the Packing approach is used during concept exploration, section 1.3. Therefore the required logistic systems developed by the LM should be added to the concept designs created by the Packing approach. This requires the LM to be able to provide information to or be implemented in the Packing approach.
On the other hand the Packing approach should also be able to provide information on each concept design to the LM as the size and location of required logistic systems is dependent on the configuration of the functional systems.
6. **Able to analyse designs with regards to logistic performance:** Part of concept exploration is making and finding trade-offs between various design options in order to get design insight. Various performance measures have been used in the past to differentiate designs, for instance technical feasibility (positive stability, sufficient reserve buoyancy) or ship characteristics (costs, size, shape of the superstructure) Zandstra et al. (2015). Logistic performance is key in logistic driven vessels, therefore logistic performance of concept designs has to be investigated. Insight in the logistic performance of concept designs can be used to steer the concept exploration towards logistically more promising designs.

2.2. Finding paths in concept designs

Now the requirements for the LM are set, this section elaborates on the path finding approach of the LM introduced in section 1.5. The use of network theory will be further explained and investigated in this section.

2.2.1. Network theory

In section 1.3 the choice for networks to be used in the path finding has been discussed. With regards to ship design, networks can describe various primary architectures, (Brefort et al., 2018). Please note that the architectures described by Brefort et al. (2018) *could* be described by networks, but other descriptions could also be applied. The *physical architecture* describes spatial relationships in the vessel's layout. For instance, the physical architecture could describe the vessel's structural subdivision in compartments, like is done by a network in Shields et al. (2018). Nodes would represent those compartments, while edges describe possible connections between those compartments. 'Missing' edges between horizontal adjacent compartments represent watertight bulkheads between these compartments. The *logical architecture* represents system relations, for instance information flow between the bridge, radar and weapon systems or power flow between a generator set and power using systems. Further the *operational architecture* is defined as the description of the temporal behaviour of the ship or ship's systems. Figure 2.1 visualises the relation between the physical, logical and operational architectures. In this thesis temporal aspects of logistic processes are not taken into account, see section 1.1. Therefore the operational architecture will not be used. The physical (the ship) and logical (the logistic system relations in the ship) architectures will both be used to create a physical solution, i.e. to route logistic systems between logistically connected systems in a logistic driven vessel. The physical architecture will be described by means of a network. One of the main advantages of networks is that it enables the relatively easy and efficient application of path finding algorithms, like Dijkstra's and Yen's (Yen, 1971) algorithms.

2.2.2. Path finding and selection

Since the route of a logistic system from a source to a sink system can be seen as a path through a ship, the application of network theory can be justified. Indeed, network theory is often used in path finding problems,

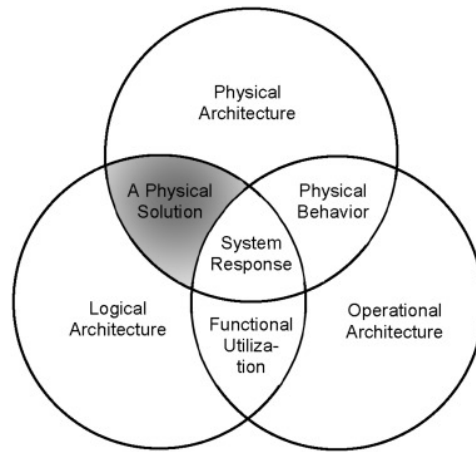


Figure 2.1: Visualisation of the relation between the three primary architectures applicable to distributed systems in ships, (Brefort et al., 2018). Highlighted in grey is the area of focus for this thesis.

see for instance (Jensen and Bard, 2003) and algorithms like Dijkstra's shortest path algorithm are available. Using existing algorithms increases the time available for the development of the LM.

The remainder of this section describes how path finding based on a network representation of a ship can be done. For explanatory reasons only simple example cases are presented here. Figure 2.2 shows that the longitudinal position of a vertical connection can be described continuously (some x on $x=[0:LOA]$) or discrete (for instance in steps of compartments). In the examples only the discrete positions are used. Discretisation can simplify calculations significantly, but also allows for easy application of network theory.

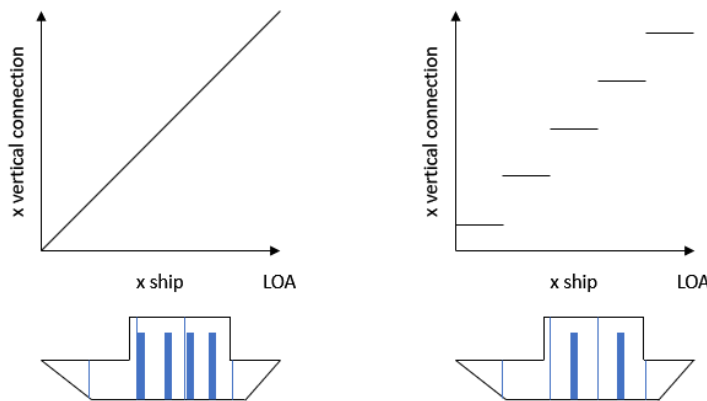


Figure 2.2: Continuous (left) and discrete (right) positions of a vertical connection. Continuous positions offer many (infinite) possible positions, while discrete positions offer only five positions in this case. Using discrete positions will therefore simplify of choosing positions for logistical systems.

Figure 2.3 shows a reduced model of the side view of a ship. This example ship consists of sixteen compartments, four in x -direction and four in z -direction. For simplification reasons, the y -direction is not considered in this example. Each compartment is represented by a node, while each connection is represented by an edge. Assume system A in compartment 1 and system B in compartment 10, which are logistically related, see fig. 2.3. The figure shows four possible paths between those systems. In total 132 routes between system A and B are, from a routing perspective, possible. This example highlight two issues, namely the existence of *undesirable paths* and *enumeration issues*, caused by the number of possible paths. They are explained in detail below.

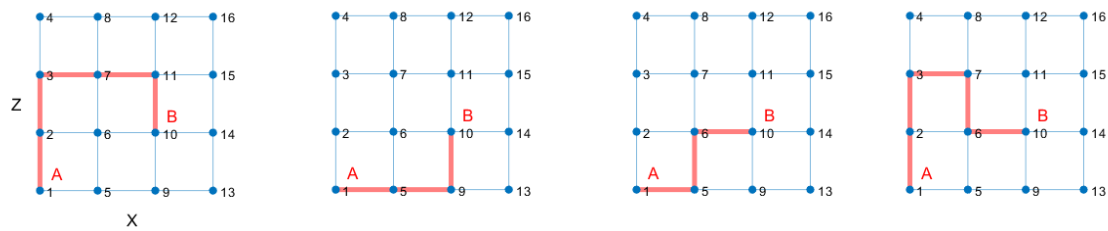
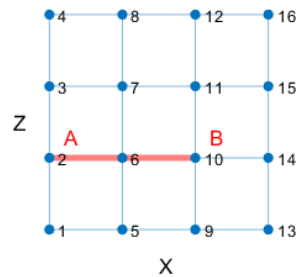


Figure 2.3: System A and B positioned in a simplified side view of a ship. Also four out of 132 possible paths between these systems are shown.

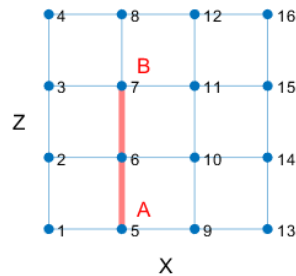
1. Undesirable paths

Although paths might be possible from a routing perspective, not all paths are desirable, (Hölscher et al., 2006). Analysing path structures, the following characteristics were found.

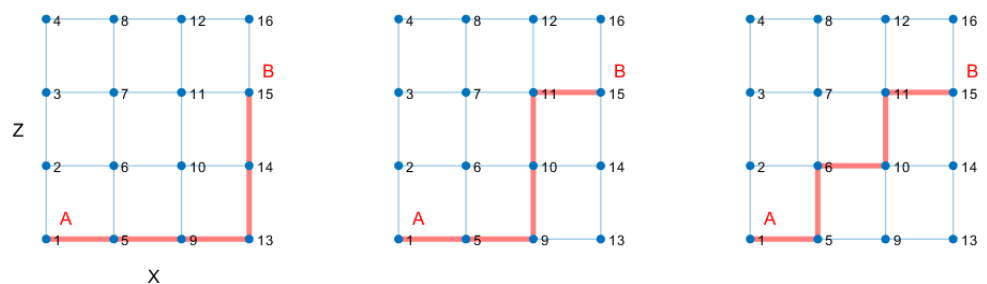
- Shortest distance paths
 - Horizontal connection only, path structure 1.



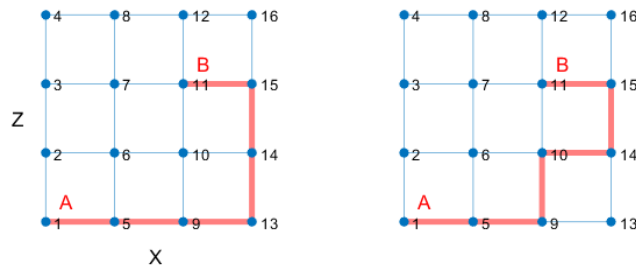
- Vertical connection only, path structure 2.



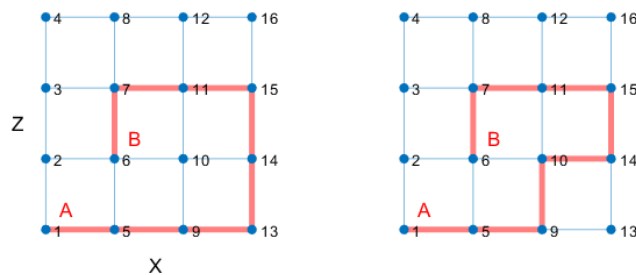
- Combination of horizontal and vertical connections, including different degrees of directional switch, path structure 3a - 3c.



- Longer distance paths
 - Minimal number of vertical connections, including different degrees of directional switch, path structure 4a - 4b.



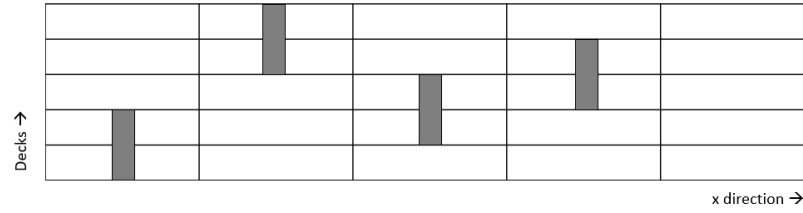
- Number of vertical connections larger than minimal number of vertical connections, including different degrees of directional switch, path structure 5a - 5b.



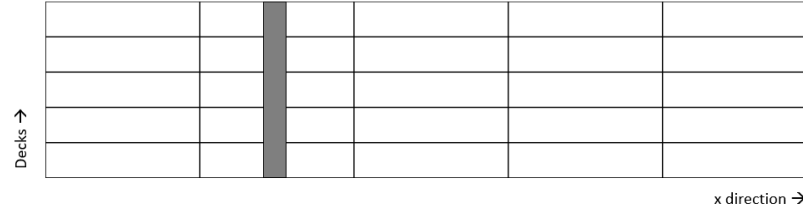
Before drawing up a conclusion on the different path structures, the term *degree of directional switch* or shortly *directional switch* is explained.

The *directional switch* is a term adopted to describe the number of directional changes needed to complete a path. Each time an edge has another direction than the preceding edge, the directional switch is increased by one. Hölscher et al. (2006) describes a study on human way finding in multi-level buildings. They identified that staircase design could present major navigation issues. Indeed, a stairway should not only serve as a spatial connector but also as a visual focus. In general, stairways should help integrating vertical information while exploring multilevel buildings and they should ease experiencing the layout spatially with respect to the building as a whole (Hölscher et al., 2006). In ships, vertical connections serve as visual focus too (personal communication, the author's personal experience, BBC (2018)). Certainly in the case of naval ships, the view outside the ship is limited, and therefore way finding in the ship depends on internal visual references. Staircases are one of the main visual references for recognising one's longitudinal position in a ship. However, this heavily depends on the staircase design. Multiple small staircases spread over the ship give less positional reference than one large staircase. An example is given in fig. 2.4a, where design A has many spread staircases, while design B, shown in fig. 2.4b, has one large staircases. Way finding in design B is may more straightforward compared to design A. In design B the path between any pair of points in the ship have directional switch equal to either zero, one or two. In design A the directional switch ranges from zero to eight. Hence directional switch is chosen as a measure for route complexity.

Returning to the different path structures, intuitively the overly complex route concepts 5a and 5b are discarded, unless a more direct routing is not possible. Further, shorter paths are generally more preferred than longer routes, to minimise movement effort. Also, less directional changes are generally more preferred (Hölscher et al., 2006). So option 3a is preferred over option 3b. However, the preference of shorter routes with multiple directional switch (concept 3c) over longer routes with less directional switch (concept 4a) is unclear. While concept 3c has a shorter route and requires two short vertical connections, concept 4a requires only one long connection. A long connection might be preferred over multiple short connections in the case of a lift. Also, again, from a personnel movement and aboard navigation perspective, a simple vertical connection layout is preferred as vertical connections serve as



(a) Design A, multiple small staircases.



(b) Design B, one large staircase.

Figure 2.4: Two different vertical connection designs. Way finding is straightforward in design B, while way finding in design A is difficult due to the lack of consistent visual reference.

visual focus in layouts (Hölscher et al., 2006).

Summarising, the following general rules for single route selection have been found so far:

- (a) *Shorter routes are preferred over longer routes;*
- (b) *Routes with less directional changes are preferred over routes with more directional changes;*
- (c) *Routes with minimal number of vertical connections required are preferred.*

The route concepts shown are simple cases. Indeed, in the case of a bigger grid and more separation between systems even more complex paths are possible. How can a suitable path between any systems be found? Is enumeration of all route options required? Full enumeration is seen as impractical due to computational effort and memory required (Shields et al., 2018). Therefore the second issue is:

2. Enumeration issues

In the example given in fig. 2.3 the number of loopless paths between system A and B is 132. Because the logistic systems *have* to be added to the design, one route *should* be chosen. The rules listed above can help in the selection of a suited path for each system relation.

In addition to systems A and B, a second set of system relations is added to the routing example, system C and D in compartment 2 and 5 respectively. System C and D have a total of 98 number of loopless paths. The complexity of the routing problem for the four system case increases as the total number of route combinations is $n_{routes,AB} \cdot n_{routes,CD} = 132 \cdot 98 = 12936$. As one route combination has to be chosen in order to be able to implement logistic systems in the concept design, one of the 12936 combinations has to be chosen. The selection rules for individual paths can be used to reduce the number of options. In general, the number of route combinations is calculated by eq. (2.1). However, besides the number of route combinations, computation time becomes an issue in larger grids.

$$n_{combinations} = \prod_{i=1}^{n_{systemrelations}} n_{routes_i} \quad (2.1)$$

In table 2.1 an overview is given of the maximum number of route combinations, for different numbers of system relations and for different sized grids. Also the required computation time for all routes is given. A ship is generally larger than five by five compartments and can include more than 1000

system relations (Gillespie et al., 2013), so the full enumeration of all possible paths for multiple logistic system relations can take hours and is considered to be impractical. Indeed, the Packing approach generates thousands of concept designs, which all require this path finding and selection, in just hours. Increasing the time required to generate one concept design from seconds to hours is considered to be an unwanted situation, since it limits exploration efforts. See for instance Shields et al. (2018) and (Duchateau, 2016).

Therefore, considering the calculation time required, the unwanted paths and memory required to store all paths, there is a need for a novel *path finding and selection method*, taking into account the rules for one pair of systems listed above. However, taking rules for one pair of systems only is not enough.

System relations			Size grid [nodes]		
			3x3	4x4	5x5
5	Time required to calculate all paths	[sec]	0.02	0.28	253.27
	Number of route combinations	[-]	$2.5 \cdot 10^5^*$	$2.1 \cdot 10^{11}$	$4.7 \cdot 10^{19}$
10	Time required to calculate all paths	[sec]	0.04	0.56	506.55
	Number of route combinations	[-]	$6.2 \cdot 10^{10}$	$4.4 \cdot 10^{22}$	$2.2 \cdot 10^{39}$
20	Time required to calculate all paths	[sec]	0.08	1.12	1013.09
	Number of route combinations	[-]	$3.8 \cdot 10^{21}$	$2.0 \cdot 10^{45}$	$4.8 \cdot 10^{78}$

* The number of route combinations is calculated as follows, explained for the case of a grid size of 3x3 nodes and five system relations. For each system relation up to twelve paths are possible. The number of route combinations is then $12^5 = 2.5 \cdot 10^5$.

Table 2.1: Route enumeration, corresponding computation time and route combinations to choose from, given for small grids

Indeed, other design rationale has to be involved as well. Again, assume the simple example case with the systems A, B, C and D. Assume only the shortest paths to be selected from, named 1a - 1c and 2a - 2b, for system relation AB and CD respectively. The shortest paths are shown in fig. 2.5. A total of six route combinations are possible, which are shown in fig. 2.6. Different combinations require different number of vertical connections in the ship, for instance. Combination 3 and 6 require just one vertical connection, compared to two required vertical connections for the other options. Combining connections could reduce the volume required for logistical systems in the ship. From a ship design point of view choices have to be made regarding combination of paths in order to reduce ship size. On the other hand, the overlap of paths might need to be reduced to prevent congestion. In that case combination 1 is preferred. The following rule can be added, which has to be taken into account in the selection of paths:

- (d) *The impact of the combination or separation of paths to reduce or increase the number of logistic systems on the ship size has to be considered.*

However, the number of path combinations is still a challenge. See section 3.7 for a further elaboration on path finding and selection in the LM.

2.2.3. Summary

The LM is based upon network theory, in which the ship is described in a network. Although path finding in a network is simple and algorithms, like Dijkstra's shortest path algorithm, are available, investigation of paths presented two issues: undesirable paths and enumeration challenges. The following four characteristics describe which paths are preferred:

1. Shorter routes are preferred over longer routes;
2. Routes with less directional changes are preferred over routes with more directional changes;
3. Routes with minimal number of vertical connections required are preferred;
4. The impact of the combination or separation of paths to reduce or increase the number of logistic systems on the ship size has to be considered.

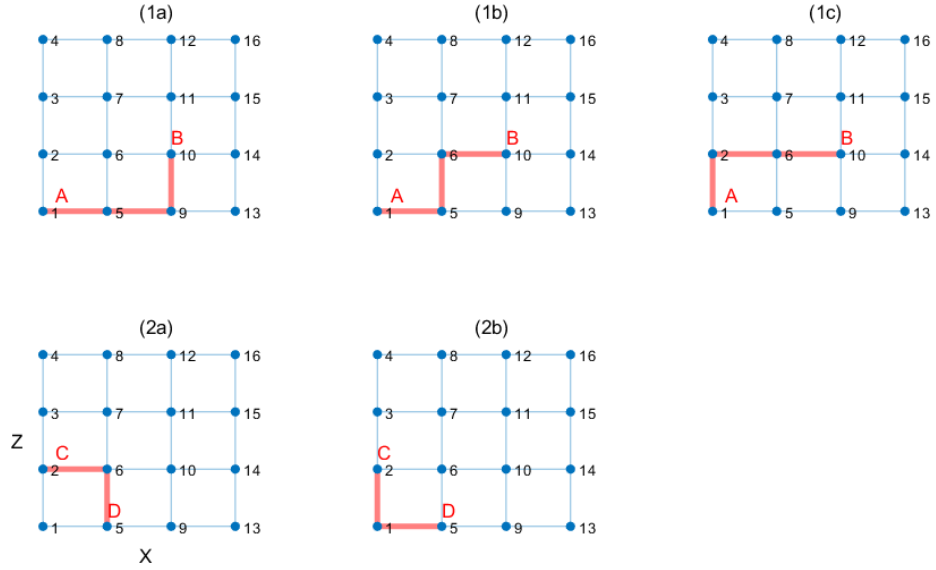


Figure 2.5: Three shortest paths between system A and B, two shortest paths between system C and D.

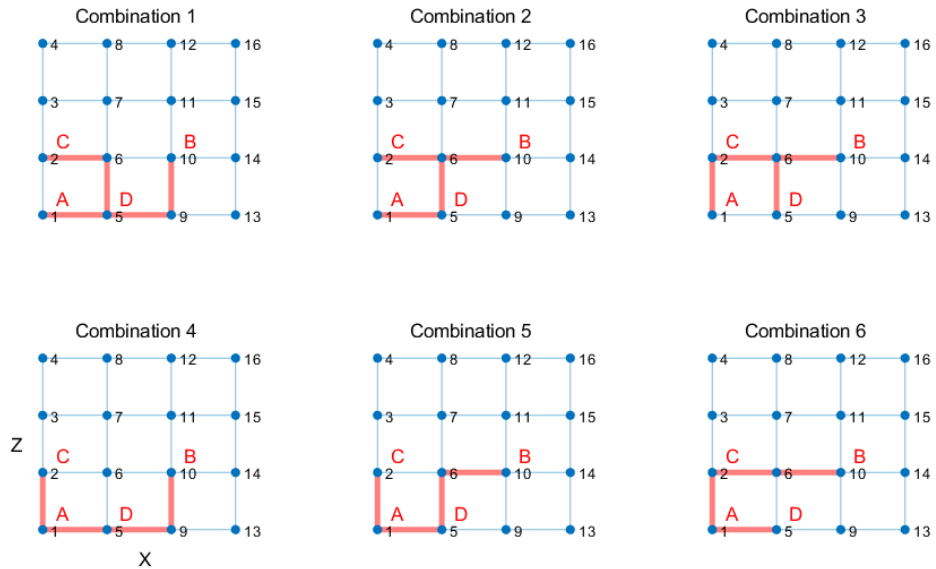


Figure 2.6: Six shortest path combinations, showing different number of required vertical connections.

These characteristics or ‘rules’ can be used to solve a part of the enumeration issue. Indeed, the number of route combinations increases such that enumeration of all routes becomes impractical in both terms of time and memory. Therefore the rules for preferred routes can help to reduce the number of routes that needs to be investigated and thus reduces the enumeration problem. Finding desired paths efficiently proves to be a challenge with existing path finding algorithms. Further, in the case of multiple desired paths, one path has to be chosen. To find desired paths efficiently for all logistic system relations, a novel *path finding and selection method* is required.

In this section the locations of systems and the subdivision of the ship are assumed to be known. However, it is not yet explained how this information is obtained. Therefore the next section discusses the Packing approach and how it can provide this information.

2.3. Complement Logistic Model to Packing approach

The LM should be complement to the Packing approach, because the required logistic systems need to be added to the concept designs. This section investigates the possibilities the Packing approach offers and describes challenges associated to the integration of the Packing approach and the LM.

2.3.1. Complementing the Logistic Model with the Packing approach

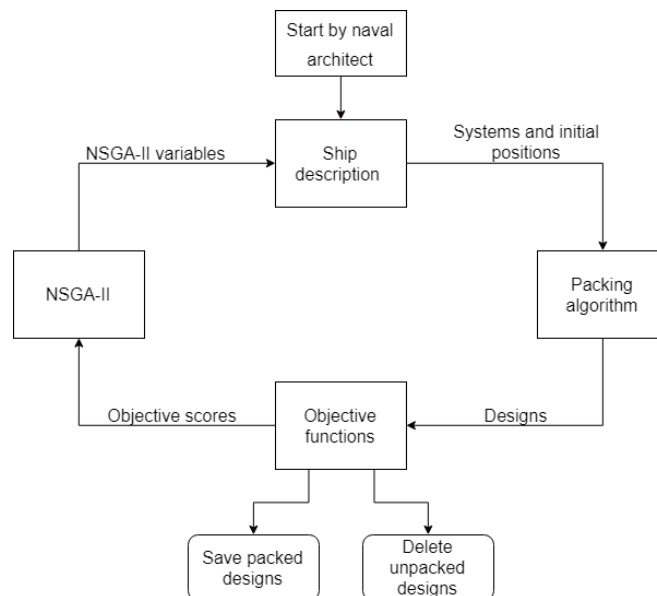


Figure 2.7: Outline of the TU Delft Packing approach

In fig. 2.7 an overview of the Packing approach is given. The Packing approach was originally developed to provide 3D concept designs, (Van Oers, 2011). However, reduced computational effort was required, allowing for a more efficient and wider exploration process, (Van Oers and Hopman, 2012). The Packing approach has been discussed in literature often, see for instance (Van Oers, 2011; Van Oers and Hopman, 2012; Zandstra et al., 2015; Wagner et al., 2010; Van Oers et al., 2017; Duchateau, 2016). In the remainder of this thesis only the relevant characteristics of the approach will be explained. For an in-depth explanation of the approach, see Van Oers (2011).

In section 1.4 it was discussed that, in order to take logistic processes into account from the very start of the concept exploration, three main components are required: known systems, known logistic system relations and known locations of systems. Although systems and their logistic relations are defined upfront by the naval architect, the locations of systems are not known in the concept exploration phase, which makes this problem hard to tackle. However, the working principle of the Packing approach gives an answer.

The NSGA-II is a genetic algorithm which is used to steer the search for ‘more promising’ designs. For a discussion on design steering, see section 3.14 and (Van Oers, 2011; Duchateau, 2016). The genetic algorithm steers the search for designs by altering the initial positions of systems and the hull size. The initial positions and hull size are described by variables. Given the ship description, the packing algorithm carries out overlap management to fit all systems in the hull. Thus, before the packing algorithm carries out overlap management the ship description and an indication of the desired, initial, positions of systems are known. These initial positions are used to fill the gap in information.

Summarising, the LM uses the initial positions of systems provided by the Packing approach, and combines these with the systems and logistic system relations developed by the naval architect to find routes between systems and to create the required logistic systems. Indeed, the ship description does not include logistic systems. The logistic systems are only added after the LM defined them. The Packing approach extended by the LM is presented in fig. 2.8. The intended approach presents some additional challenges, which are discussed in the following paragraph.

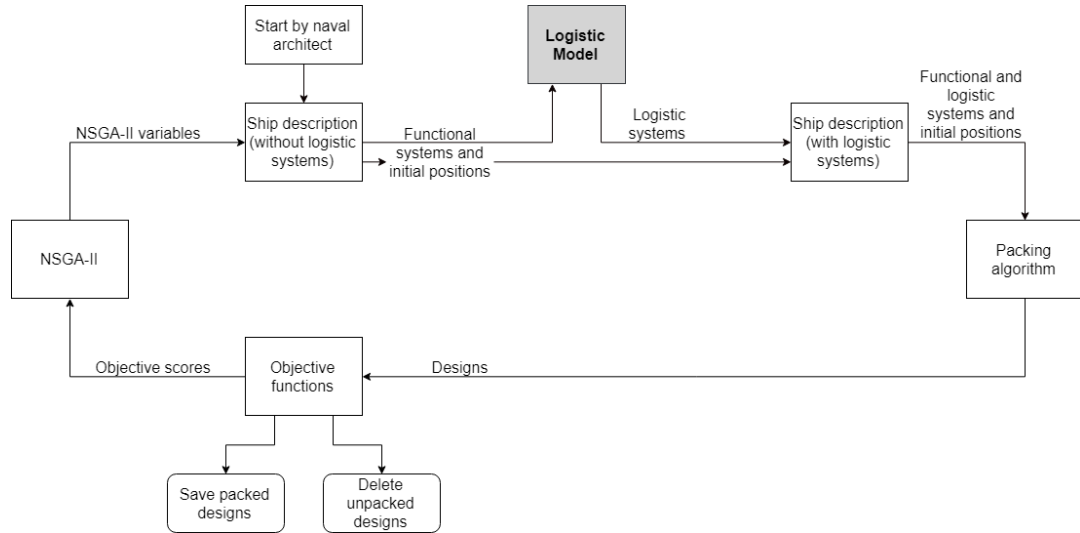


Figure 2.8: An outline of the Packing approach extended by the Logistic Model

2.3.2. Challenges

Although the Packing approach can provide initial positions of systems to be used in the LM, three possible challenges were identified. These challenges will be explained here and addressed later in this thesis.

1. How well do the initial positions of systems resemble the final design after overlap management? Or in other words, do the initial positions of systems give a reliable estimation of the final positions of systems? Overlap management can move systems from their initial positions in order to let systems physically fit in the hull. As initial positions of systems might be too close together to be physically possible, the final positions of systems might differ from the initial positions. However, since these initial locations are used to predict the logistic systems required, the initial positions need to resemble the final positions such that the initial prediction of the required logistic systems is still valid in the final design. I.e. the logistic systems, defined based on initial positions, should provide required connectivity after overlap management. The more the initial positions resemble the final positions, the more likely logistic systems will provide this required connection in the final design.
2. How to steer the design exploration towards logistically promising designs? The Packing approach is used to explore the design space and to find promising designs (Van Oers, 2011). A promising design scores better on objective functions which are predefined by the naval architect. What objective function is needed to assess the logistic performance of concept designs? Further, the NSGA-II needs to be able to steer the concept exploration such that more logistically promising designs are found. A more elaborate discussion on this issue is given in section 3.14.
3. The minimal required information required to predict the required logistic systems (systems, their locations, and the logistic system relations) is now known. The LM predicts the required logistic systems. How to add logistic systems to the ship description and can the Packing approach handle the addition of (a variable number of) extra systems? This issue is further elaborated on in section 3.13.

2.4. Conclusion

This chapter has given a set of requirements which the Logistic Model has to fulfil. In table 2.2 these requirements have been summarised and the current status is indicated. Path finding can be efficiently done by means of networks. Using small networks two issues connected to path finding and selection were highlighted. First, undesired paths are paths that are possible from a network perspective, but are undesired from a ship design perspective. Second, enumeration all possible paths for each design is considered to be impractical, given the required calculation time and memory space. This requires a novel *path finding and selection method*, which takes into account the four ‘rules’ for preferred paths presented in this chapter.

Finally, the implementation of the LM in the Packing approach was investigated, and three challenges were identified. In chapter 3 the LM will be developed further and these challenges will be addressed.

	Requirement The LM should be	Status
1	Based on known systems and logistic system relations	Investigated
2	Able to determine positions and size of required logistic systems	–
3	Able to take the structural subdivision of ships into account in the determination of the size and position of logistic systems	Investigated
4	Able to add the logistic systems to the concept designs	–
5	Complement to the Packing approach	Investigated
6	Able to analyse designs with regards to logistic performance	–

Table 2.2: Status of requirements for the Logistic Model

3

Logistic Model

The concept of the LM has been described in section 2.2, highlighting some enumeration and path finding selection issues. This requires a path selection methodology to be implemented in the LM. Further, to solve the routing problem, three main components should be known: the systems, the locations of systems and logistic system relations describing how systems are connected. The first and latter are defined by the naval architect, but the second is missing. Section 2.3 elaborated how the Packing approach can be used to obtain an estimation of the positions of systems. The current chapter elaborates on the LM in detail. First an overview of the model will be given in section 3.1. Subsequent the different parts of the model will be elaborated on. Then the implementation in the Packing approach will be explained in section 3.13. Following section 3.14 covers objective functions and section 3.15 provides a proof of concept.

3.1. Overview of the Logistic Model

An overview of the LM is given in fig. 3.1. Using input from the Packing approach and the naval architect, the LM combines the initial positions of systems, the physical and logical architecture to a starting point of the path finding and selection. Once paths for the different logistic system relations have been determined, the required connections for these paths are defined. This also includes the size of these connections. It might happen that the logistic system relations are not able to fulfil the required connectivity of all compartments. For example, some watertight compartments might not be connected by logistic systems. Therefore a check for whole ship connectivity and an update of the list with required connections is made. Finally the output consists of the full list of required connections. The following sections describe the LM, and the definition of logistic systems, their required sizes and initial positions, step by step.

3.2. Step 1. Input

The input of the LM can be divided into two categories. First, the information provided by the Packing approach and second, the information provided by the naval architect.

- The information provided by the Packing approach consists of a list with systems in the ship description and a vector with variables, which both describes the ship's hull shape and size, as well as the initial positions of systems, see section 2.3.1. Further, the vector with variables contains variables used in the selection of paths, see section 3.7.
- The information provided by the naval architect consists of the list of logistic system relations, describing the relation between logistically connected systems. Each logistic system relation is described by a source system, a sink system, the moving unit involved and a weight factor, see table 3.1. The weight factor can be used to give priority to certain logistic system relations or to certain moving units, section 3.14. The naval architect further provides the LM with information on the logistic systems that can be used by the moving units, see further section 3.8.

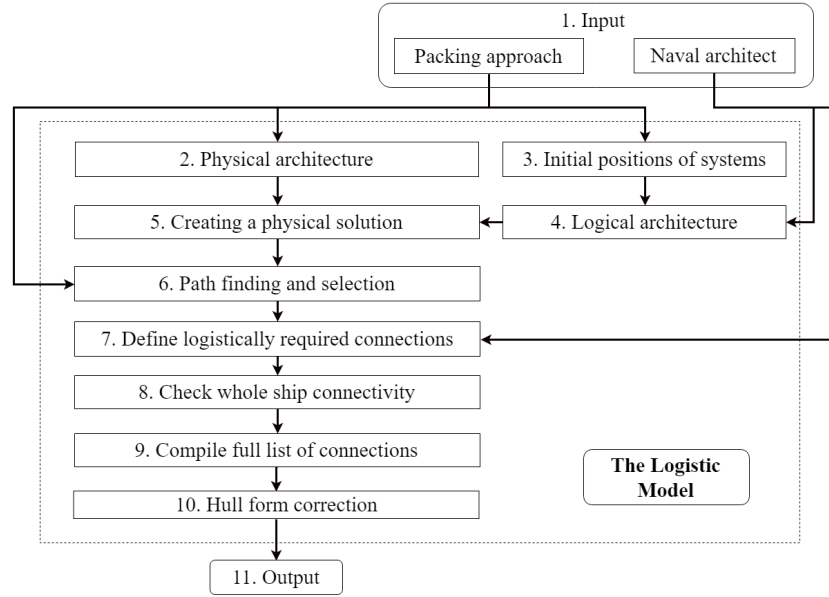


Figure 3.1: A schematic overview of the Logistic Model.

Source system	Sink system	Moving unit	Weight
Mess	Accommodation	Crew	1

Table 3.1: An example of a logistic system relation

3.3. Step 2. Physical architecture

As described in section 2.2.1 the physical architecture is the network description of a physical system, in this thesis a logistic driven ship or more specific a LPD. This section elaborates on the physical architecture developed to describe a LPD. The physical architecture has four important characteristics. First, it should describe the generic layout of the ship correctly. Second, the physical architecture should enable the allocation of logistic systems to locations in the ship. Further, it should enable the mapping of the logical architecture to the physical architecture. Finally, path finding for each logistic relation in the logical architecture has to be enabled. Since networks enable the application of these four characteristics, a network representation will be used as physical architecture.

In this section first the flow of processes aboard a LPD is investigated. Further a generic description of the layout of a LPD is created. Subsequently the physical architecture is developed. The application of the physical architecture to other vessel types is discussed in chapter 7.

3.3.1. Level of detail of processes

A visualisation of the logistic processes aboard the *Rotterdam*-class LPDs in service with the RNLN is given in fig. 3.2. This figure shows that the logistic processes take mainly place in longitudinal and vertical direction. The transverse component of logistic processes between functional systems is small in comparison with the longitudinal and vertical components for two reasons.

First, the number of systems in transverse direction of these LPDs is limited. Therefore the flow between transverse adjacent functional systems is also limited. Van Oers and Hopman (2012) describe that the number of systems in transverse direction is limited for ships in general, but in LPDs this is even further reduced because of the width of the functional systems.

Second, the longitudinal and vertical distance between functional systems is significant larger than the transverse distance between functional systems in general. Therefore the movement between functional systems takes mainly place in longitudinal and vertical direction.

Although the horizontal and vertical movement is more important than the transverse movement, choices regarding transverse separation of logistic systems have to be made. Four deck layouts can be distinguished in general, see fig. 3.3. Separation of horizontal and/or vertical connections can be used to separate logistic processes or to create circular flow in the ship for instance. For making the decision whether to implement one of these layouts during concept definition, the naval architect should have knowledge on the flow of processes through the ship. See fig. 3.4 for a physical architecture with flow indicated by different sizes of edges. So, the longitudinal cross section can be used to observed to determine the number of processes at certain locations in the ship. Therefore it has been decided to look at logistic processes in 2D. This approach has both advantages and disadvantages.

- + Taking 2D processes into account removes the need for a 3D physical architecture, which also simplifies the path finding. Indeed, a 3D network would present even more complex paths than discussed in section 2.2.2.
- + A less complex network reduces the required computation time, and thus enables a wider exploration search.
- Although a 2D approach might be used, sufficient space for logistic systems needs to be implemented. When no information is available whether one or two hallways will be used, it is also unknown if approximately two or four meters of the available width of the vessel is occupied by logistic systems. So, despite using a 2D approach, the space required in a more detailed design needs to be correctly represented.
- In the case the number of systems in transverse direction increases, the transverse flow between systems will increase as well. Therefore in more detailed designs the transverse direction of logistic processes has to be taken into account, and hence a higher detailed physical architecture might be required.

Given the elements pointed out above, a 2D approach is adopted in this thesis. Therefore the physical architecture only needs to describe the ship in the longitudinal cross section. See section 3.8 for a solution for the sizing of logistic systems.

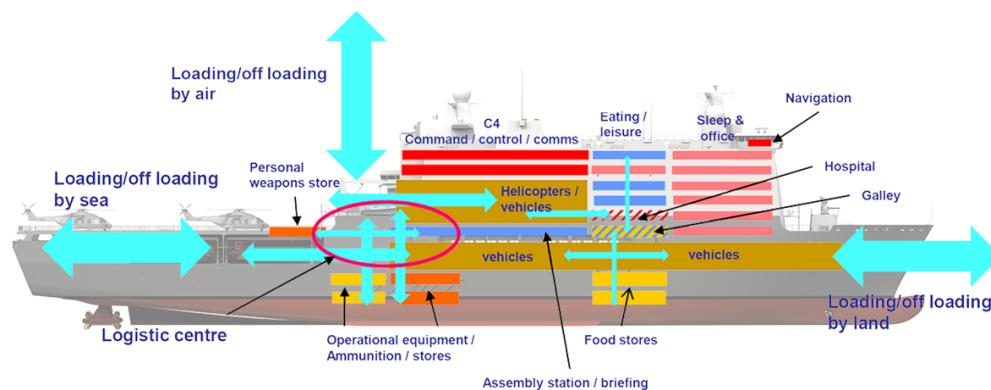


Figure 3.2: A visualisation of the logistic processes in a LPD. Generally, logistic processes take place in the longitudinal and vertical direction. Courtesy of J.J. Hopman and (Damen, n.d.)

3.3.2. Generic LPD layout

Since at this point the ship itself is not designed yet, it is also unknown which paths are available for logistic processes. Since paths are required to determine the routing of logistic systems, some description of the ship should be available beforehand. For instance, a logistic system routing through the free space above the helicopter deck is infeasible and should therefore not be considered. Based upon only the bulkhead spacing, deck spacing and the initial locations of a few systems a generic physical architecture of the vessel can be generated. The generic division of a LPD described below is shown in fig. 3.5. The words printed in *italics* in the text of this section refer to terms in this figure.

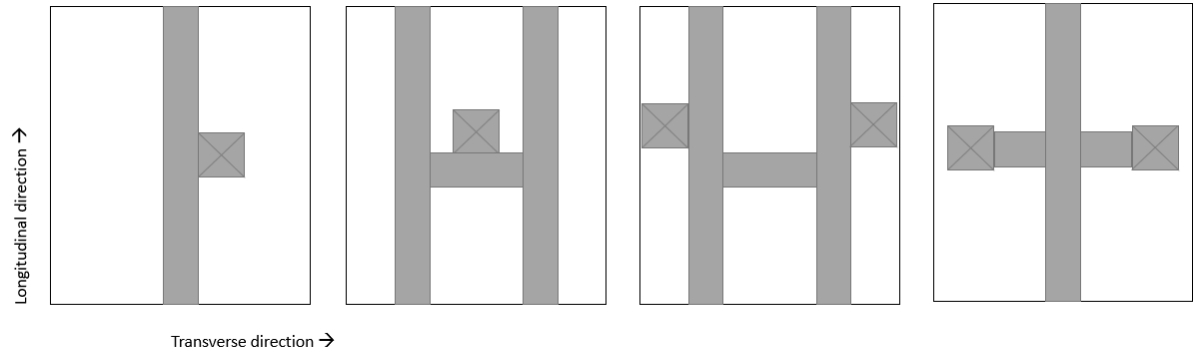


Figure 3.3: Four possible deck layouts, regarding hallways and vertical connections.

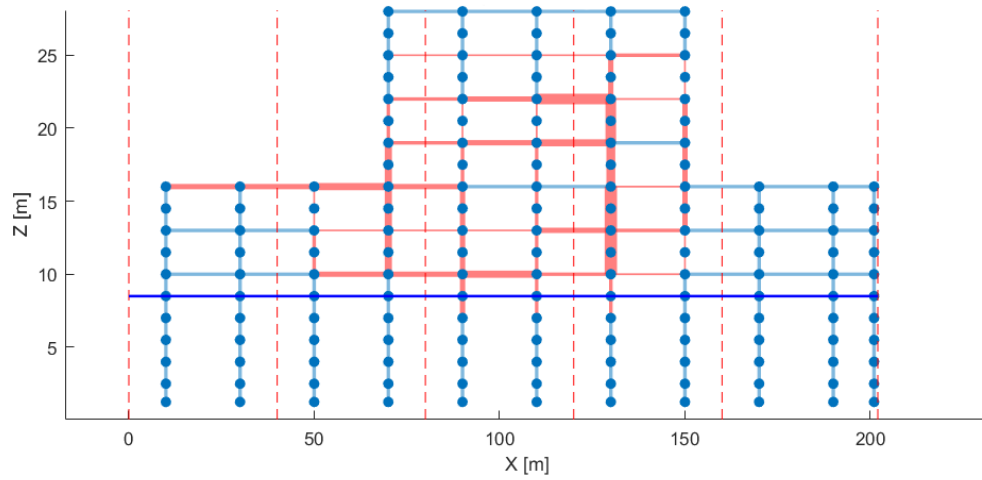


Figure 3.4: Distribution of processes over a ship, visualised by different sized, red, edges in a 2D physical architecture.

Note, this figure has been specifically created for justification of the 2D approach to processes. See chapter 7 for recommendations regarding the use of graphs in analysis of concept designs.

Ships are divided by *decks* and *bulkheads*. A space enclosed by bulkheads and decks is called a *zonedeck* (Nick, 2008) or a *compartment* (Van Oers, 2011). In this research the name '*compartment*' is used. Decks and bulkheads significantly contribute to the structural strength of the vessel. Further, watertight bulkheads are placed below the damage control deck, which is the first deck which provides horizontal access through transverse bulkheads. Watertight bulkheads play an important role in the watertight integrity of a ship. Since watertight bulkheads cannot be penetrated to provide access to other watertight compartments, connectivity is provided by vertical logistic systems to the damage control deck.

Further, bulkheads can divide the ship in zones. This zonal distribution aboard of vessels is driven by hazards like fire or chemical, biological, radiological and nuclear (CBRN) attacks. These hazards request a zonal distribution which enables the crew to safeguard zones from the effects of such hazards, e.g. by applying over-pressure to keep toxic gasses outside. Further zonal distribution is often used to separate systems, such that zones can be operated independently from other zones. This requires for instance independent energy supply in each zone. This distribution divides the length of the vessel in multiple zones, spanning all decks. It is assumed that zones are subject to a maximum length equal to 50 meters.

Besides the required connection between logistic connected systems, two other types of connection are required. Indeed, first, the subdivision in watertight compartments require a connection to the damage control deck, to ensure connectivity between each compartment in a watertight zone and all other compartments of the ship. Second, in each zone all decks have to be connected by at least one vertical connection, to ensure connectivity between all compartments in each zone, independent from connections in other zones.

Three other features observed in the design of LPDs concern the top side of the vessel. The fore, middle and aft sections of a LPD are limited in height by the *foredeck*, the *deck above the bridge* and the *helicopter deck* subsequently.

- The foredeck is assumed to be situated at the same deck as the helicopter deck, for simplicity. Above the foredeck no systems can be placed with exception of weapon systems.
- A quick search for LPDs shows that the bridge is usually situated at the highest deck. The main reason is the required bridge visibility for safe navigation.
- The helicopter deck can not be used by other systems in order to provide save and smooth helicopter operations. In this thesis the helicopter deck is assumed to be positioned aft of the superstructure. However, the size of the helicopter deck might require a starboard arrangement of the superstructure to provide for a full length flight deck. Examples of the latter configurations are the former HMS Ocean (L12) and the US Navy *Wasp* class Landing Helicopter Docks (LHD). See chapter 7 for a possible approach to the design of these vessels, while using the physical architecture developed in this thesis.

These features are used to remove parts from the physical architecture in order to limit the number of infeasible paths, and thereby increase the reliability of the model. Indeed, if the physical architecture enables path finding in the open space above the helicopter deck, undesired paths through this space might be found. The implementation of these features in the mathematical model is further discussed in the next section.

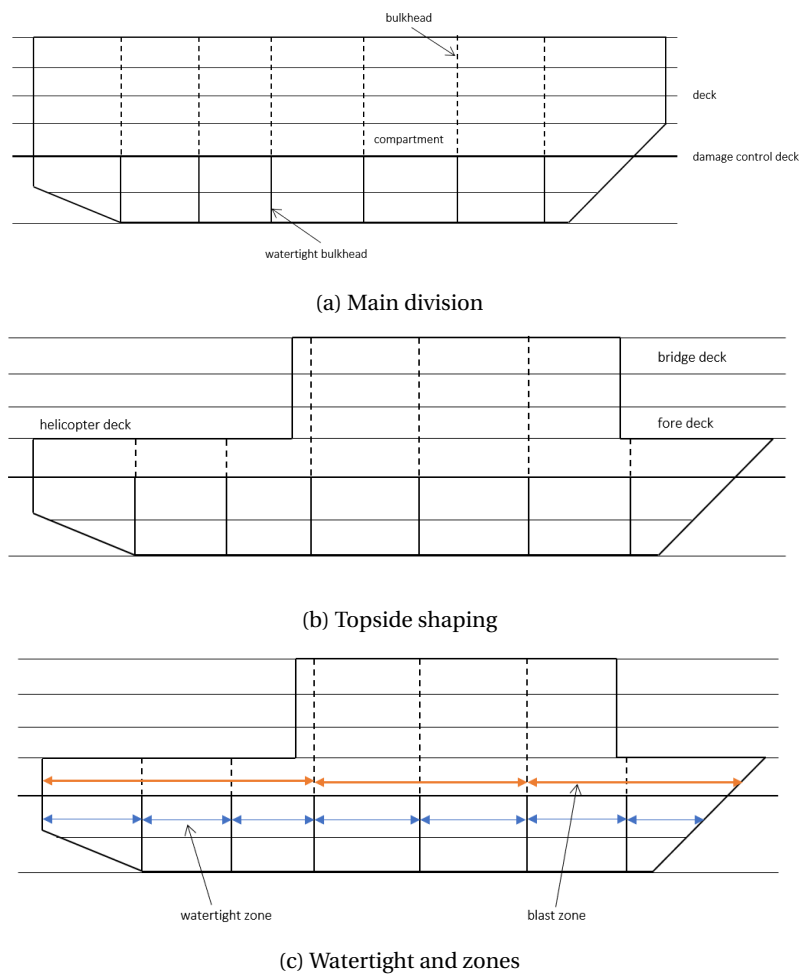


Figure 3.5: The generic division of a ship, applied to a LPD.

3.3.3. The LPD physical architecture

In this section the development of the physical architecture as a mathematical model of the generic LPD layout discussed in the previous section, is elaborated on. The physical architecture used is shown in fig. 3.6b, representing the layout in fig. 3.6a. Compartments are horizontally and vertically adjacent to neighbouring compartments. For vertical adjacency between compartments a vertical connection is required. Remember it is yet to be determined which compartments have to be vertically connected by routing logistic systems over the network, since this is dependent of the locations of the logistically connected systems. Therefore nodes representing possible vertical connections between compartments added to the network. Each compartment is represented by a node in the centre of the compartment. Nodes representing vertical connections are positioned between the compartments they serve, thus on the level of the decks.

The compartment size is determined by the positions of the bulkheads and decks. These are given as input to the LM by the Packing approach. Scaling up the example provided in fig. 3.6b, a physical architecture of a ship's subdivision is given in fig. 3.7. Although the subdivision of the ship in compartments is correctly represented, features described in section 3.3.2 are not yet included. Five features were either added to the network or taken into account in a later step in the LM:

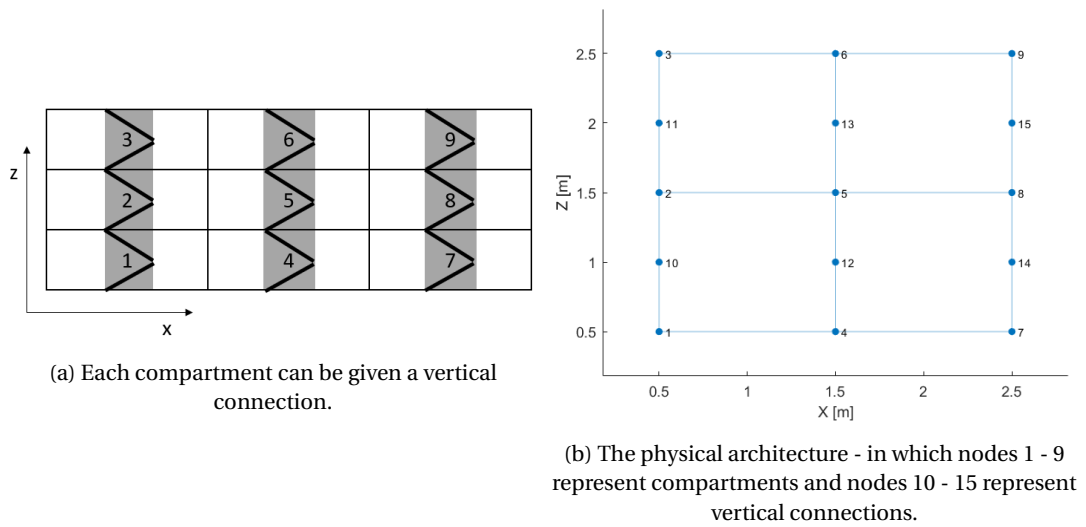


Figure 3.6: A detail of a ship's compartments and possible vertical connections, as well as the related physical architecture.

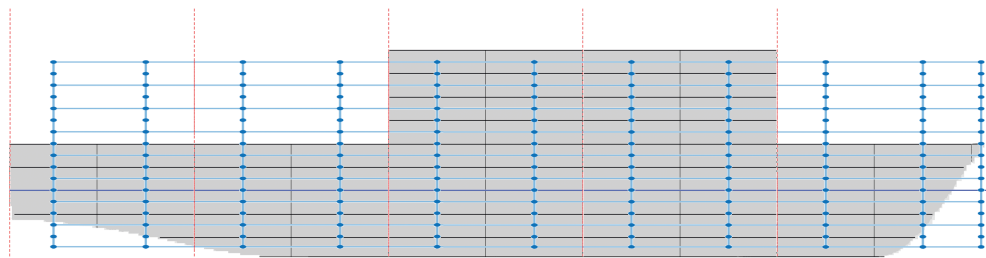


Figure 3.7: A ship's physical architecture before detailing features are added.

- *Helicopter deck.* Nodes and edges above the helicopter deck are removed from the network as no routing is possible in this area. Only the nodes representing compartments directly above the helicopter deck are kept. This is done for two reasons. First, the helicopter deck needs to be assigned to a compartment. How this allocation is done is explained in section 3.6. Second, passage over the helicopter deck should be possible, for instance to move helicopters from the helicopter deck to the hangar.

- *Foredeck.* Similar to the helicopter deck, the nodes and edges above the foredeck are removed with exception of the compartments directly above the foredeck. The length of the foredeck is assumed to be 15% of the LOA. The main reason is the free arc needed to operate a weapon system at the foredeck, for which 15% LOA seems appropriate. The naval architect is able to decrease or increase the size of the foredeck. From a ship motions perspective this value could be even larger, depending on the operational use of the ship. Indeed, Brown (1987) (cited in Pawling et al. (2013)) places the bridge of a frigate at $\frac{LOA}{3}$, measured from the bow, to reduce motions on the bridge.
- *Watertight division.* The ability to sustain damage and stay afloat is one of the principle drivers in the design of vessels, as explained in section 3.3.2 and section 3.13.2. The watertight division of a vessel removes connection between horizontally adjacent compartments. This is represented in the physical architecture by removing edges between horizontal adjacent compartments below the damage control deck.
- *Zone division.* A zone is not represented in the physical architecture. However, it is an important feature in naval vessels and therefore taken into account in the definition of extra required logistic systems, see section 3.9. The size of a zone is assumed to have a maximum size of 50 meters and to be enclosed by bulkheads.
- *Hull shape.* Till this point the shape of the hull below water has been treated as a block. However, a ship's hull is rarely barge shaped. Seen from the side the hull of a ship is shaped more like a trapezium, see fig. 3.5. In fig. 3.8 the aft part of a ships hull and the physical architecture of that ship is shown. The physical architecture does not correctly represent the hull shape. Therefore it is required to correct the logistic systems for the hull form by trimming the parts of the logistic systems stabbing through the hull. This adaption is further explained in section 3.11.

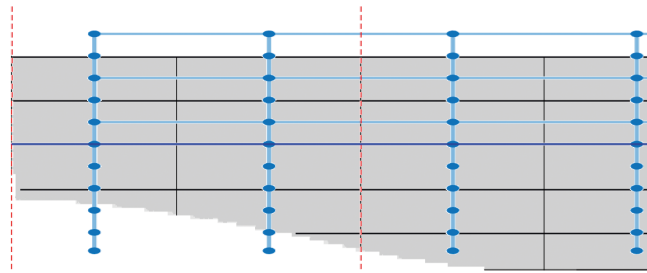


Figure 3.8: Discrepancy between actual hull form and the physical architecture

Concluding the physical architecture developed in this thesis represents the subdivision of a LPD. Although not all relevant features are described in the network itself, like the hull shape, the physical architecture developed proved to be suitable for mapping of the logistic to the physical architecture and the application of path finding and proper definition of required logistic systems. The logistic systems are corrected for the hull shape in section 3.11.

3.4. Step 3. Initial positions of systems

The initial positions are defined based on input of the NSGA-II and subject to location constraints. The initial positions of systems serve as a starting point for the overlap management performed by the packing algorithm. Note that the initial positions in the Packing approach are taken as the most aft and lower corner of every system in the longitudinal cross section. Initial positions thus do not represent the geometric centre of systems. The same applies for the final positions of systems. See section 5.1.1 for a discussion on the impact of this location definition on the results of this thesis.

The genetic algorithm provides two values for each system i , ranging between 0 and 1: x_{genetic_i} and z_{genetic_i} . The first is used to determine the initial global longitudinal position, x_{global_i} , and the latter is used to find the initial vertical position, z_{global_i} , of system i .

The initial longitudinal position of a system is function of a minimum allowed position x_{min_i} , a maximum allowed position x_{max_i} and $x_{genetic_i}$. The location limitations can be used to limit the longitudinal position of a system to, for instance, $[0.2 : 0.7] \cdot LOA$. x_{global_i} , in meters measured from the stern, is calculated using eq. (3.1), in which x_{max_i} and x_{min_i} are given in meters measured from the stern as well.

$$x_{global_i} = x_{min_i} + (x_{max_i} - x_{min_i}) \cdot x_{genetic_i} \quad (3.1)$$

Similar, the initial vertical position of a system is function of a minimum allowed deck z_{min_i} , a maximum allowed deck z_{max_i} and $z_{genetic_i}$. To determine the initial deck on which a system is placed, z_{global_i} , $z_{genetic_i}$ is used to select between the allowed decks. The allowed decks obviously range from the minimum to the maximum allowed deck.

The initial locations of systems are stored in a MATLAB structure (MATLAB, 1998) with the following layout, table 3.2, and are used as input for the creation of the physical solution, section 3.6.

Name of system	Initial x-location	Initial z-location

Table 3.2: Layout of the structure containing initial locations of systems

3.5. Step 4. Logical architecture

The naval architect provides the LM with a list of logistic system relations, as explained in section 3.2. Since a system can be duplicated in the Packing approach, the logistic system relation provided by the naval architect could describe multiple system relations in reality. For instance, the ‘mess’ is modelled as one mess object, while the ‘accommodation’ can consist of four accommodation blocks. Since these four blocks can be positioned at different locations in the ship, connection for each block needs to be assured. Therefore the list with systems in the ship description is compared with the logistic system relations provided as input for the model. This way a full list of logistic system relations for all systems actually in the ship description is created. An example of this mapping is given in table 3.3. Now all logistic system relations are known, the physical architecture of the ship, the physical and logical architecture of the systems can be combined into a physical solution. This is done in the next step, section 3.6.

3.6. Step 5. Creating a physical solution

A physical architecture of logistic driven ships is developed in section 3.3. In section 3.4 and section 3.5 the logistic systems relations are derived. The physical architecture describes the adjacency of *compartments* in the ship, and the logical architecture describes relations between *systems*. Therefore the systems need to be allocated to compartments. This is called a physical solution in this thesis, (Brefort et al., 2018).

3.6.1. Initial position translation

The initial positions of systems is explained in section 3.4. Above the foredeck and the helicopter deck no systems can be placed. However, it might be that the allowed position of a system is above these decks. To improve the estimation of the LM the initial locations of systems positioned above the fore and/or helicopter decks are horizontally translated into the superstructure, using eq. (3.2). This will place the systems in available compartments of the physical architecture. In fig. 3.9a and fig. 3.9b the initial positions of systems before and after the described translation are shown subsequently.

$$x_{glob_{new}} = \max(x_{min}, ss_{aft}) + (\min(x_{max}, ss_{fwd}) - \max(x_{min}, ss_{aft})) \cdot x_{genetic_i} \quad (3.2)$$

In which:

$x_{genetic_i}$: NSGA-II variable describing the initial x location of a system, without taking allowed positions into account.

$x_{glob_{new}}$: The global initial position of a system after translation into the superstructure.

ss_{fwd} : Position of the front end of the superstructure.

ss_{aft} : Position of the aft end of the superstructure.

x_{min} : The lower bound of the x position of a system.

x_{max} : The upper bound of the x position of a system.

Source system	Sink system	Moving unit	Weight
Mess	Accommodation	Crew	1

(a) An example of a logistic system relation

Name of system	Initial x location	Initial z location
Mess	50	15
Accommodation	60	17
Accommodation	60	20
Accommodation	65	20
Accommodation	33	14

(b) A portion of the systems included in the ship description and their initial x and z positions in meters, measured from the stern and bottom respectively.

Source system	Sink system	Moving unit	Weight	Initial x source	Initial z source	Initial x sink	Initial z sink
Mess	Accommodation	Crew	1	50	14	60	17
Mess	Accommodation	Crew	1	50	14	60	20
Mess	Accommodation	Crew	1	50	14	65	20
Mess	Accommodation	Crew	1	50	14	33	14

(c) The five systems and their initial x and z positions [in meters, measured from the stern and bottom respectively] presented in table 3.3b are combined with the logistic system relation presented in table 3.3a to four logistic system relations.

Table 3.3: An example of mapping systems and system category relations to logistic system relations

3.6.2. Allocating systems to compartments

Subsequently each logistically connected system is allocated to a compartment, based on the minimal Euclidean distance between systems and compartments. In the case the Euclidean distance between a system and two or more compartments is equal, the competing compartment situated most aft and low in the ship is selected. As system locations are defined in the most aft and lower point of the system, section 3.4, there will always be a choice between a compartment above and below the system. However, the initial location indicates that the Packing approach will try to place the system on the deck and in the compartment above the system, see section 3.4. Therefore each initial z-location is enlarged by 0.5 meters to remove this allocation issue. Once the allocation of systems to compartments is done, the mapping of the logical architecture to the ship's physical architecture is also done. Indeed, the allocation of systems to compartments provides the information needed to map a logistic system relation to a relation between the right compartments. Therefore, the compartments to which the source and sink systems are allocated are added to each logistic system relation. As a result the compartments which need to be connected by logistic systems are known.

Summarising, the ship has been described by a network of compartments, initial locations of systems are known and systems have been allocated to compartments. Further, logistic system relations are known. The only elements not defined yet are the logistic systems. The number of logistic systems, their locations and size have to be determined. Section 3.7 describes how logistic system relations and the physical architecture are used to find paths between compartments containing logically connected functional systems. After selecting a path for each logistic system relation, the number and locations of logistic systems are known. Sizing of logistic systems is elaborated on in section 3.8.

3.7. Step 6. Path finding and selection

In the previous section a physical solution has been presented. This physical solution consists of a network representing the ship, including systems which are allocated to compartments. Further logistic relations between systems are known. The final step before sizing logistic systems is to find paths between these logistic related systems in order to find the location and the number of required logistic systems.

In section 2.2.2 two main challenges regarding path finding and selection have been highlighted. This

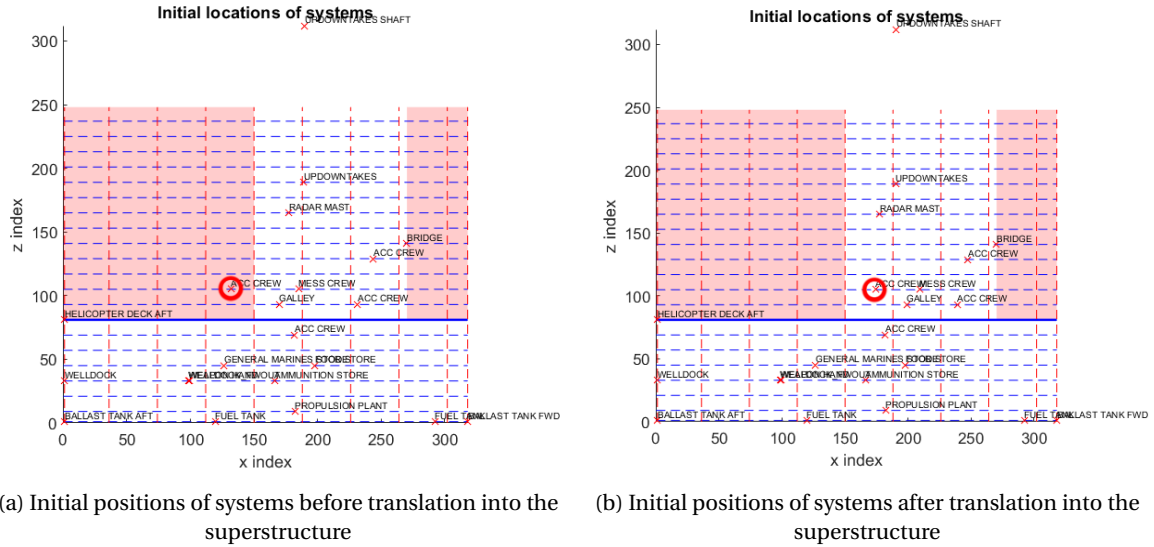


Figure 3.9: Initial positions of systems before and after translation by eq. (3.2). Note that only systems above the helicopter deck are shifted. In this case an accommodation object is moved inside the superstructure.

resulted in four generic rules to be used to select feasible and desirable paths. However, this does not present a solution for finding the right paths among the large amount of possible paths. As a solution the path finding was limited to shortest paths only, for the following reasons.

1. Searching for shortest paths only reduces the complexity of the path selection. Indeed the complex path structures 4 and 5 presented in section 2.2.2 are now excluded. A reduction in possible paths, results in a smaller number of path combinations, eq. (2.1). These assumptions lead to table 3.4. From this table can be concluded that paths can be selected based on minimal directional switch, although the impact of the combination of paths on ship size still needs to be considered.
2. Due to overlap management the initial and final positions of systems can differ significantly. This results in an uncertainty regarding the development of logistic systems. As section 3.14 points out, the logistic systems might be disconnected from the functional systems, or functional systems might be placed such that another routing is more preferred. It is therefore useless to spend computation time on finding and selection too complex routes, which might be infeasible after overlap management.
3. Searching for shortest paths only reduces the computation time significantly compared to a search for all possible paths. Since a reduction in computation time enables a wider exploration search, a time efficient path finding method is preferred.

Rule	Taking shortest paths into account only
1 Shortest route is preferred	Fulfilled
2 Less directional switch is preferred	
3 Minimal number of vertical connections is preferred	Fulfilled
4 Impact of path combination on ship size to be considered	

Table 3.4: Fulfilling path finding rules by taking shortest paths into account only.

For these three reasons the limitation of path finding to shortest paths was seen as appropriate. The impact of the combination of paths on ship size will be further analysed in chapter 5. With regards to path finding and selection two questions remain:

1. How to find all shortest paths?
2. How to select paths in the case multiple options with the same minimal number of directional switches exist?

1. Finding all shortest paths

The shortest path problem is a well known problem in graph theory. The problem is to find a path between two nodes in a graph such that the sum of the weights of the used edges is minimised. Various algorithms have been developed to find minimal paths in a graph, for instance Dijkstra's algorithm and Bellman-Ford's algorithm. The former only finds one shortest path between two nodes, (Jensen and Bard, 2003), while the latter finds all shortest paths between one node and all other nodes (Bang-Jensen and Gutin, 2000). What these algorithms have in common is that they are only suited to find one path with the minimal distance between any pair of nodes. However, the current research needs an algorithm which is able to find all possible (shortest) paths between any pair of nodes. This problem is called the K-shortest path problem, (Yen, 1971). K stands for the maximum number of paths investigated between two nodes. Note that the shortest paths found are not only the absolute shortest paths, but could also include the second, third up to K^{th} shortest paths, till no more possible paths are found or the number of paths found is equal to K. Two types of K-shortest paths exist: one in which loops are allowed and one in which loops are not allowed. The latter is clearly suited for this thesis. Some of the algorithms able to find K-shortest paths are (Yen, 1971; Bock et al., 1957; Clarke et al., 1963; Pollack, 1961). In this research Yen's algorithm, (Yen, 1971), is used because it was available and it is relatively fast. The latter is important because path finding has to be done for all logistic system relations in each design.

As Yen's algorithm proved to be still quite time consuming and the number of absolute shortest paths in most cases was smaller than ten, $K = 10$ has been adopted. Further the algorithm has been adapted to only find absolute shortest paths, again to reduce calculation time. Using the algorithm up to ten absolute shortest paths for each logistic system relation is found. Each path, as a list of subsequent nodes, and its corresponding length is then saved for further path selection.

2. Selecting paths

Now a maximum number of ten absolute shortest paths between logistic related systems is found, a further selection of one of these paths is required. Remember less directional switch is preferred, so for each path the number of directional switch is calculated, as follows. In fig. 3.10 an example path is provided. The calculation of the directional switch is based on the x location of the nodes, although the z location could be used as well. The calculation is outlined below. The reduction of directional switch is another reason to limit K in Yen's algorithm. Indeed, increasing K only results in the finding of more complex paths.

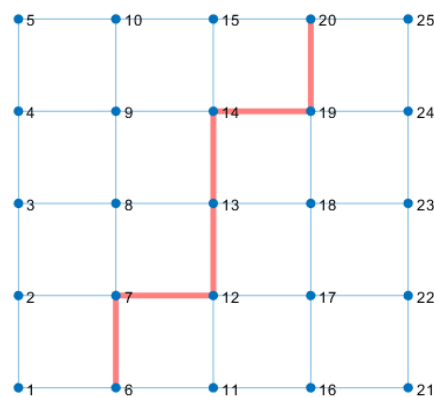


Figure 3.10: Example used for explanation of directional switch calculation. Clearly this route changes direction four times, hence the directional switch is four.

Explanation of the directional switch

For the example path in fig. 3.10 Yen's algorithm returns:

route = [6 7 12 13 14 19 20]

length = 6

The x location of the nodes is given by the following vector:

$x_{nodes} = [2 \ 2 \ 3 \ 3 \ 3 \ 4 \ 4]$

The following step is not necessary in the example case but is in the case of compartment sizes other than one [meter] and/or non-integer locations. For those cases the x location of nodes are scored.

$x_{score}(1) = 1$

For $i = 2 : \text{length}(x_{nodes})$ (in this case $i = 2 : 7$)

If $x_{nodes}(i) = x_{nodes}(i-1)$

$x_{score}(i) = x_{score}(i-1)$

Else $x_{score}(i) = x_{score}(i-1) + 1$

End

End

In the example this results in:

$x_{score} = [1 \ 1 \ 2 \ 2 \ 2 \ 3 \ 3]$

Now the diff-function of Matlab is used. The diff-function calculates the difference between entries in a vector, such that $\text{diff}(X)$, for a vector X , is $[X(2)-X(1) \ X(3)-X(2) \ \dots \ X(n)-X(n-1)]$ (MATLAB, 1998). The diff-function is applied twice.

$x_{diff} = \text{diff}(\text{diff}(x_{score})) = \text{diff}([0 \ 1 \ 0 \ 0 \ 1 \ 0]) = [1 \ -1 \ 0 \ 1 \ -1]$

Finally the sum of the absolute value of the elements of x_{diff} is taken to obtain the directional switch of the path.

directional switch = $\text{sum}(|x_{diff}|) = \text{sum}([1 \ -1 \ 0 \ 1 \ -1]) = \text{sum}([1 \ 1 \ 0 \ 1 \ 1]) = 4$.

For each logistic system relation one path needs to be selected. If there is only one shortest path, this path will automatically be connected. Further, for each logistic system relation the minimal number of directional switch is calculated. If only one path fulfils the minimal directional switch requirement, this path will automatically be selected. Finally there might be the case multiple shortest paths with minimal directional switch are left. Given the path selection criteria those paths are equally 'good'. An example is provided in fig. 3.11, in which path 1b is eliminated because of a higher directional switch and paths 1a and 1c are left for further selection. To select between these paths left, the Packing approach's genetic algorithm is used. In addition to the variables needed to describe the ship and the initial locations of systems, additional variables are used to select between paths. The whole path finding and selection approach is outlined in a pseudo code below.

The path selection method outlined below only considers one path at a time. Paths could be combined by this method if the shortest paths overlap or the NSGA-II decides to overlap the paths in the case multiple paths are available. However, a more holistic approach could be considered as well. Indeed, the combination of routes could reduce the number of logistic systems required for instance. A holistic approach could consider to combine a longer path for one logistic system relation with a shortest path for another logistic system relation in order to overlap the required vertical or horizontal connections. However, this needs an upfront decision on the desired balance between path length and number of connections. See for instance fig. 3.12a and fig. 3.12b. The first path combination requires three vertical connections and has a total length of five meters, compared to two vertical connection and a total length of seven meters in the latter path. From a logistic perspective both combinations could be evenly preferred, if the logistic processes take place sequentially, or combination one could be preferred over combination two if the processes take place simultaneously, except when the space allows parallel

processes to take place. So, deciding which path is better from a holistic point of view appears difficult, and requires more insight in the processes. Further, this needs temporal aspects to be taken into account, which is outside the scope of this thesis, section 1.1. Also, a holistic approach requires at least second shortest paths to be considered, like is done in fig. 3.12. However, this introduces various issues, as discussed in section 2.2.2. Therefore a holistic path selection has not been adopted in this thesis.

Outline path selection method

```

For each logistic system relation i
  Find m absolute shortest paths (using Yen's algorithm)
  If m = 1
    Select path
  Else
    Calculated directional switch d for each path p and  $d_{min}$  for all paths
    If  $d(p) > d_{min}$ , exclude path p from selection
    n = number of paths left
    Elseif n = 1
      Select path
    Else
      Selection of one path out of n paths by genetic algorithm
      Retrieve NSGA-II variable v(i)
      For x = 1 : n
        If  $\frac{x-1}{n} < v(i) \leq \frac{x}{n}$ 
          select path x
        End
      End
    End
  End
End
Next

```

In which:

K = maximum number of paths to be found by Yen's algorithm

$m \leq K$

$p \leq n$

$0 \leq v(i) \leq 1$

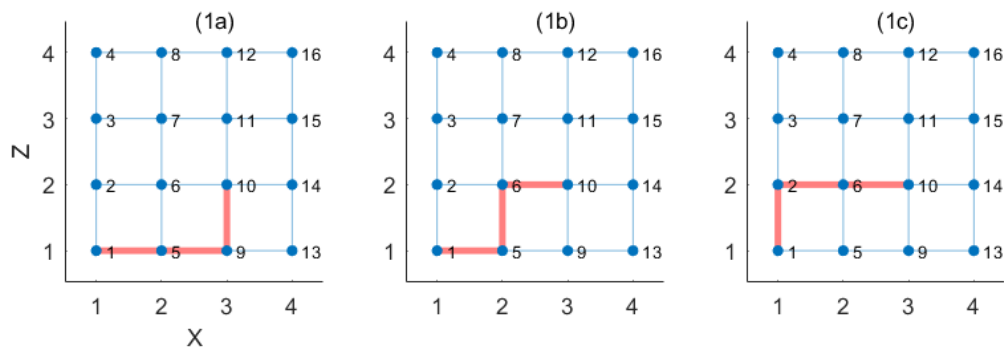


Figure 3.11: Example of paths with different number of directional switch. Path 1a and 1c have directional switch = 1, while path 1b has directional switch = 2. Path 1b is therefore eliminated from further selection.

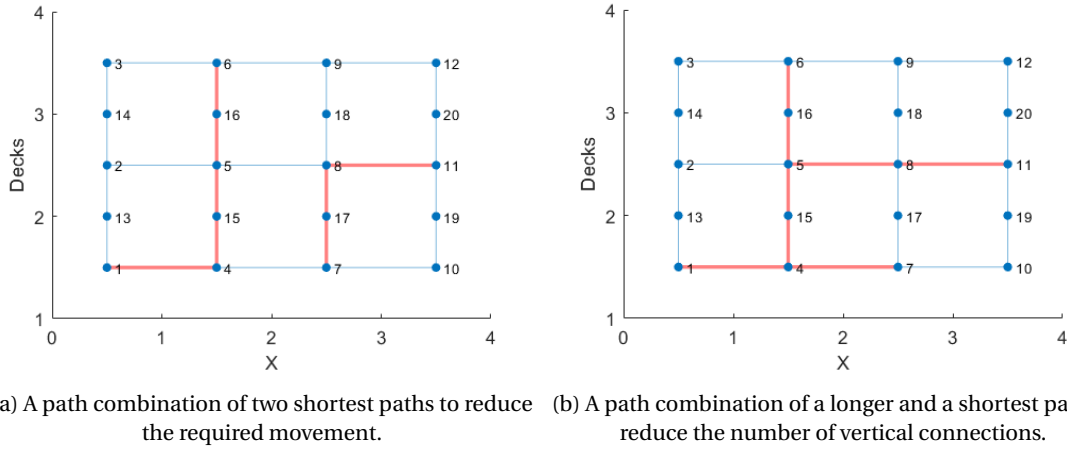


Figure 3.12: Two path combinations. A holistic path selection approach requires the consideration of temporal aspects, which is outside the scope of this thesis.

3.8. Step 7. Define logistically required connections

For each logistic system relation a path has been chosen, as has been elaborated on in the previous section. Now the logistically required connections will be defined. First, all chosen paths are combined to find all locations of horizontal and vertical logistic systems. Also the number of paths, or activities, for each moving unit through a logistic system is added. To illustrate this procedure, an example will be given.

Assume the physical architecture given in fig. 3.13. In this figure also two paths are given between compartment 1 and 6 and between compartment 3 and 8 respectively. The first path involves MU1 and the second path involves MU2. In table 3.5 the movement in the nodes is captured. Note that vertical movement is not captured in nodes representing compartments. This means that in compartment 1, 2, 4, 5 and 8 horizontal connections are required and that at the location of nodes 11 till 13 vertical connections are required.

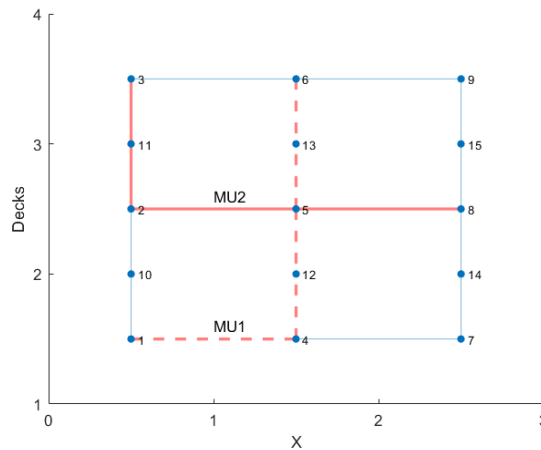


Figure 3.13: Example to illustrate the required connections based on chosen paths.

From this point horizontal logistic systems are neglected for two reasons:

1. Level of detail limitations of the Packing approach. This issue will be further elaborated on in section 3.13 and section 4.5. Here it is sufficient to note that the limited number of transverse positions of systems, (Van Oers and Hopman, 2012), requires either vertical or horizontal logistic systems to be excluded.
2. Vertical logistic systems are considered to impact the layout of a ship more than the horizontal logistic

Node number	MU1 n_{act}	MU2 n_{act}
1	1	0
2	0	1
4	1	0
5	0	1
8	0	1
11	0	1
12	1	0
13	1	0

Table 3.5: For each node the number of activities for each moving unit is captured in a table. Vertical movement is allocated to the corresponding nodes representing vertical connections, while horizontal movement is allocated to the corresponding nodes representing compartments.

systems. Although horizontal logistic systems are essential for whole ship connection too, they mainly impact the layout of one deck. Contrary, vertical logistic systems impact the layout of multiple decks. Indeed, once a vertical logistic system is placed, it occupies space on various decks, possibly restricting placement of functional systems. Also, horizontal connections need to be routed such that vertical logistic systems are connected. This requires the knowledge of the locations of vertical connections in the first place.

Each vertical logistic system connects at least one deck with another deck. To find all vertical logistic systems required, table 3.5 is further investigated. All nodes representing a vertical logistic system, that are situated at subsequent deck levels in vertical adjacent compartments and are used by one type moving unit, are combined into one vertical logistic system. The reason for separating logistic systems for different moving units is explained later in this section. The generic bottom of a vertical logistic system is the lowest deck connected, while the top is the highest deck connected, increased by one to account for required head room (in the case of staircases) or lift casing. With regards to the horizontal position of each vertical logistic system, three parameters are used. Similar to the locations of the functional systems, each vertical logistic system is given a range of allowed positions and an initial position. The range of allowed positions is described by a minimal and a maximal allowed longitudinal position. These positions are equal to the longitudinal position of the aft and forward bulkhead of the compartment containing the logistic system. The initial x position is given by the longitudinal position of the node representing the vertical logistic system in the physical architecture and is the starting point for the overlap management by the packing algorithm. The z positions is constraint to the decks connected by the logistic system.

Now the location of required logistic systems has been determined, the logistic systems need to be sized. The following factors drive the size of vertical connections. Note that many factors are also applicable for horizontal logistic systems.

1. *Minimal size requirements by moving units.* Each moving unit has a certain size, and therefore the minimal size of logistic systems is the size of the moving unit using these logistic systems. For instance, a vehicle is larger than a crew member, therefore a vehicle lift needs to be larger than a staircase for crew for instance.
2. *Type of logistic system required by moving units.* Besides restricting the size of logistic systems, moving units can also pose requirements for the type of logistic system used. Several types of logistic systems can not be used for certain moving units. For instance, a vehicle requires a lift or ramp, and cannot use a staircase, see also *function sharing of logistic systems*. Remember that such requirements don't imply that a vehicle lift has to be implemented in the design anyway. This depends on the need for vertical movement of vehicles, which is a result of the ship's layout.
3. *Function sharing of logistic systems.* In this thesis the issue of function sharing means that different moving units can use the same logistic systems. For instance, crew can use staircases intended for marines and marines can use a vehicle ramp to go to the well dock. However, the difficulty is the irreversibility of function sharing. Indeed, a vehicle cannot use a staircase like marines can use a vehicle

ramp. Also, marines can use a staircase designed for crew, but this might lead to congestion because a staircase for crew is generally smaller than a staircase for marines. A more extended example is given in table 3.6. From this table is concluded that in most cases function sharing is not possible or function sharing is (partly) irreversible. Also note that function sharing might only be possible if the logistic system is not used. For instance, if a vehicle ramp is used for transport of vehicles, marines might not be allowed to use this ramp for safety reasons. Therefore function sharing is connected to *simultaneity of processes*.

	Staircase marines	Staircase crew	Lift goods	Lift vehicles	Ramp vehicles
Marines	++	+	--	--	+
Crew	++	++	-	--	+
Goods	--	--	++	++	-
Vehicles	--	--	-	++	++

The meaning of the notations in the table is as follows. '++': very compatible; '+': compatible; '-': might be compatible; '--': non compatible

Table 3.6: Example of compatibility of function sharing between logistic systems for different moving units.

4. *Simultaneity of processes*. Logistic systems should be designed for the anticipated peak load, (NATO, 1993). Thus, when multiple processes take place in the same logistic system at the same time, the logistic system should have sufficient flow capability to prevent congestion (NATO, 1993). As temporal aspects are neglected in this study, it is assumed that all processes take place at the same time. This could lead to an overestimation of the required size of logistic systems.
5. *Number of moving units*. The number of moving units is closely connected with the following two items. However, the number of moving units itself requires a minimal size of logistic systems. Indeed, when 100 marines move to the mess, more space is required to prevent congestion, in contrast to five marines going to the laundry. On the other hand the number of moving units is function of the logistic processes taking place. Indeed, to prevent congestion, other dimensions of logistic systems are required in the case marines disembark in groups of 20 or the case they disembark in groups of 100.
6. *Minimal flow required for logistic processes*. Besides the minimal size needed to accommodate moving units, the minimal flow required for the logistic processes might also pose requirements for the minimal size of logistic elements. For instance, the planning of the amphibious assault might require that landing vessels are loaded with a certain speed. This could imply that marines need to decent from the weapon hand out to the well dock two by two. Assume a staircase is used, then the width of this staircase should not be the minimal required size by one marine, but the minimal required size by two marines side by side.
7. *Direction of flow*. Building evacuation studies point out that counterflow in logistic systems leads to interaction between both flows. This slows down the processes, (Kratchman, 2007). Therefore sufficient space has to be reserved to account for multi-directional flow.

Again, there is a need for appropriate estimation of the size of logistic systems. The following notions have been considered and assumptions have been made regarding sizing of logistic systems.

- As explained in section 1.1 temporal aspects have been excluded from this study. Therefore, simultaneity of processes is taken into account by assuming all processes take place at the same time. For the same reason the direction of flow has not been further considered. Indeed, if time is not taken into account, the interaction between counterflow processes cannot be observed.
- Function sharing might take place in reality. However, because different types of moving unit might require a different type of logistic system and logistic systems have to be designed for the anticipated peak load, function sharing is excluded from the design of logistic systems. If at a certain location in the ship a logistic system is needed for different moving units, one logistic system for each moving unit is added to the design.
- The mathematical sizing of logistic systems is based on:

- the types of logistic systems required for different moving units, to be selected by the naval architect.
- a minimal size to be decided on by the naval architect, taking into account the minimal required size by moving units and the logistic processes (referring to items 1 and 5 above respectively). To define the minimal size of a logistic connection the naval architect has to decide upon two parameters: *the minimal width* (W_{min}) [m] and the *minimal length* (L_{min}) [m] of a logistic connection. He has to take into account the choice for a single or multiple logistic systems of one type in a compartment.
- the number of moving units using the logistic system. Individual moving units, like individual marines, are not taken into account in the sizing. Instead, the sizing is based on the number of logistic activities taking place in a logistic system. If multiple activities involving marines use the same vertical connection, the vertical connection needs to be bigger compared to the case in which just one activity takes place in this connection. At some point two vertical connections might be placed next to each other, one on the starboard side and one on the port side of the ship. Modelling two logistic systems next to each other is not possible due to the reduction in level of detail described in section 3.13.4. Therefore two staircases next to each other are modelled as one staircase with doubled width. For the same reason it is assumed that the size of a logistic system increases in transverse direction only when the number of processes through that logistic systems increases. The naval architect has to decide upon the *width growth rate* (W_{gr}) [m/extra process¹] of the logistic system.

Thus, the length of a logistic connection is fixed at the L_{min} the naval architect has decided upon. The width of a logistic system is calculated for each node i in that logistic system, using eq. (3.3). This could mean that a vertical connection has a different size at each deck. This is unwanted as it will cause congestion (City of New York, 2014; BuildingCodeNYC.com, n.d.). Therefore the final width is equal to the maximum required size for any node in the logistic system, eq. (3.4).

$$W_{node_i} = W_{min} + (n_{act_i} - 1) \cdot W_{gr} \quad (3.3)$$

In which:

n_{act_i} : the number of logistic activities of a certain moving unit in the node in consideration.

$$W_{logisticsystem} = \max(W_{node_1}, \dots, W_{node_i}) \quad (3.4)$$

In the remainder of this section an example will be provided, aiming to illustrate the definition of logistically required connections. Assume a small ship with nine compartments, as shown in fig. 3.14. Nodes 10 till 15 represent vertical connections. Further assume that certain logistic activities take place in this ship. In these activities two moving units are involved, MU1 and MU2. For the moving units the following sizing parameters for the logistic systems are defined, table 3.7a.

After path finding and selection the vertical connections are used as shown in the second and third column in table 3.7b. These columns present n_{act_i} for each moving unit and each node. So for instance in node 10 two activities involving MU1 take place, while no activities involving MU2 take place. The minimal required size of the vertical connection in each node is calculated per moving unit using eq. (3.3). For instance $W_{node_{11}}$ is calculated as follows:

For MU1:

$$W_{node_{11}} = W_{min} + (n_{act_{11}} - 1) \cdot W_{gr} = 2 + (2 - 1) \cdot 0.4 = 2.4[m]$$

For MU2:

$$W_{node_{11}} = W_{min} + (n_{act_{11}} - 1) \cdot W_{gr} = 1 + (2 - 1) \cdot 0.2 = 1.2[m]$$

This means that two staircases are required between deck two and three with width 2.4 and 1.2 [m] respectively. The same calculation is repeated for each node. The results of this calculation are presented in the

¹The number of processes or activities in a node is measured by the number of paths in that node.

fourth and fifth column of table 3.7b.

The final size of each logistic system is determined per moving unit. For instance, nodes 10, 11, 12 and 13 require a staircase suitable for MU1, as presented in table 3.7b. As nodes 10 and 11 are situated in the first zone and nodes 12 and 13 are situated in the second zone, two staircases are required. The staircase in both zones serve deck one to three. To account for the free space required above the staircases, the top deck of these staircases is deck four. The width of each staircase is determined using eq. (3.4):

$$W_{staircase_1} = \max(W_{node_{10}}, W_{node_{11}}) = \max(2.4, 2.4) = 2.4[m]$$

$$W_{staircase_2} = \max(W_{node_{12}}, W_{node_{13}}) = \max(2.8, 2) = 2.8[m]$$

Both staircases are presented in table 3.7c as logistic system 1 and 2 respectively. The determination of the size of logistic system 1 and 2 is visualised in fig. 3.15. This calculation is repeated for MU2 to find the logistic systems 3, 4 and 5.

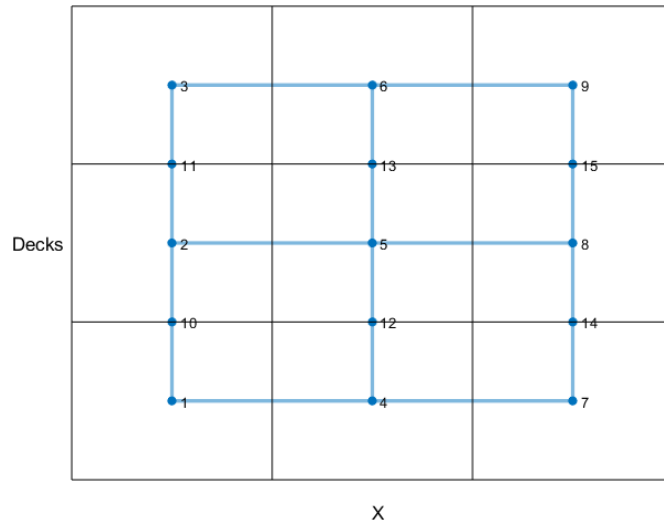


Figure 3.14: A small example case with nine compartments enclosed by decks and bulkheads. Nodes 10 till 15 represent vertical connections.

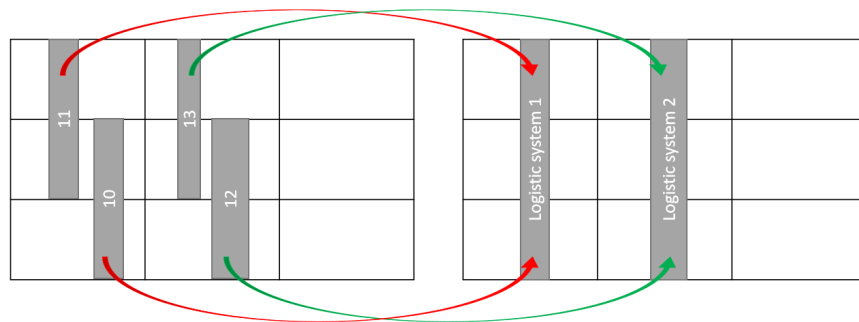


Figure 3.15: Determination of the size of logistic systems 1 and 2 based upon the required minimal size by activities in nodes 10 till 13.

Moving unit	Type	W_{min}	L_{min}	W_{gr}
MU1	Staircase	2	2	0.4
MU2	Staircase	1	1	0.2

(a) Sizing parameters for the logistic systems for each moving unit

Node	n_{act_i}		W_{node_i}	
	MU1	MU2	MU1	MU2
10	2	0	2.4	0
11	2	2	2.4	1.2
12	3	1	2.8	1
13	1	1	2	1
14	0	1	0	1
15	0	0	0	0

(b) Number of activities in each nodes and corresponding required sizes of the logistic systems in each node.

Logistic system	Bottom deck	Top deck	Length [m]	Width [m]
1	1	4	2	2.4
2	1	4	2	2.8
3	2	4	1	1.2
4	1	4	1	1
5	1	3	1	1

(c) Final dimensions of the five required logistic systems in this example case.

Table 3.7: Example of definition of connections in step 7.

3.9. Step 8. Check whole ship connectivity

The previous steps defined the logistic systems required for the connection of logistic connected systems. Although most of the ship's compartments will be connected by these logistic systems, some compartments may not. Since independent connectivity of each compartment has to be assured, additional vertical connections have to be added. In this thesis the following scenarios have been anticipated:

- Watertight compartments are not connected to the damage control deck. Compartments in the tank top are assumed to have no vertical connection requirement to other compartments.
- Compartments above the damage control deck are not connected with other compartments in a zone.

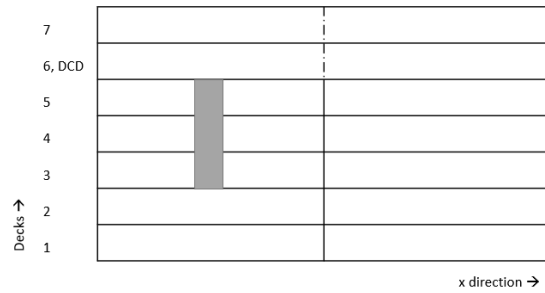
Since all logistic processes should be taken into account in the design, compartments that miss connection don't contain systems or contain systems that are not logistically connected to other systems, like generator rooms. This means that only crew should be able to reach these compartments for maintenance purposes. Therefore the additional required vertical connections are sized as standard staircases for crew.

In most cases connection will be partially fulfilled by logistic systems that are required to accommodate logistic processes. Therefore, simply adding vertical connections reaching from the lowest required deck to the upper required deck will likely lead to an overestimation of space required for logistic systems. To illustrate this issue, fig. 3.16a shows a section of a ship, in which one vertical connection has been defined between deck 3 and 5. Assume this vertical connection is a staircase, and thus can be used by crew. Above and below this staircase, connection to the damage control deck is missing. Three solutions have been considered:

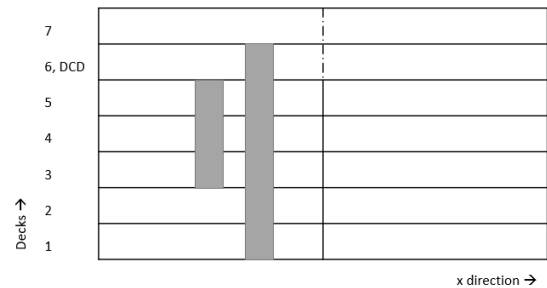
1. Add a vertical connection between deck 1 and 6, see fig. 3.16b. As deck 3 till 5 are already connected by the staircase, this introduces a significant oversizing of logistic systems, doubling the space required at deck 3 till 5. Therefore, the second solution is:
2. Add two vertical connections, one connecting deck 1 till 3 and one connecting deck 5 and 6, see fig. 3.16c. Assuming a deck height of three meters, staircase width and length of two meters, indeed the second solution requires 12 m^3 less volume compared to the first solution.

3. The third solution considered is to extend the existing staircase, fig. 3.16d. Although this requires minimal extra space, it can be a problem when multiple logistic driven staircases exist as it could force vertical connections of different sizes to be connected. However this is unwanted as this could cause congestion. See for instance fig. 3.17, which shows that extending existing staircases can be a cause for congestion. Therefore staircase sizing as shown in fig. 3.18 is undesired. For this reason this connection is not considered further.

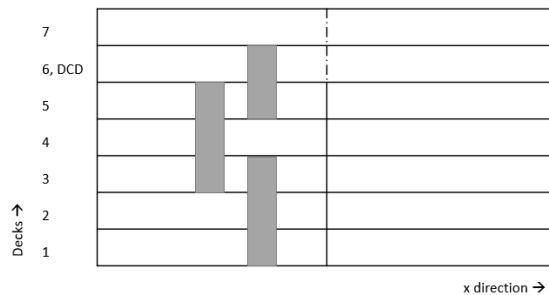
The second solution is selected over the first because of its improved space estimation. Once the required extra connection is determined, the additional vertical connections are sized. For more details on sizing of logistic systems, see section 3.8 and section 4.5.3.



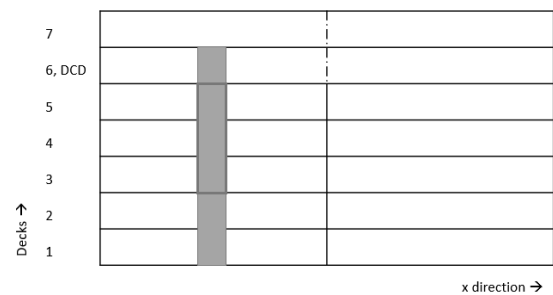
(a) Example of logistically required connection between watertight compartments and missing connection to the damage control deck.



(b) Solution 1: add one connection



(c) Solution 2: add two connections



(d) Solution 3: extend existing connection

Figure 3.16: A comparison between three solutions for missing connection in watertight compartments

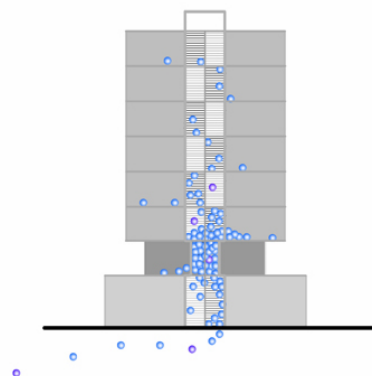


Figure 3.17: Varying size in staircase can be a source of congestion, (BuildingCodeNYC.com, n.d.)

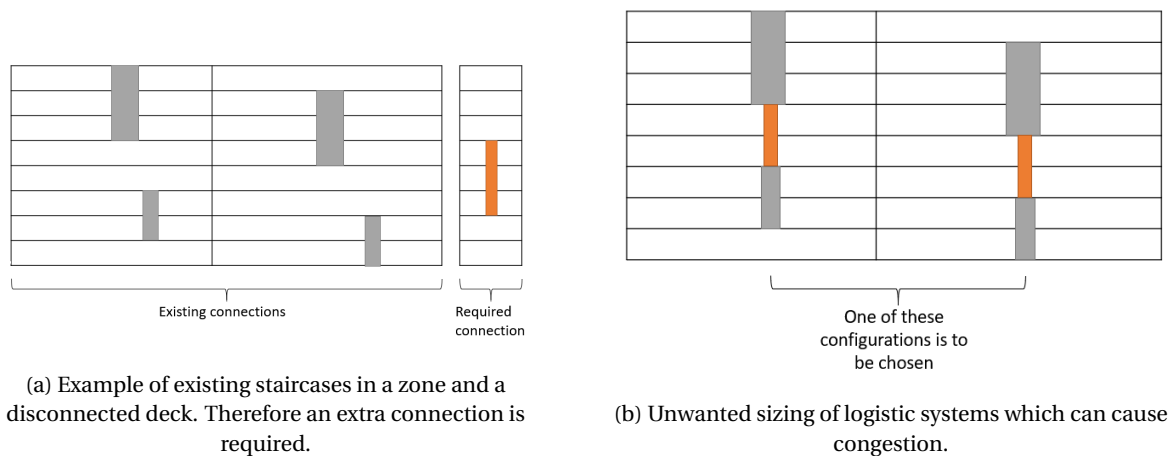


Figure 3.18: Solution 3 can cause congestion due to changes in size of the connection

3.10. Step 9. Compile full list of connections

In the previous sections the selection and definition of required logistic systems has been described. Summarising, logistic systems could be driven by three ship aspects. First, logistic systems could be required to provide connection between logistically connected functional systems. Second, watertight compartments require connection to the damage control deck. If connection is not yet provided by the logistically driven logistic systems, extra logistic systems are defined. Lastly, full connection between the damage control deck and the highest decks in the superstructure, could require extra logistic systems. The last step of the LM is compiling the full list of required logistic systems. The full list of logistic systems is stored in a structure with the following layout, table 3.8.

Initial x location [m from stern]	Bottom of connection [deck]	Top of connection [deck]	Width of connection [m]	Type of connection or MU	Lower x boundary [m from stern]	Higher x boundary [m from stern]

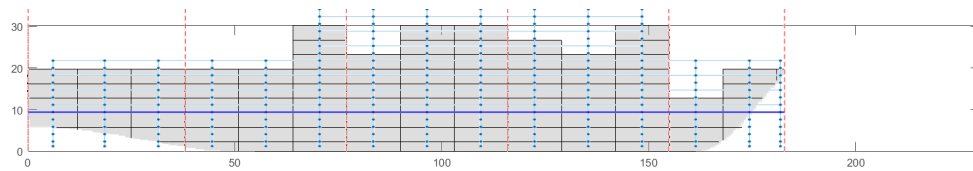
Table 3.8: Layout of the structure containing required logistic systems

3.11. Step 10. Hull form correction

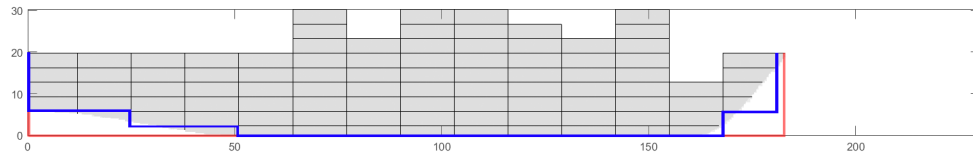
In section 3.10 the full list of required vertical logistic systems has been created. In section 3.3.3 the discretisation of the hull shape has been discussed. Since the ship hull has been treated as a barge, logistic systems in the bow and stern might stab through the ship hull. Not only is this unrealistic, the Packing approach will not be able to place these logistic systems either. Therefore the extending logistic systems are trimmed based on a deck discretisation of the hull form. In fig. 3.19a an example of a hull form, with bulkhead and deck positions, is given. The discretisation applicable to this example is shown in fig. 3.19b. Note that decks with insufficient space for logistic systems are not included in the discretisation. This approach does not affect the logistic performance of the designs since no functional systems can be positioned outside the hull.

3.12. Step 11. Output

The output of the LM is the full list of required logistic systems, as described in section 3.10. The output serves as input for the main system file. For a detailed description how the logistic systems are added to the main system file, refer to section 3.13. This concludes the description of the LM. The remainder of this chapter will cover the implementation of the LM in the Packing approach and required objective functions to steer towards 'logistically promising' designs.



(a) An example of a hull form with deck and bulkhead position indications and overlaying physical architecture.



(b) A discretisation of the hull form based on available deck length. In red is the barge discretisation as a result of the physical architecture. The deck discretisation is shown in blue.

Figure 3.19: An example of a hull form and its deck discretisation.

3.13. Implementation in the Packing approach

In the preceding sections of this chapter the LM has been explained in detail. Furthermore a new objective function called LPM has been defined. The current section describes some changes made to the Packing approach in order to retrieve information on the concepts design earlier. Also some other issues are discussed.

3.13.1. Logistic systems as objects in the Packing approach

In the Packing approach systems are modelled as objects. An object can represent for instance an engine, an engine room, accommodation or a weapon system. Different types of objects with different characteristics are described by Van Oers (2011). In order to add the logistic systems to the ship description, a suitable object type has to be selected. From (Van Oers, 2011) the following three promising (out of seven) object types have been selected for further investigation:

1. *Hard objects.* Hard objects represent systems that fulfil a wide range of functions. Their common characteristic is that their shape cannot change without loss of function of the system.
2. *Soft objects.* Soft objects, like hard objects, represent systems that fulfil a wide range of functions. Key features are that these systems can be defined by either required surface area or volume and that their shape may change without loss of function. Minimal sizes might be required to prevent too slender systems.
3. *Connection objects.* Connection objects provide connection between two systems, for instance between the engine room and the exhaust. Connection objects require the presence of two other objects that form the start and end point of the connection and, therefore, cannot be packed independently. This means that the to be connected systems need to be packed before the connection object can be packed.

All three system types can be used to model the required logistic systems. Hard objects can be given fixed dimensions, like these of logistic systems. Only little modelling effort is required to model hard objects. Since the dimensions of the logistic systems are predefined, the soft objects have to be constraint such that their shape does not change, and thus lose their specific characteristic. Actually they will behave like hard objects, but require significant more modelling. Connection objects are even harder to model and are discarded for that reason. Since the dimensions of logistic systems are fixed and hard objects require minimal effort to model, logistic systems are modelled as *hard objects* in the Packing approach.

3.13.2. Bulkhead positioning routine

Bulkheads have an important role in a vessel's hull strength. Besides providing structure, bulkheads influence the ship's ability to contain flooding in case of damage. Therefore the Packing approach bases the positioning of bulkheads on a floodable length curve ensure bulkhead configurations can cope with the nonnegotiable reserve buoyancy requirement at the design draught (Van Oers, 2011). See fig. 3.20 for an example.

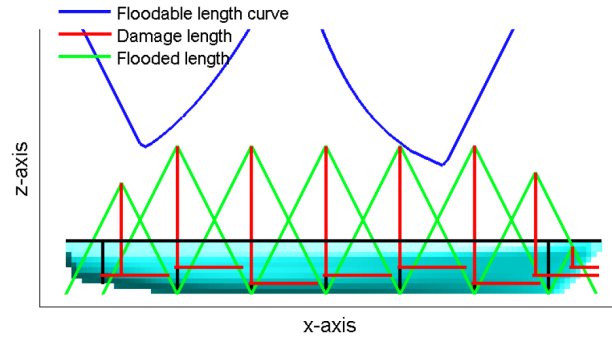


Figure 3.20: Subdivision by bulkheads to limit flooding (Van Oers and Hopman, 2012)

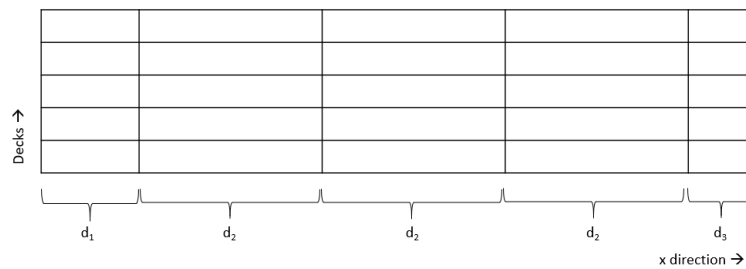


Figure 3.21: Visualisation of the bulkhead distance parameters as used in this research.

However, referring to fig. 2.7, the positioning of the bulkheads is done in by the packing algorithm. As the size of compartments is determined by the positioning of bulkheads, both the size of compartments and the number of compartments is not known beforehand. Therefore a change in the bulkhead positioning routine was investigated. Instead of using a floodable length curve to determine allowable positions of bulkheads, additional NSGA-II variables, d_1 and d_2 , were introduced to determine bulkhead spacing. d_1 prescribes the distance between the stern and the first bulkhead and d_2 is the spacing between the other bulkheads. These parameters are visualised in fig. 3.21. The length of the aft compartment is therefore equal to d_1 . The length of the foremost compartment is equal to d_3 , which is calculated by eq. (3.5). The length of the other compartments is equal to d_2 .

$$d_3 = LOA - d_1 - d_2 \cdot (n_{compartments_x} - 2) \quad (3.5)$$

In which: $n_{compartments_x}$ is the number of compartments in x-direction, and is determined by the number of transverse bulkheads minus one.

3.13.3. Packing order

An extensive elaboration on the importance of the order or sequence in which objects are treated by the packing algorithm is given by Van Oers (2011). The general packing order proposed and used at the DMO is as follows, (Van Oers, 2011):

1. First the hull envelope is positioned.
2. Second, the decks are positioned. Decks are part of the subdivision of the vessel, on which other systems will be placed.
3. Thirdly, systems that are large, constrained or otherwise difficult to place, like machinery rooms, are positioned next. They are placed before the bulkheads because they might otherwise require the positions of bulkheads to be altered.
4. Bulkheads are placed using the floodable length curve to assure sufficient reserve buoyancy.

5. All other objects are placed in the order from large and/or constrained, to small and/or less constrained. Furthermore, free space objects are placed fairly early on, to restrict the shape the superstructure part of the envelope may take.
6. After all objects are successfully positioned the topside structure is added.

Since the size of compartments has to be determined before overlap management takes place, and therefore a new bulkhead positioning routine has been introduced, the packing order needs to change. Indeed, since the bulkhead positions are set, the positioning of systems currently in the third position of the packing order is bound to the new bulkhead positions. So, Van Oers (2011) proposed to place an engine room first and then to position the bulkheads around this engine room based upon a floodable length curve. Now first the bulkheads are placed and an engine room (and other systems) are placed between these bulkheads.

Since the helicopter deck blocks the upward route for exhausts of the engine room, the helicopter deck is positioned before the engine room. Further the positioning of the bridge is important as it determines the height of the superstructure. Therefore the bridge is also packed early in the packing sequence.

The hard objects representing *logistic systems* are positioned next for three reasons:

- Salvatori (2018) remarked that the Packing approach has difficulties to handle hard objects. A hard object is a system that can not or hardly change shape, in contrast to soft objects. The latter only require a minimal area (such as accommodation space) or volume (like fuel tanks). Therefore it is appropriate to place the hard objects representing logistic systems early in the packing order.
- Further, almost all other systems are modelled as soft objects, see section 3.13.4 and section 4.5. These are thus less restricting and can be placed later according to Van Oers (2011).
- Lastly, logistic systems have a high impact on the performance of the vessel. The LM develops an 'optimal' set of logistic systems for each design, so therefore the positions of logistic systems need to comply to their given positions as much as possible. Further, soft objects can wrap around hard objects. So for instance, an accommodation object can wrap around a staircase. On the other hand, if logistic elements are placed later, the soft objects have to be placed such that sufficient space is available between them to accommodate logistic systems. This is visualised in fig. 3.22. Packing design becomes hard fast as logistic systems require space at several decks. Also, the figure shows that much more space is required and vessel size will increase while the density of the ship systems decreases when logistic systems are packed later. See section 5.3.2 for a further elaboration on the impact of logistic systems on the size of logistic driven vessels.

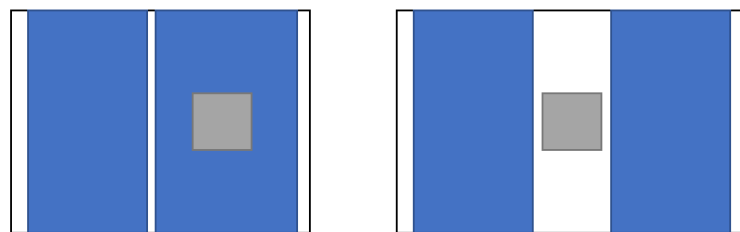


Figure 3.22: Difference between packing a soft (blue) object after (left) or before (right) a hard (grey) object. This also influences the size of the envelope required.

The general packing sequence used in this thesis is therefore as follows:

1. First the hull envelope is positioned.
2. Second, the decks are positioned.
3. Thirdly, bulkheads are placed based upon a new routine.
4. Then, the helicopter deck, bridge and engine room are packed.

5. Subsequently, the logistic systems are inserted.
6. All other system are placed in order from large and / or constrained, to small and / or less constrained.
7. After all objects are successfully positioned the topside structure is defined.

To show that the number of failed packing designs increases when the logistic systems are placed later in the packing order, two exploration runs with the systems and logistic system relations of test case four, see section 5.1.2, are investigated. The first run has the proposed packing order as presented above. The second run has the same packing order, with exception of one system: the mess is packed before the logistic systems. In fig. 3.23 the histogram of the number of unpacked systems in both runs is given. The Packing approach cannot pack (some of) the logistic systems if the number of unpacked systems is larger than the value indicated by the vertical lines. Clearly the yield of the exploration is restricted if the logistic systems are packed later in the process. This is also backed up by the total infeasible designs for both runs, which is 292 and 487 out of 2020 designs for the first and second run respectively.

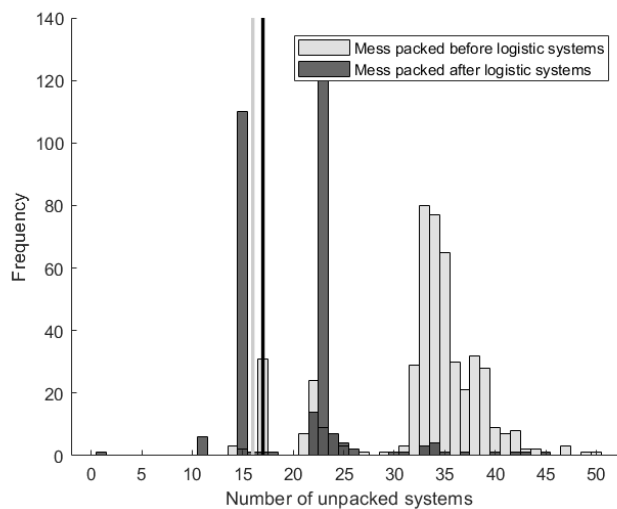


Figure 3.23: Histogram of the number of unpacked systems if the logistic systems are packed earlier (dark) or later (light) in the design. If the number of of unpacked designs is larger than the value indicated by the vertical line with the corresponding colour, the logistic systems can not be packed.

3.13.4. Limitations of level of detail

The first version of the Packing approach developed by Van Oers (2011) generated 3D ship designs. However, to limit computation time the Packing approach was changed to a 2.5D variant. See (Van Oers and Hopman, 2012) for a detailed explanation of this 2.5D approach. Since the latter version is computationally more efficient and generally suited for concept exploration, this version is also in use at the DMO, (Van Oers et al., 2017), and subsequently used in this research. In short, each system can be placed on any longitudinal and vertical position, but only on one of three transverse positions, as shown in fig. 3.24. This means that at each longitudinal and vertical position a maximum of three systems can be place side by side.

Logistic systems need to be assigned to one of these slices when added to the ship description. Because the estimation of required logistic systems is based on a 2D representation of the ship, it seems appropriate to add the logistic systems to the centreline slice. Because the number and longitudinal position of logistic systems will vary between designs, the whole centreline slice is reserved for logistic systems. Indeed, assigning functional systems to the centreline slice will either result in a location restriction for the logistic systems (when the functional systems are packed before the logistic systems) or in situations in which it is impossible to pack functional systems (when the functional systems are packed after the logistic systems). Therefore the functional systems are assigned to the starboard and port side slices, i.e. just two transverse locations are available for functional systems. This implies that either *the level of transverse detail of systems needs to be reduced* or *the number of slices needs to be increased*.

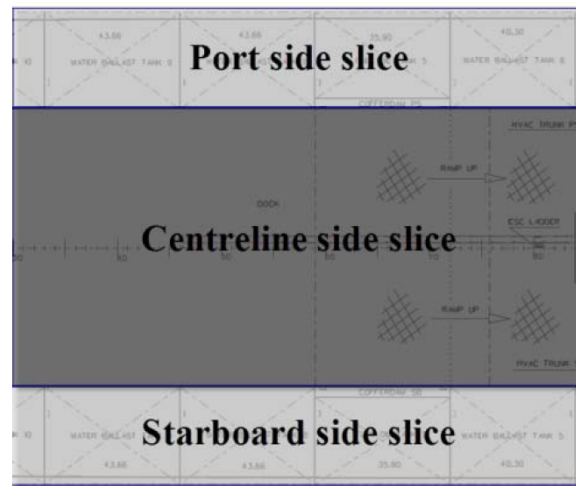


Figure 3.24: Top view of a well dock aboard a Landing Platform Dock with three transverse slices, (Van Oers and Hopman, 2012). The centreline slice contains the well dock itself, while the port and starboard side slices contain ballast tanks.

1. **Reduce the level of transverse detail of systems.** When the number of slices is not altered, the level of detail of functional systems needs to be reduced. For instance, the well dock and ballast system presented in fig. 3.24 can not be modelled as a well dock and two ballast tanks, since this requires three slides. Therefore the well dock and ballast system could be modelled as one object, positioned in both the starboard and port side slice. Another example of such issue is given in section 4.5. The vehicle deck in a LPD could be flanked by others systems. This issue can significantly reduce the design space, since the number of systems and thus the number of system configurations is reduced.
2. **Increase the number of slices.** Cieraad (2016) adapted the 2.5D Packing approach to a 2.75D approach for the application of the tool to submarines. The 2.75D approach contains five slices, enabling the Packing approach to place systems between the inner and outer hull of a submarine. In the current research the aft part of the ship is modelled such that five positioning slices are available. This enables separate modelling of the well dock and ballast tanks, section 4.5. Three positioning slices are available in the other parts of each design. It is believed that a larger level of detail is needed to correctly model a LPD when the LM is applied, see chapter 7.

With exception of the well dock area, the first solution has been adapted. Indeed, the correct modelling of a LPD itself was not the objective for this research, but is only used as a test case to validate the LM. This is further described in chapter 4 and chapter 5.

Almost all systems are modelled as soft objects, for the following reasons:

- Soft objects can wrap around other object when positioned later, as described in section 3.13.3. Since nearly all functional systems are packed after the logistic systems are positioned, the soft objects will wrap around the logistic systems, like shown in fig. 3.22.
- The test case only serves to validate the LM. Therefore the level of detail of systems can be kept relatively low.
- The low level of detail is further supported by the characteristics of systems in a LPD. Indeed, many of the large systems concern for instance accommodation or vehicle decks, which only require a minimal area and aspect ratio, (Van Oers, 2011).
- Lastly, an increase of level of transverse detail decreases the validity of the assumption that processes can be described and treated in a 2D approach, as discussed in section 3.3.1. Indeed, as transverse detail increases, logistic processes will more and more take place between transverse adjacent systems. This in turn requires logical systems in transverse direction as well.

Besides soft objects, hard objects are also used to model for instance the engine room or a weapon system. See chapter 4 for more detail on the modelling of a LPD in the Packing approach.

3.14. Objective functions

The Packing approach makes use of a genetic algorithm to search for better designs. Usually the packing density (PD) is used as objective function to search for different ship configurations. Packing density helps to distinguish between dense and spacious designs. Van Oers (2011) explains that a variable packing density enables the Packing approach to cover both space-driven and weight-driven ship types, describe configurations at a variable level of detail and, lastly, cover configurations that use excess space to improve performances, e.g., logistic performance. However, packing density itself can not be used to assess the logistic performance of designs. Indeed, a spacious design can have a logistically bad or good systems configuration. This section will discuss a new objective function, defined to assess logistic performance of concept designs of logistic driven ships. Furthermore the suitability of PD as objective function for this thesis is discussed.

3.14.1. Assessing logistic performance

Objective functions help to steer the concept exploration towards more promising designs, (Van Oers, 2011). What promising is, depends on the ship the naval architect is looking for. For container vessels a promising design might be a design that uses minimal power to transport a maximum number of TEU over a required distance at certain speed, or minimal $\frac{\text{€}}{\text{TEU} \cdot \text{mile}}$. Since the performance of logistic driven ships is driven by logistic processes. Therefore the question is: How to assess the logistic performance of logistic driven ship concept designs? An objective function capturing logistic performance needs to take the following factors into account:

1. *Required movement.* From a logistic point of view, movement for logistic activities is seen as waste. Therefore designs requiring minimal movement are preferred over designs that require more movement in order to carry out the same logistic processes. Minimal movement can be achieved by carefully optimising the layout of a vessel.
2. *Importance of moving units.* During an assault the movements of marines are likely to be more important than the movement of crew for instance. This already indicates a relation with the following factor:
3. *The importance of individual processes.* Some logistic processes are more crucial to the performance of a logistic driven ship than others. For instance, logistic processes taking place in a LPD during an amphibious assault are more important than for instance the process of bringing dirty clothes to the laundry at the same moment.
4. *Time required to complete a logistic process.* This is connected to the minimum flow required for logistic processes presented in section 3.8. Therefore it is related to the importance of processes as well. The time required for a processes to take place is the sum of the time required for the value-adding activities in the functional systems and the time required for the movement between functional systems. The time required for movement to take place is in its basics function of distance and speed. Indeed, $time = \frac{distance}{speed}$.
5. *The distance between functional systems.* Minimising the distance between systems reduces the space required for logistic systems, section 1.2, and the movement required for logistic processes. Determining the distance between systems is relatively easy after a design is configured, since the positions of all systems are known at that point. In a logistic driven ship mainly the distance between logistic connected systems is of interest. However, the Euclidean distance between the locations of these systems is not sufficient. Indeed, the location of available logistic systems should be considered when calculating the distance.
6. *The mobility of moving units.* The mobility of moving units is characterised by two aspects: manoeuvrability and speed. Manoeuvrability of moving units is directly connected with the space that is required to manoeuvre. For instance, wounded marines are carried on stretchers, which are hard to manoeuvre in small spaces. Therefore the logistic systems itself need to be designed such that sufficient space to manoeuvre is available, (NATO, 1993). Taking speed into account is more difficult. Indeed, different moving units can achieve different speeds, both in vertical and horizontal movement. For instance, a human generally achieves different speeds on staircases compared to moving on a flat surface (Fujiyama and Tyler, 2004).

Summarising the factors presented above, two aspects can be highlighted. In the first place, individual processes and moving units might be more important than others. Therefore there is a need to account for possible preference of logistic processes or moving units in the new objective function. In addition a naval architect might want to vary the importance of processes and/or moving units to find unexpected design solutions. Secondly, required movement, time required to complete a logistic process and mobility of moving units are all related to the distance between systems. The distance between systems is relatively easy to compute after a design is configured, although routing between logistically connected systems needs to be taken into account.

In addition a third aspect is of importance. It has been explained that the Packing approach carries out overlap management, which can move systems to other positions than their initial positions. With regards to the prediction of required logistic systems the following four cases can be distinguished.

1. The functional systems are not moved. The available logistic systems provide sufficient connection.
2. The functional systems are moved such that the logistic performance of the ship is improved compared to the situation before overlap management.
3. The functional systems are moved such that the logistic performance of the ship is decreased compared to the situation before overlap management.
4. An extreme case of the previous one is that functional systems can be moved outside the reach of available logistic systems. This introduces *disconnection*. In such designs not all logistic processes can take place.

The impact of overlap management on logistic performance is further investigated in section 3.14.2. Considering the three aspects discussed above the Logistic Performance Measure (LPM) is developed, which is given by eq. (3.6).

$$\min LPM = \sum_{i=1}^{n_{lsr}} ls_i \quad (3.6)$$

In which:

n_{lsr} is the number of logistic system relations.

ls_i is the *logistic score* for logistic system relation i. ls_i is further defined as:

$$ls_{ij} = \begin{cases} \text{if source and sink systems can be connected} & d_i \cdot w_{lsr_i} \cdot w_{mu_i} \\ \text{if source and sink systems cannot be connected} & p_i \end{cases}$$

In which:

d_i is the length of the route between the source and sink system in logistic system relation i in the packed design. If required, this route makes use of the logistic systems in the design. The determination of d_i will be further detailed below.

w_{lsr_i} is the weight the naval architect gives to logistic system relation i, in order to give priority to this logistic system relation. For instance, logistic system relations related to an amphibious assault could be given the weight $w_{lsr_i} = 2$ and other logistic system relations could be given $w_{lsr_i} = 1$ in order to make the amphibious assault twice as important.

w_{mu_i} reflects the importance that the naval architect gives to the type of moving unit involved in logistic system relation i.

p_i is a penalty for logistic system relation i in the case the source and sink system are disconnected due to overlap management. A suitable value for p_i is 10000 as the LPM score of fully connected designs is lower than 10000. Each design with LPM larger than 10000 has at least one disconnection.

Since the w_{lsr_i} and w_{mu_i} are constant for each design, minimising LPM will minimise the distance between logistically connected systems. Movement is seen as waste and has to be removed or reduced from a logistic point of view, section 1.1. A logistically promising design thus is considered to be a design in which logistic movement is minimised. Because movement of moving units is closely related with the distance that the moving units need to move, minimising distance will lead to logistically promising designs. Related to the LPM performance is the overlap management. Therefore the impact of overlap management on the LPM

score is investigated in section 3.14.2.

In order to find the logistic performance of a design, the distance d_i between the, packed, source and sink system for each logistic system relation has to be calculated. Therefore a 2D network of logistically connected systems and logistic systems was created, similar to the approach taken in the development of the physical architecture. Therefore the transverse distance between systems is not taken into account. Since function sharing is not taken into account this grid is generated for each moving unit involved in the design. In fig. 3.25 a design from test case 3 (section 5.1.1) is given. Since this test case involves the MUs ‘crew’ and ‘goods’, two networks are generated, presented in fig. 3.26a and fig. 3.26b respectively. The length of the shortest path between the source and sink system is adopted as d_i . The watertight integrity is not yet implemented in these networks, which could lead to the calculation of d_i , while in reality a route is blocked by a watertight bulkhead. See section 5.3.4 for an example and see chapter 7 for an improvement of the LPM calculation.

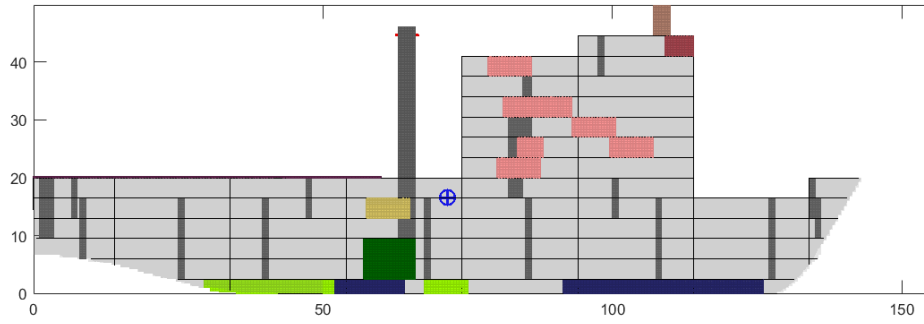


Figure 3.25: Example design for the LPM network generation shown in fig. 3.26.

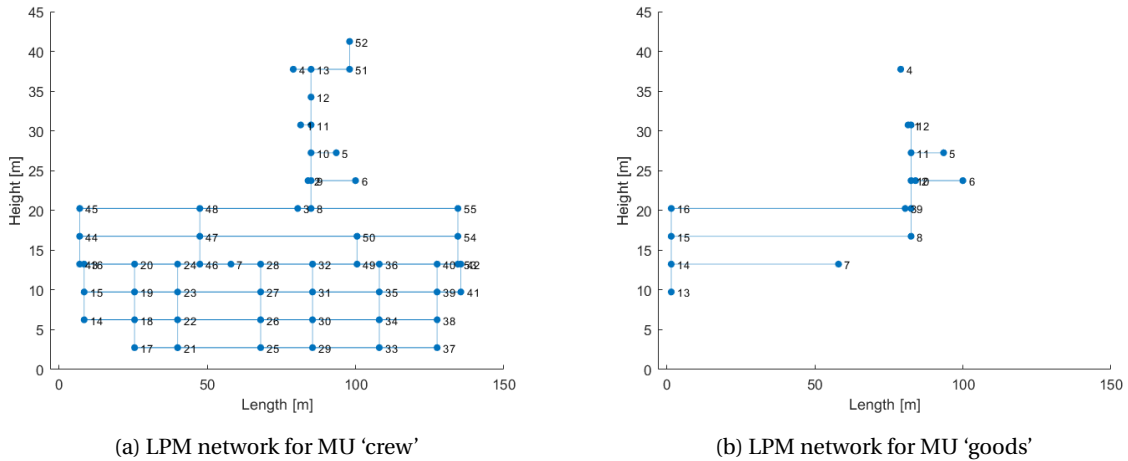
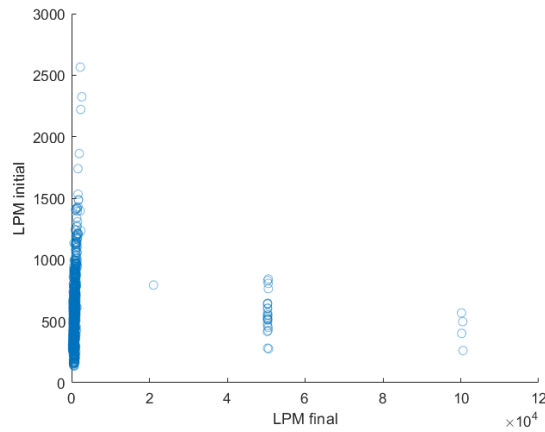


Figure 3.26: Generating networks to calculate d_i in order to find the LPM value of a design.

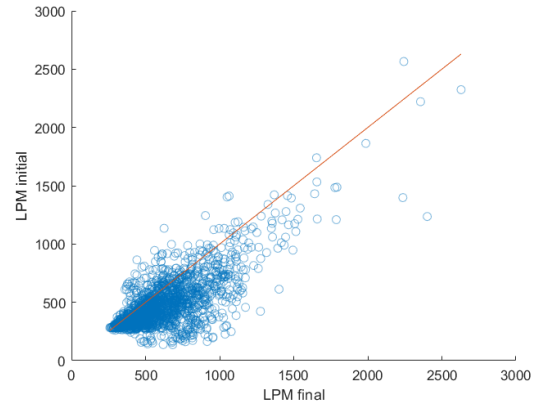
3.14.2. Impact of overlap management

In section 3.14.1 the issue of disconnection has been mentioned. Because the Packing approach performs overlap management the initial positions of systems might differ from the final position. In fig. 3.27a an unfiltered data set of an exploration run is given. This plot shows the relation between the LPM value before and after overlap management. Since p_i is 10000 for each disconnection in a design, the designs with disconnection can be distinguished and filtered easily. The figure shows that this data set includes multiple designs with disconnection. When these designs are filtered from the data set, the relation between initial and final LPM is given in fig. 3.27b. The regression line is also plotted. It seems that the initial LPM is positive correlated

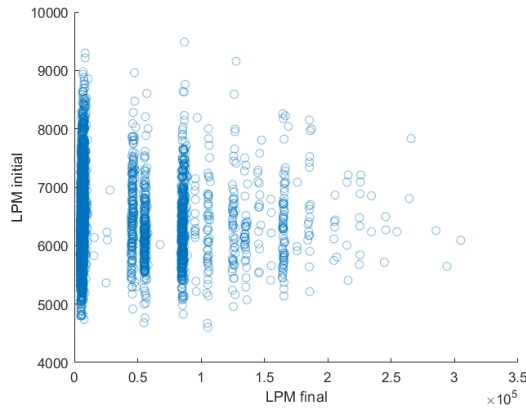
with the final LPM. The reason for this correlation could be that the initial positions are very similar to the final positions. The difference in initial and final positions of systems have not been investigated for this data set. This data set is a weighted run for test case four, section 5.1.2. Because the number of systems in this test case is low, it is expected that the Packing approach is able to place system close to their initial positions. However, in a more realistic design overlap management might move systems to significant other positions. This would lead to a larger discrepancy between the initial and final LPM. Indeed, fig. 3.27c and fig. 3.27d show the relation between the initial and final LPM values obtained in the LPD exploration run in section 5.3. Although a slight positive trend can be observed, these figures prove that systems are moved significantly by overlap management when the number of systems increases and the designs are constraint to additional objectives and constraints as well, see section 3.14.3. While the designs in the test cases in section 5.1.1 and section 5.1.2 are so spacious that the Packing approach can find promising logistic configurations rather easily, additional objective functions and constraints need to be applied in the LPD exploration to find more realistic designs.



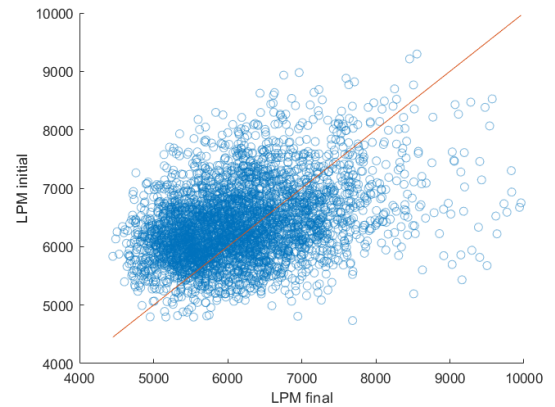
(a) Results of test case four. Initial versus final LPM, unfiltered. The red line indicates equal LPM initial and LPM final



(b) Results of test case four. Initial versus final LPM, designs with disconnection are filtered.



(c) Results of the LPD exploration run. Initial versus final LPM, unfiltered



(d) Results of the LPD exploration run. Initial versus final LPM, designs with disconnection are filtered. The red line indicates equal LPM initial and LPM final

Figure 3.27: Initial versus final LPM, showing results of the fourth test case of the LPD exploration run in chapter 5

3.14.3. Additional objective functions and constraints

Assessment of logistic performance is not sufficient to find feasible ship designs. This is because the LPM only concerns the configuration from a logistic perspective. It neglects other naval architectural aspects, like stability. To account for these additional requirements, additional objective functions and constraints are selected in this paragraph.

- To avoid unutilised space in a design the volume of the ship has to be decreased. This can be done by adding an objective function. In the past the packing density (PD) has been and is frequently used to limit the size of ships. See for instance (Van Oers, 2011) for a discussion of PD as an objective function. PD is given by eq. (3.7). Generally the number of functional systems remains constant during an exploration run. However, the number of logistic systems can vary, as a result of the configuration of functional systems and the result of path finding and selection method. Therefore also the total volume of the logistic systems, and thus of all systems, can vary. Given the formulation of the Packing density, it might happen that the maximisation of PD leads to designs with excess logistic systems because this results in denser designs. However, this is an undesired effect. Indeed available space should not be filled by logistic systems, just because this space is available. This would lead to excess logistic systems.

$$PD = \frac{\text{volume}_{\text{objects}}}{\text{volume}_{\text{ship}}} \quad (3.7)$$

Therefore the second objective suited to limit the void space in concepts designs is the enclosed volume of the hull. Since the enclosed volume is described by eq. (3.8), minimising the enclosed volume will lead both to less void space and a decrease in volume of logistic systems. Therefore the minimisation of the enclosed volume has been chosen as objective function for the concept exploration of logistic driven ships in this thesis. The PD and enclosed volume of the hull are closely related though, as shown in fig. 3.28.

$$\text{volume}_{\text{enclosed hull}} = \text{volume}_{\text{functional systems}} + \text{volume}_{\text{logistic systems}} + \text{volume}_{\text{void space}} \quad (3.8)$$

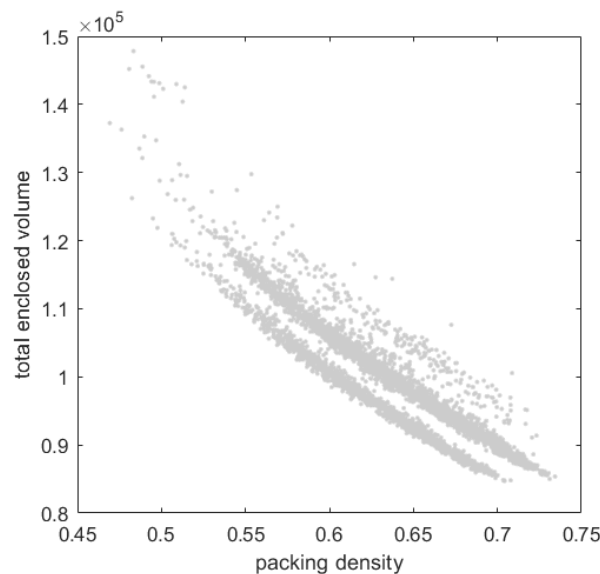


Figure 3.28: There is a strong relation between the packing density and the enclosed volume of the hull. The three distinct groups visible in this figure are formed due to some systems which are not necessary enclosed by the hull. An example is the hangar, which might be separated from the superstructure in the model used.

- Non-negotiable requirements, or feasibility requirements, are design requirements which have to be met. The ship should comply to these requirements in order to be physical, financial or political acceptable, (Van Oers, 2011). In this thesis the following non-negotiable requirements are considered to constrain the designs:
 1. **Space constraint.** The space constraint ensures that all systems are placed in the ship. This is required since all systems are required to fulfil the functional requirements of a vessel.
 2. **Stability constraint.** One of the main requirements of any ship is the ability to float upright. Therefore the intact stability needs to be positive at least. Intact stability is measured by the meta-centric height GM_t .

3. **Draft constraint.** To ensure the hull provides sufficient buoyancy, the actual draft needs to be equal or smaller than the design draft. This is also required from the resistance calculation and related engine sizing and fuel capacity estimation point of view.

Since the NSGA-II algorithm is used as a *search algorithm* (Jaspers and Kana, 2017; Duchateau, 2016; Van Oers, 2011) objective functions have to enable diversity. On the other hand, the NSGA-II also has to improve designs such that designs are properly sized. In multi-objective optimisation, objectives may conflict. For instance, minimising distances between logistically connected systems to improve the logistic performance of a design might introduce excess void space between clusters of systems, which is unwanted as the volume of the designs needs to be reduced. The LPD exploration run in section 5.3 is performed with two objective functions: ‘LPM’ and ‘volume_{enclosed hull}’. The set non-dominated designs lie on the Pareto front (Deb, 2011). In fig. 3.29 the LPM, enclosed volume and PD are plotted. Also a performance constraint is applied to show the scores for the logistic promising designs (LPM<5000). Clearly the LPM and enclosed volume objectives conflict as the most promising designs found are not the smallest designs found. Note that the logistic promising designs indeed have excess void space compared to other designs. This can be observed by the lower packing density of the former designs.

The convergence of the LPM and enclosed volume objective functions are shown in fig. 3.30a and fig. 3.30b respectively. The convergence is considered to be acceptable, although further convergence can likely be achieved by increasing the population size and the number of generations.

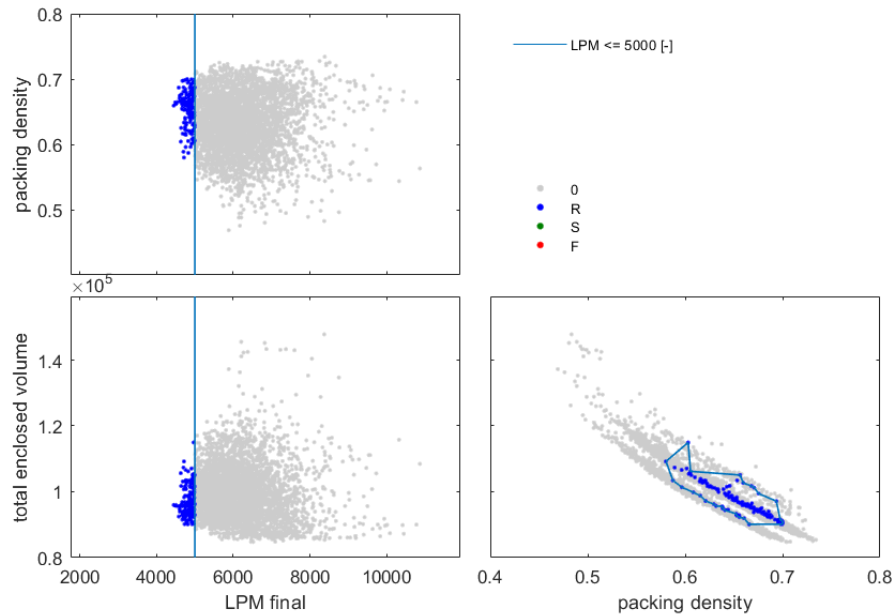
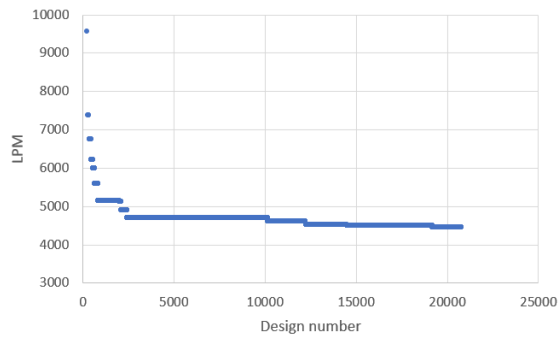


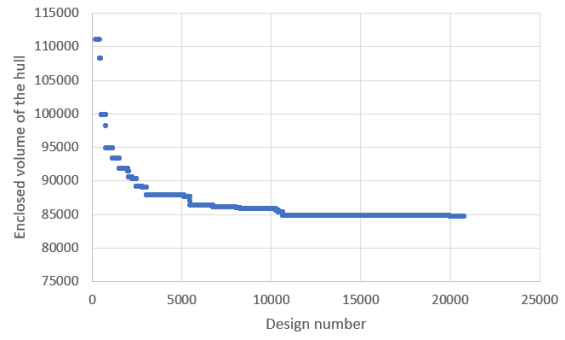
Figure 3.29: Matrix plot showing the enclosed volume, LPM and PD scores for the LPD exploration run.

3.15. Proof of concept

In the previous sections the Logistic Model and the Logistic Performance Measure have been described. Since chapter 5 extensively validates the LM, the proof of concept is given by only one design. In fig. 3.31a a LPD concept design is shown. This design has LPM score 4935. See for more details on the LPD design chapter 4 and section 5.3. The logistic systems in this design are shown in a longitudinal cross section in fig. 3.31b and under an angle in fig. 3.31c. The latter shows that the logistic systems are placed at the centreline of the ship. In fig. 3.31d a partly exploded view is given, showing that the soft objects warp around the logistic systems. The proof of concepts indicates that the LM works as intended.

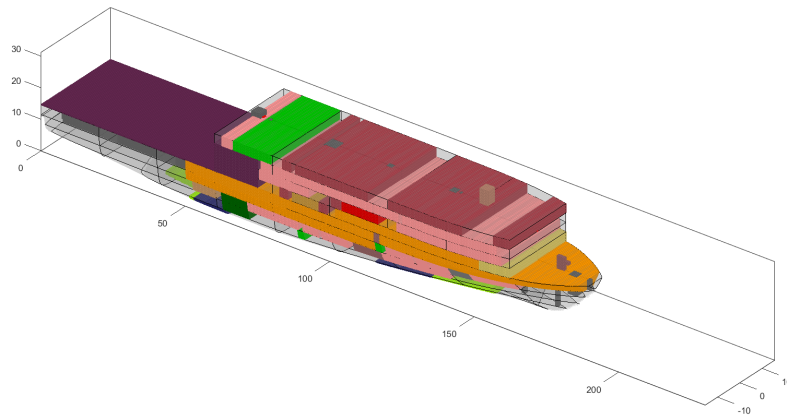


(a) Convergence of LPM score

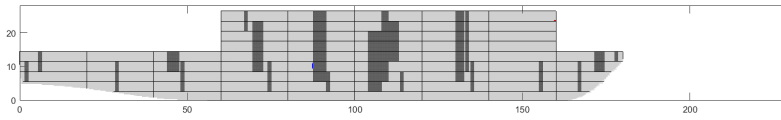


(b) Convergence of enclosed volume

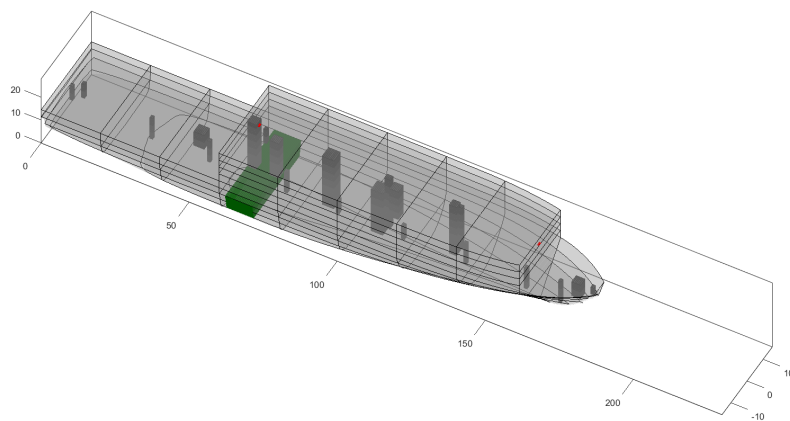
Figure 3.30: Convergence of the objective functions for the LPD exploration presented in section 5.3



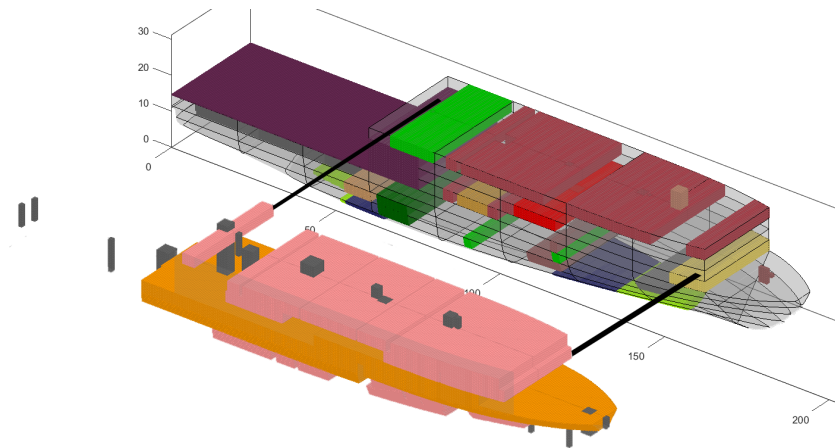
(a) The LPD design used as proof of concept



(b) Longitudinal cross section of the logistic systems in this design



(c) Another view of the logistic systems in this design, in which also the engine room and exhaust is made visible.



(d) Partly exploded view of the LPD design, revealing that soft objects wrap around logistic systems.

Figure 3.31: Proof of concept

3.16. Conclusion

In this chapter the LM has been described in detail as well as how the logistic performance of logistic driven concept designs could be measured. The latter resulted in the development of a new measure, the LPM. A proof of concept indicated that the LM works as intended. Indeed, the LM should fulfil the six requirements given in section 2.1. In table 3.9 the current status of these requirements is given: each one is fulfilled. However, it has yet to be seen if the LM is also useful when applied to a design case. Therefore a test case design is developed in chapter 4. Subsequently the LM is validated in chapter 5.

	Requirement The LM should be	Status
1	Based on known systems and logistic system relations	Fulfilled
2	Able to determine positions and size of required logistic systems	Fulfilled
3	Able to take the structural subdivision of ships into account in the determination of the size and position of logistic systems	Fulfilled
4	Able to add the logistic systems to the concept designs	Fulfilled
5	Complement to the Packing approach	Fulfilled
6	Able to analyse designs with regards to logistic performance	Fulfilled

Table 3.9: Status of requirements for the Logistic Model

4

Test case development – Design of a LPD

In the previous chapter the LM has been described in detail. To validate the model the LM is used in a test design case of a notional LPD. The aim of the design case is therefore not to support concept exploration of a LPD but to provide a frame work in which the LM can be proven to give reliable results as well as to give useful design insight during concept exploration. Consequently, the level of detail of systems will be low and will be based upon existing LPDs. As highlighted in section 1.3 the systems engineering V-diagram will be used as a basis of the design process. First the primary functions will be given in section 4.1, after which the design requirements will be discussed in section 4.2. Subsequently the operational processes in a LPD are covered in section 4.3. The primary functions and operational processes drive the quest for support functions, section 4.4. Finally all support functions have to be fulfilled by systems, which are described in section 4.5.

4.1. Primary functions

The mission or the main task to be fulfilled is described by the primary function of a vessel. As the primary function is the main reason to build a vessel, it is the first element to be established in the design (Klein Woud and Stapersma, 2002). All other ship functions and aboard processes are aimed or required to fulfil the ship's primary function. The design requirements are developed based on the primary functions. Strictly speaking, functional requirements should not preempt the choice of material solution, for instance the choice for a LPD (Andrews, 1986). However, for the purposes of this thesis, the upfront choice for a LPD is considered to be acceptable. For a LPD four primary functions have been specified. The LPD should:

1. Transport and maintain marines to theatre over sea;
2. Deploy and retrieve marines in theatre at sea;
3. Transport and maintain equipment to theatre over sea;
4. Deploy and retrieve equipment in theatre at sea.

4.2. Requirements

Warship requirement definition within the Dutch defence is an iterative process between various stakeholders, as explained by Van Oers et al. (2017) and Knecht (2018). Van Oers et al. describe the process of warship concept exploration within the Dutch defence organisation. Basically three organisations are involved. First, the Defence Staff is responsible for the available budget and for the definition of functional requirements. Secondly, the RNLN is the end-user and maintainer of the warship, but is also responsible for the overarching operational requirements and the concept of operations. Finally the Defence Materiel Organisation (DMO) is responsible for the technical specification and procurement. Based on requirements and budget constraints the DMO develops various concept designs and consults the other stakeholders on technical feasibility of the set of requirements. Indeed, a constant dialogue between the various stakeholders is needed to find technical feasible solutions for realistic functional requirements that cover both operational needs of the navy as well as fit in the available budget. This process leads to an increase in design knowledge and results in a definition

of features that are crucial to the operational effectiveness and the technical and financial feasibility of the warship. After the warship concept is defined, the concept design is handed over to industry partners for detailed design and actual ship building.

Although this iterative process is not imitated in this thesis, the role of design requirements is crucial for the definition of the design space. Indeed, design requirements, including primary functions, are the starting point of each design (Zandstra et al., 2015). Requirements therefore define the design space in which a method like the Packing approach or the LM is used. As mentioned in the introduction of this chapter, the requirements for the LPD design case will be based upon existing LPDs, as the focus is to provide a test case for the LM only.

For the same reason no full set of design variations is developed, which is normally done to investigate the requirements and design alternatives that comply with these requirements, (Van Oers, 2011; Zandstra et al., 2015). Instead, capability wise the notional LPD designed in this thesis will be based on the current RNLN *Rotterdam*-class LPDs. Since the aim of this research is not to design future RNLN LPDs and requirements are based upon existing LPDs, the notional LPD will not resemble future LPDs as these will certainly differ from the current LPDs active within the RNLN. Indeed, operational requirements might have changed, other budget limitations will play a restricting role and due to technical developments design solutions will differ. Besides the requirements based on the current RNLN LPDs, a limited list of requirements based on available data of worldwide existing LPDs is developed. The data was obtained from Wikipedia (n.d.). The aim of this analysis is to find main dimension constraints for the LPD concept designs. Therefore only main dimensions were taken into consideration. The range of main dimensions and their relations to other size metrics is shown in fig. 4.1. In these figures the current RNLN LPDs are encircled in red. These two vessels are of average size in comparison with the other LPDs in the data set. As requirements for the to-be-designed LPD are assumed to be equivalent to the current RNLN LPDs, it is expected that the size of the concept LPD design will not differ much from the existing vessels. Therefore the range of main dimensions of existing LPDs is used to constraint the main dimensions of the concept design. As a result, the main dimension constraints are given in table 4.1.

		Lower bound	Upper bound
Length	[m]	122	210
Beam	[m]	20.5	32
Draft	[m]	4.9	7.1
Displacement	[m ³]	7650	25000

Table 4.1: Range of LPD sizes based on (Wikipedia, n.d.) and used to constrain the design space.

Note that for confidentiality reasons not all requirements can be presented. Also note that characteristics of other existing LPDs can offer additional design knowledge, for instance on relations between ship size and transport capability. However, since transport capabilities and other requirements of the notional LPD are based on the current RNLN LPDs, additional characteristics of operational LPDs are not investigated. Also the validation of the LM does not require design knowledge based on existing vessels. Investigation of existing vessels is otherwise good practice in ship design. Some of the (general) requirements are given below. Note that

- Helicopter deck to land two helicopters simultaneously and hangar capacity for at least four helicopters;
- Submersible well dock suitable for two or four landing vessels;
- Vehicle deck capacity in 'lane meters' for large vehicles, like trucks, and small vehicles, like All Terrain Vehicles;
- Accommodation and other facilities for 600 marines with their equipment and basic ship crew of 150 members;
- The minimal range is 10000 nautical miles;
- The design speed is 18 knots

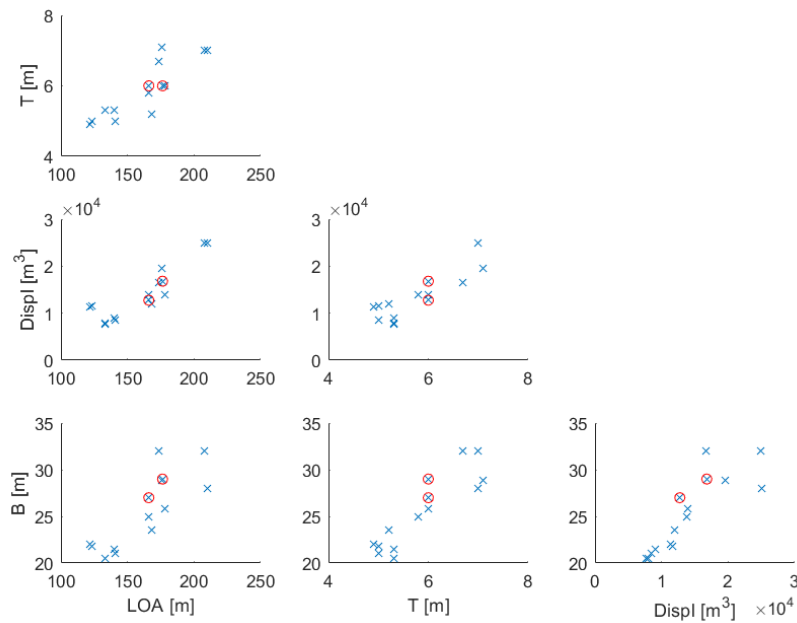


Figure 4.1: Main dimension comparison between sixteen active LPDs. The Dutch *HNLMS Rotterdam* and *HNLMS Johan de Witt* are encircled in red.

4.3. Operational processes

In a LPD various operational processes take place in order to fulfil the primary functions described in section 4.1. In this thesis the focus is on operational processes of a logistical nature. These logistic processes can be described by a set of activities, as has been explained in section 1.1. Activities in turn can be divided into value adding activities and non-value adding activities. In the current section the logistic processes in a LPD are described. Using the logistic processes and the functional systems, the logical architecture can be developed, which is done in section 4.5.

4.3.1. Logistic processes

Logistic processes have been defined as a sequence of value adding and non-value adding activities. These logistic processes have been identified after investigation of LPD general arrangements and consulting of a DMO naval architect who was involved in the design of the *HNLMS Johan de Witt* (W.H.F. Burger, personal communication, April 6, 2018). In fig. 4.2 an overview of the value adding activities in a LPD are given. The arrows indicate a logistic relation between the activities. Depending on the layout of the systems involved in the value adding activities, non-value adding activities might be required to fulfil connection between the functional systems involved in the activities. Since the layout is not known, it is also unknown if non-value adding activities, i.e. movement, need to take place. Therefore the non-value adding activities are not included in the figure. The logistic processes taking place during embarkation are assumed to be similar to the activities taking place during an amphibious assault, but in reverse order, with exception of the embarkation of wounded marines. Therefore the processes related to embarkation are not shown in the figure.

4.3.2. Selection of suited moving units

The use of moving units in the LM is explained in section 3.8. First an analysis of the entities involved in the logistic processes is required. Subsequently an appropriate set of moving units has to be selected. Referring to fig. 4.2, the following entities are involved in the logistic processes:

1. *Officers*: Besides officers who join the actual amphibious assault, officers stay aboard the LPD to lead the assault.
2. *Crew*: The crew operates the LPD, and fulfils various support functions. Sailing, system monitoring and maintenance, preparing food and damage control are some of the disciplines in which crew members have a role. In most cases the number of crew moving to a certain location or system in the ship is

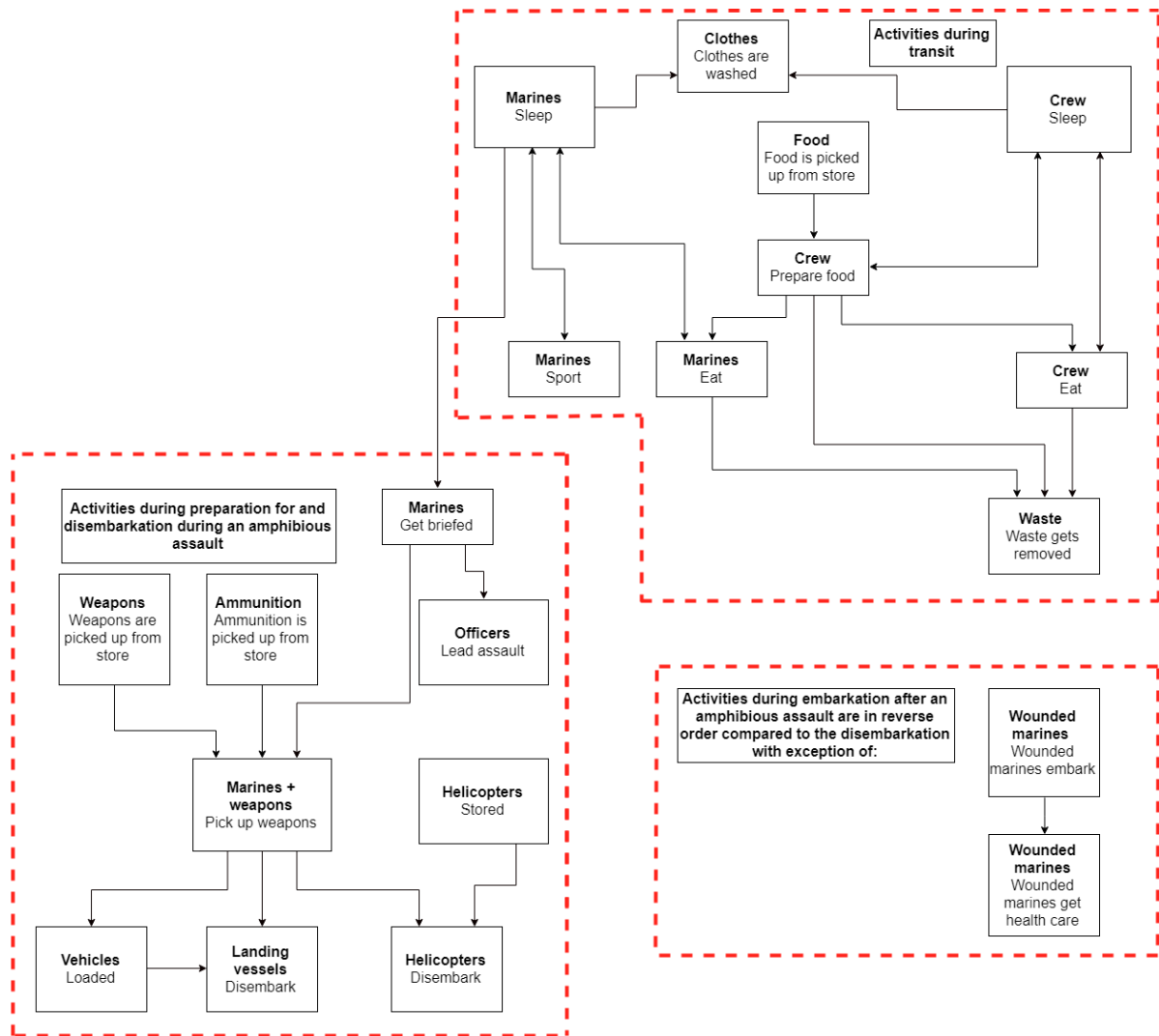


Figure 4.2: Value adding activities in logistic processes are divided into two categories, namely: activities during transit towards the theatre and activities during an amphibious assault in the theatre. Further activities during re-embarkation are partly shown. A value activity consists of an action and entities involved in that action. Arrows represent possible non-value adding activities, which are required depending on the configuration of functional systems.

limited. The crew size of a *Rotterdam*-class sized LPD is approximately 150. Observations aboard naval vessels revealed that only two events require movement of many crew members, namely:

- Emergency situations:** The most unwanted emergency situations aboard naval vessels are fire and flooding. If these situations are not handled well, they may lead to the sinking of the vessel. In general a significant part of the crew is involved in fighting emergency situations. Therefore the ship should enable easy movement of crew. Certainly in the case of abandon ship, the whole crew has to be able to leave the ship safely and quickly. Fortunately emergency situation don't happen often, but the crew has to train for emergency situations. Therefore the number of crew moving during drills is also high.
- Messing:** Three times a day a meal is served to all the crew. Although crew may eat in shifts, significant parts of the crew need to be able to move from their accommodation (when not on duty) or working stations (when on duty) to the mess simultaneously.

During an amphibious assault the number of crew moving through the ship is assumed low. Although crew will employ and retrieve marines, they mainly assist on specific locations or during specific activities, e.g. loading of landing vessels. A few crew members will move through the ship as they guide

marines to for instance the disembarkation points.

3. *Marines*: Two primary functions of the LPD concern marines. A *Rotterdam*-class sized LPD is able to transport around 600 marines. During the transit to the theatre marines have to be fed and they will need sport facilities. Therefore marines need to be able to move from their accommodation to the mess and to sport facilities. Note that the number of marines is significant larger than the number of crew. This has implications on the required size of logistic systems. Marines need significant larger logistic systems compared to crew, see section 4.5.3. The layout and available space for movement of marines becomes crucial in two situations:
 - Emergency situations, in particular these in which the marines have to abandon the LPD safely and quickly.
 - Certainly in the case of an amphibious assault the layout and available space for movement of marines becomes crucial. First, the movement of marines aboard possibly effects the speed of the amphibious assault outside the ship. Further weapons are added to the flow. Hence the following entity is:
4. *Marines equipped with weapons*: During an assault logistic bottlenecks in the LPD can slow down the whole amphibious assault. Marines have to be briefed, pick up weapons and have to disembark by means of helicopters or landing vessels. Moving to vehicles before boarding the landing vessel might also be required.
Picking up weapons basically increases the size of each marine, which requires an increase in size of related logistic systems.
5. *Wounded marines*: During an assault marines might get wounded or even killed. Both wounded and killed marines are to be transported back to the LPD. In the case wounded marines are unable to move by themselves, they are transported on stretchers, which puts additional requirements to minimal turning circles between embarkation locations and the aboard hospital. Also vertical movement is more difficult when carrying a stretcher, so staircases for instance are not allowed to be too steep, (NATO, 1993).
6. *Weapons*: Similar to marines their equipment has to be transported and employed too. Weapons are stored separately from ammunition for safety reasons. Weapons are to be transported from their stores to the weapon hand out location. After marines picked up their weapons, the logistic systems should enable the further transport of weapons to the disembarkation stations.
7. *Ammunition*: Similar to the transport of weapons, ammunition has to be transported from its store, via the weapon hand out location to the disembarkation stations.
8. *Food*: Food and food ingredients are stored, and have to be transported to the galley for preparation of meals. Subsequently meals have to be transported to the messing areas of crew and marines.
9. *Waste*: Various types of waste can be distinguished. For instance, accommodation results in the generation of grey water and black water. Grey and black water is transported by means of piping, which is involves movement as well and is therefore a logistic process. However, the routing of piping is not covered in this thesis. The preparation of food results in non-fluid waste. This waste has to be stored or destructed aboard. Note that the transport of waste has to be separated from some other logistic processes, like the transport of wounded marines to prevent infections.
10. *Clothes*: A small logistic process aboard ships concerns the washing of clothes, which is typically not done in the accommodation itself.
11. *Vehicles*: For transport over land marines use a wide array of vehicles, ranging from small SUVs to trucks and tanks. Loading and offloading of vehicles has to be carefully considered in the design of a LPD. As vehicles are transported to shore by landing vessels a suitable connection between the well dock and vehicle deck is required.
12. *Helicopters*: Helicopters are the first of the two main entities used to transport marines and equipment to shore during an amphibious assault. Helicopters might be stored in a hangar to protect them from heavy weather or for maintenance. The hangar has therefore to be connected to the helicopter deck, which might be a design challenge when the hangar is situated below the helicopter deck.

13. *Landing vessels*: Landing vessels are the second of the two main entities used to transport marines and equipment to shore during an amphibious assault. Landing vessels operate from the well dock. The size of the well dock is partly determined by the number of landing vessels that are to be operated simultaneously as well as by the size of these landing vessels. See section 4.5.1, chapter 7 and (Leopold and Reuter, 1971) for additional remarks on well dock design.

Now the thirteen entities involved in the logistic processes aboard a LPD are known and analysed, the moving units can be selected. A simple choice would be to represent each entity as a moving unit. However, taking into account that the issue of function sharing, discussed in section 3.8, the number of moving units needs to be reduced. Function sharing means that different moving units can use the same logistic systems. To solve this issue each MU gets its own connection type or types. Therefore the number of connection types will be equal or larger than the number of MUs. Implementing eleven types of, similar, logistic connections in a single ship design is unrealistic. Function sharing between similar entities will be done in reality and therefore not be completely neglected. Based on the characteristics the list with entities will be reduced to a list of moving units. The five MUs listed below were selected to represent the eleven entities. An update of fig. 4.2, in which the entities are changed to the selected MUs, is given in fig. 4.3.

1. *Crew*: The MU 'crew' covers the entities 'Crew' and 'Officers'.
2. *Marines*: It was decided to combine the three entities involving marines ('Marines', 'Marines equipped with weapons' and 'Wounded marines') into one MU. The entities 'Marines' and 'Marines equipped with weapons' are very similar. 'Wounded marines' might be transported at stretchers. Wounded marines on stretchers can be transported through the logistical systems designed for marines, (NATO, 1993), although the turning circles around the hospital and steepness of staircases should be considered carefully in further design stages. Vertical movement with stretchers via staircases needs to be reduced as much as possible, so other logistic systems might be considered too.
3. *Goods*: The entities 'Weapons', 'Ammunition', 'Food', 'Clothes' and 'Waste' are very different. However they have in common that they cannot move by themselves, but have to be transported. Further their size or weight pose challenges for transport using certain types of logistic systems, see section 3.8 for a further discussion on suited logistic systems. It has been assumed that the minimal required size of logistic systems for goods and the type of logistic systems is driven by the size of the goods, and not by the entity transporting the goods. For instance, a pallet with provisions needs to be transported by for instance crew, using a pallet truck. The minimal size of hallways for instance will be driven by the size of the pallet, not by the size of the crew member.
4. *Vehicles*: The MU 'Vehicles' covers the entity 'Vehicles' only.
5. *Helicopters*: The MU 'Helicopters' covers the entity 'Helicopters' only.

Landing vessels have not been included as moving unit because they are operated in the well dock and outside the LPD only. Although an essential asset aboard a LPD a landing vessel is not much involved in aboard logistic processes. Hence, for the purpose of this thesis, it is assumed that landing vessels can be kept outside the scope, with exception of the impact of landing vessels on the size of the well dock.

4.4. Support functions

In the previous sections the primary functions, the requirements and the logistic processes are defined. The realisation of the the primary functions and logistic processes require support functions to be fulfilled. Klein Woud and Stapersma (2002) and Wagner et al. (2010) describe how a functional decomposition can be used to describe different levels of support functions.

Each step in the systems engineering V-diagram provides information for (specific elements in) the next step of the process. Indeed, the support functions have to support the logistic processes. Logistic processes require general support functions, e.g. a safe platform with propulsion, but also hotel functions and support of the amphibious operations. The functional decomposition of the support functions of a LPD is presented in fig. 4.4 and based on (Klein Woud and Stapersma, 2002). The figure also shows the relations between requirements, primary functions, logistic processes and support functions. The analysis of logistic processes

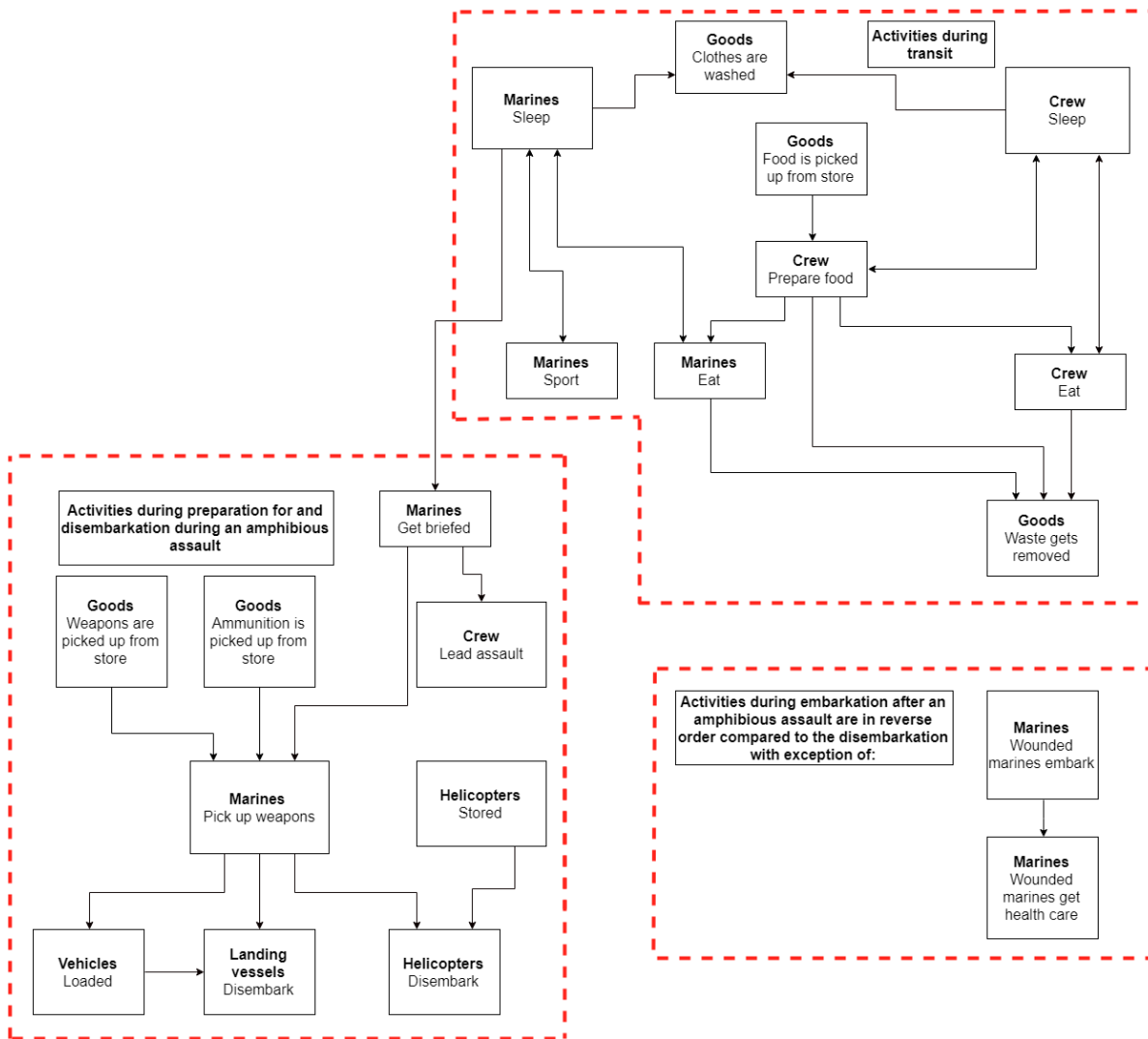


Figure 4.3: An update of fig. 4.2, encompassing the selected moving units.

revealed that all logistic processes required general support functions but that the activities during transit mainly required additional hotel facilities. On the other hand the activities during an assault need support of the logistic process.

4.5. Systems – The ship description

In logistic driven vessels systems can be divided into two categories, see section 1.3. First are the functional systems, which fulfil support functions. The functional systems in a LPD will be discussed in section 4.5.1. Second, logistic systems realise required connections in the vessel. The required connections are described by logistic system relations. These logistic system relations are described in section 4.5.2. The characteristics of the LPD specific logistic systems are given in section 4.5.3.

4.5.1. Functional systems

Functional systems fulfil support functions. Note that the support function 'provide connection' is fulfilled by logistic systems. All other support functions need to be fulfilled by at least one functional system in order to operate the ship. The full list of functional systems for the LPD concept design is given in appendix A. Note that systems like HVAC and piping are not included in the model because the level of detail does not require these systems to be modelled. The exact modelling of the functional systems in the ship description will not

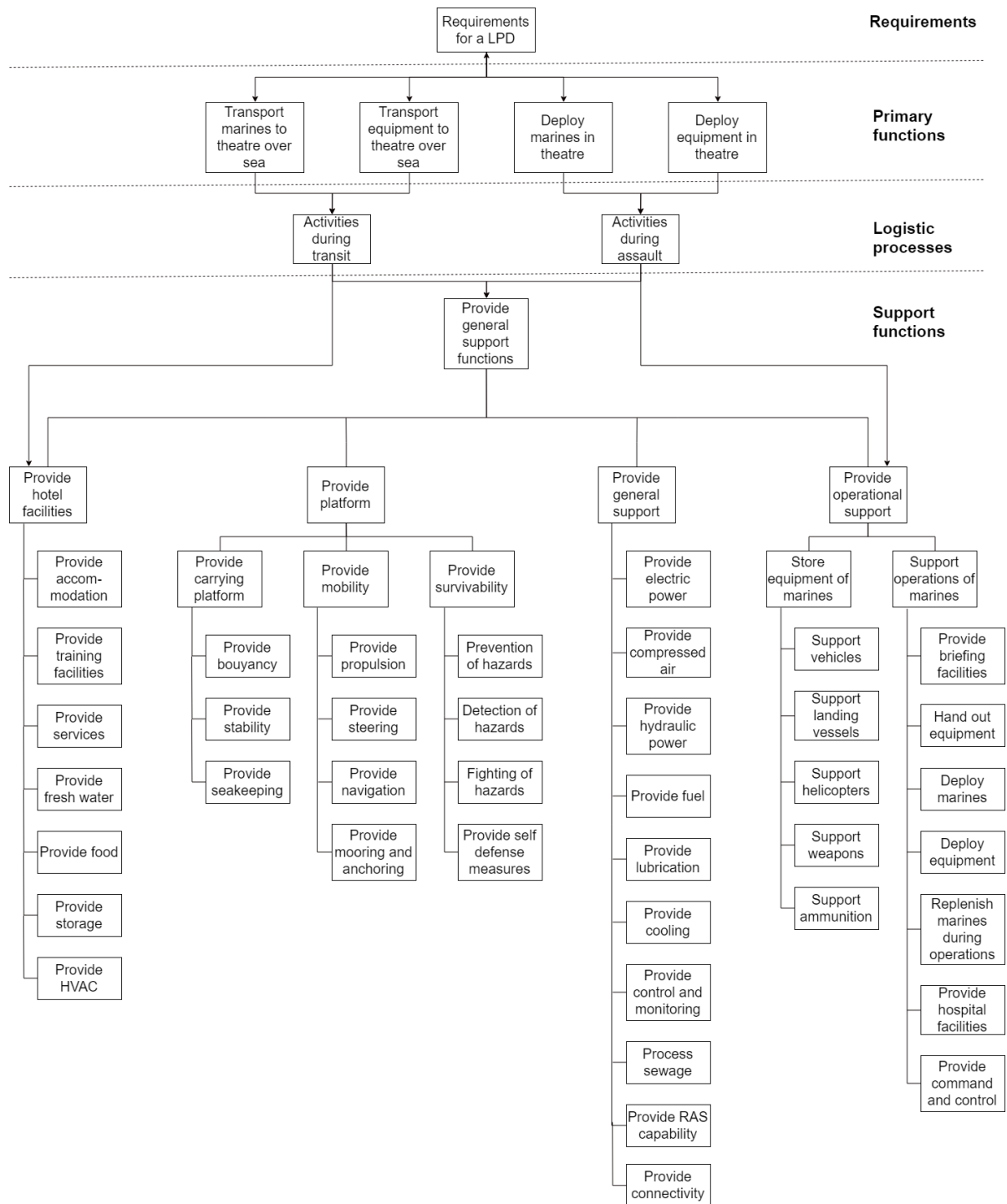


Figure 4.4: LPD's support functions, including the mapping from primary functions, requirements and logistic processes. The relation between steps is visualised by arrows.

be elaborated on here, as this is done similar to existing research. See for instance Van Oers (2011). However, the space occupied by logistic systems requires a lower level of detail of the functional systems since only two positioning slices are available, as described in section 3.13.4. Therefore the modelling of the well dock and the vehicle decks required significant compromises and are described below.

1. *Well dock.* According to the requirements the LPD should have a submersible well dock. A submersible well dock is a well dock that is situated above the waterline in normal sailing, but is submerged by

filling ballast tanks when operations with landing vessels are required. The ballasting of a LPD requires specific attention during the design of a LPD for, amongst others, the following reasons.

- Insufficient ballast capacity will make well dock operations impossible;
- The stability of a LPD is reduced in ‘submerged’ condition because of changes in the intact stability and motion of the well water. The latter is subject to the motion of the LPD and to seaway, (Leopold and Reuter, 1971). Since the focus is not to design LPDs the required ballast capacity has not been determined in this thesis. However, see chapter 7 for an outline of a method which can be used to solve this issue in future research.

In fig. 4.6 a top view of a LPD well dock and ballast configuration is shown. The well dock needs to comply to specific dimensions in order to accommodate the required number of landing vessels and enable safe well dock operations (Leopold and Reuter, 1971). In fig. 4.5a an example of a well dock and ballast system with reduced level of detail is shown. Considering the effort required to properly size the ballast capacity, reducing the level of detail of the well dock to two slices is considered to be inappropriate.

Instead the hull shape has been locally adapted to the five slices, as developed by Cieraad (2016). This enabled the well dock and ballast system to be modelled in four slices, as shown in fig. 4.5b. This way the well dock and ballast can be treated as separated systems. This enables appropriate sizing of the ballast capacity.

To provide an improved estimation of the required logistic systems, the well dock has been modelled as two systems. Since the positions of systems are indicated by the most aft and lower position, logistic processes related to the well dock will be routed to the aft end of the well dock. As a well dock is typically entered at the front end via a ramp¹, paths to the well dock have to be connected to the front end of the well dock. Therefore the well dock itself is modelled as two systems, as is shown in fig. 4.7. One object is used to model the space required for the well dock and one object is used to indicate the front end of the well dock. The logistic system relations involving the well dock are connected to this small connecting object.

2. *Vehicle deck.* Typically two styles vehicle decks are found aboard LPDs. The first is a vehicle deck spanning the whole width of the ship, as shown in fig. 4.8a. The second style is a vehicle deck that is flanked by other functional systems, e.g. stores or workshops, as shown in fig. 4.8b. The first can be easily modelled in two slices, while the latter needs four slices like the well dock. Since the systems along the vehicle deck are typically not involved in logistic processes, it was considered appropriate to reduce the level of detail of the Packing model. Instead of modelling those smaller systems and altering the Packing approach such that five positioning slices are available, the level of detail was reduced. Only the second vehicle deck style was modelled as this is the configuration present in the RNLN LPDs. In fig. 4.9 an example of such vehicle deck object is shown.

4.5.2. Logistic system relations

Logistic processes in logistic driven ships require (some of) the functional systems to be connected by logistic systems. The functional systems have been defined in section 4.5.1. The activities shown in fig. 4.3 take place between functional systems. For instance, Marines sleep in the system ‘Accommodation Marines’, eat in the system ‘Mess Marines’ and get briefed in the system ‘Briefing Room’. Consequently the following two logistic system relations can be defined, table 4.2, using the format introduced in section 3.2.

Source system	Sink system	Moving unit	Weight
Mess Marines	Accommodation Marines	Marines	2
Briefing Room	Accommodation Marines	Marines	2

Table 4.2: An example of a logistic system relation

¹Other design solutions might also be possible. For instance, embarkation of landing vessels via the side might be a solution, although this depends on the type of landing vessels. On the other hand moving units like vehicles have to enter the well dock at the front.

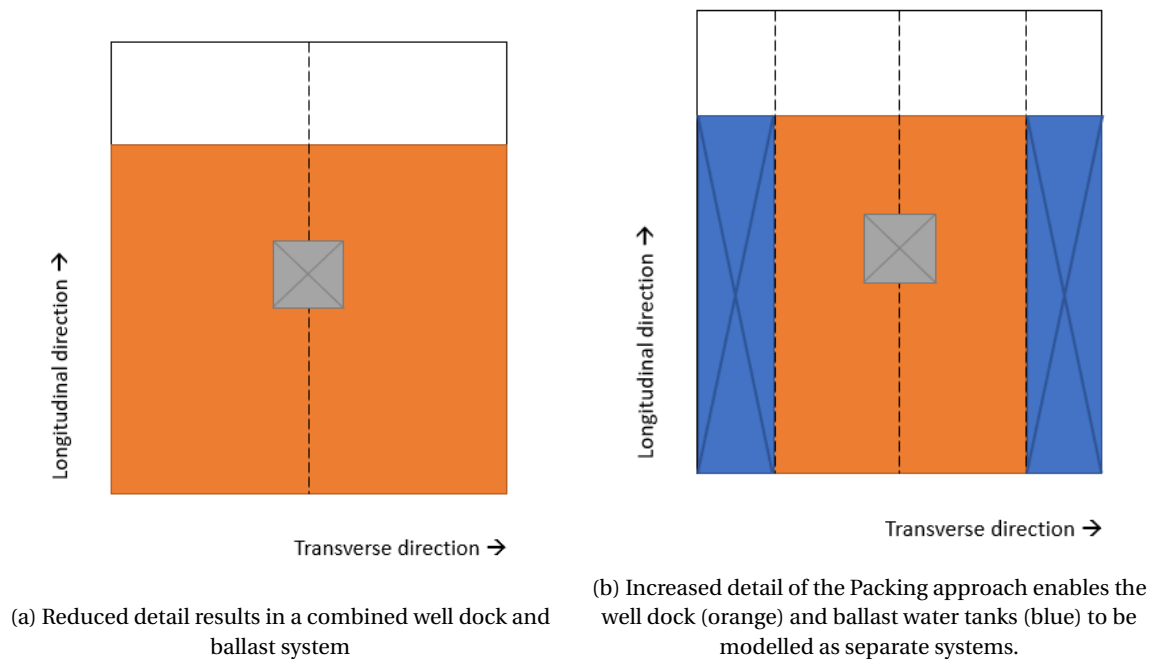


Figure 4.5: Reduced level of detail of systems versus increased level of detail of the Packing approach

Before providing the full list of logistic system category relations for the LPD, fig. 4.3 is extended to fig. 4.10. In the latter the associated systems are added to the activities. Now a full overview of the activities concerning logistic processes in a LPD is known. The logistic system relations are derived from fig. 4.10. The full list of logistic system relations used in this thesis is presented in table 4.4.

Concerning the weighing of moving units (MUs) the following weighing has been adopted, table 4.3. Here the scores are used to distinguish between the difficulty for MUs to move in the LPD. A low weight means the MU can move or be moved relatively easy compared to other MUs, while a high weight means the MU can move or be moved relatively hard compared to other MUs. The processes have been weighted equally in this thesis.

Iterative nature of operational process definition – a discussion

Note that the development of the logistic system relations is an iterative process in itself during the design of a new ship. For the test case the operational processes aboard the current RNLN LPDs have been used. However, when a new ship is designed, the use of this ship is also developed concurrently. The optimal use of the ship might differ between configurations. Also the choice for functional systems is important. For instance, a combined mess and briefing room will result in different logistic system relations and different system configurations compared to a design with a separated briefing room. These variations need also to be considered during concept exploration.

The required iterative approach to operational processes is even more important if temporal aspects are taken into account. Indeed, different configurations might have require different temporal relationships between operational processes. For instance, in a design two processes might need to take place sequentially or over a longer time because they take place on one deck, while in the other design these processes might take place concurrently because the processes are separated by the configuration.

4.5.3. Logistic systems

In the previous sections the functional systems and the logistic system relations in a LPD are defined. The last step before exploring different system configurations is the definition of the logistic systems which can be used by the LM. The generic definition of logistic systems has been explained in section 3.8. For each moving unit the possible logistic connections are defined. Different types of connections can be selected, e.g.

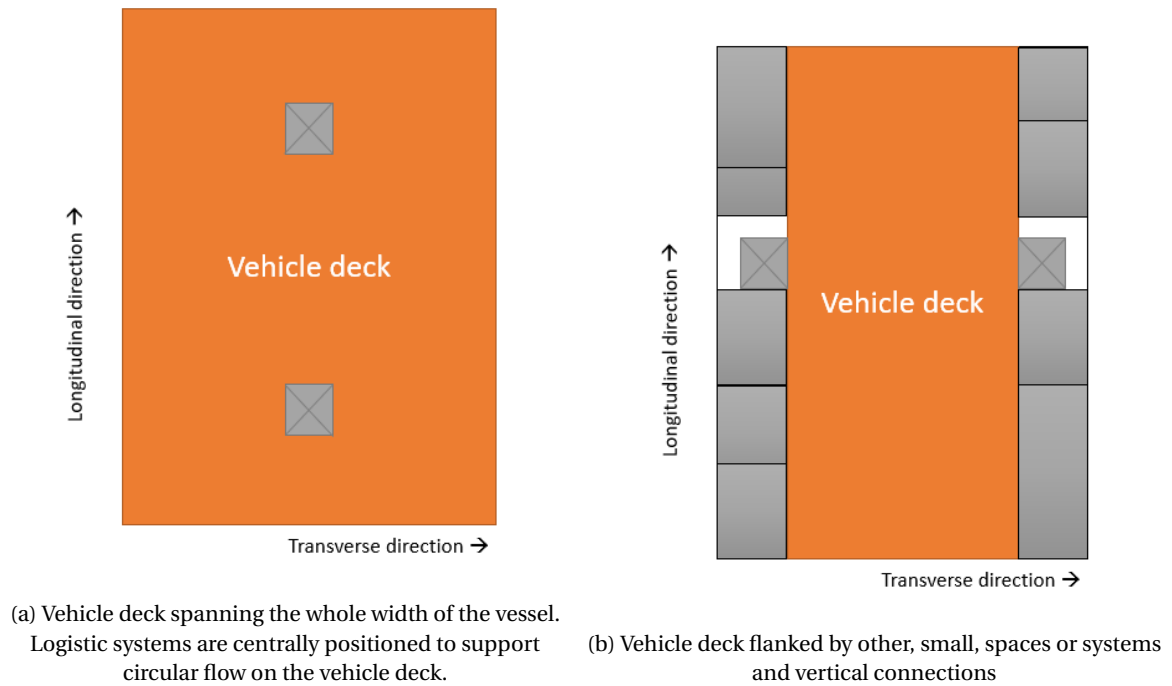


Figure 4.8: Two different vehicle deck styles.

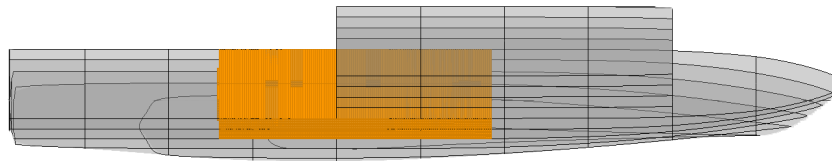


Figure 4.9: Example of a vehicle deck as modelled in the Packing approach.

Secondly, two comments are to be made regarding the logistic system for vehicles:

1. The size of vehicle lifts and ramps has been assumed to be equal. In reality both types of logistic systems have very different characteristics. Depending on the angle of the ramp, the length and width can be almost equal to that of a lift. However, a vehicle lift needs a significant engine room. On the other hand, if vehicles need to move multiple decks, the total length of a the ramp increases significantly, or large areas have to be reserved to accommodate the turning circle of vehicles. On the other hand a ramp enables a constant flow of vehicles, while a lift can move only a single or a few vehicles at once. Furthermore a vehicle lift is more sensitive to technical failures. The main reason for assuming equal size is the reduction in level of detail, as discussed in section 3.13.4 and in the following point.
2. The reduction of level of detail as described in section 3.13.4 affected the modelling of the vehicle decks, as discussed in section 4.5.1. Similar issues were found in implementing vehicle lifts and ramps to the packing model. Again, more than three transverse system positions are needed to properly model the vehicle decks, the logistic systems for vehicles and the logistic systems for the other moving units. Vehicles only need to move between the vehicle decks and the well dock. Therefore it was decided to increase the size of the vehicle decks to take the space required for the ramps or lifts into account. In addition the ramps and lifts were not modelled and the vehicle decks were forced to be adjacent to each other and to the well dock. The packing algorithm uses these adjacency rules to connect the vehicle decks with the well dock. Hence connection for processes involving vehicles is assured.

Moving unit	Weight
Marines	2
Crew	1
Goods	5
Vehicles	8
Helicopters	15

Table 4.3: Weighing for the moving units involved in the LPD

Source system	Sink system	Moving unit	Weight
Accommodation Marines	Mess Marines	Marines	2
Accommodation Marines	Laundry	Marines	2
Accommodation Marines	Gym	Marines	2
Accommodation Crew	Mess Crew	Crew	1
Accommodation Crew	Laundry	Crew	1
Accommodation Crew	Galley	Crew	1
Food store	Galley	Goods	5
Galley	Mess Marines	Goods	5
Galley	Mess Crew	Goods	5
Galley	Garbage store	Goods	5
Mess Marines	Garbage store	Goods	5
Mess Crew	Garbage store	Goods	5
Accommodation Marines	Briefing room	Marines	2
Briefing room	Joint Operations Room	Crew	1
Briefing room	Weapon hand out	Marines	2
General marines store	Weapon hand out	Goods	5
Ammunition store	Weapon hand out	Goods	5
Weapon hand out	Vehicle deck	Marines	2
Weapon hand out	Well dock	Marines	2
Weapon hand out	Helicopter deck	Marines	2
Vehicle deck	Well dock	Vehicles	8
Well dock	Hospital	Marines	2
Helicopter hangar	Helicopter deck	Helicopters	15
Helicopter deck	Hospital	Marines	2

Table 4.4: The full list of logistic system relations based on the functional systems and logistic processes in a LPD.

When to leave the arrangement of systems to the Packing approach or to combine multiple systems into a larger system is function of:

- The role of the systems in logistic processes. For a correct estimation of the required space for logistic systems all logistic system relations have to be considered. Therefore logistically connected systems should not be combined into one object. That is also the reason why a small system like the weapon hand out is modelled as a separate object in the LPD model. Indeed, this system is involved in six out of 24 logistic system relations and thus an important logistic centre aboard LPDs.
- The width of the system involved in logistic processes compared to the width of the ship. In the case the functional systems involved in logistic processes occupy a large portion of the width of the vessel the probability of these systems to be placed side by side is low. Therefore the smaller systems not involved in logistic processes, like marine engineering workshops, might be combined with the larger logistically connected systems.
- Level of detail of the Packing approach used. As discussed in section 3.3.1 an increase in the level of detail of the Packing approach, and corresponding in the detail of systems, will lead to an increase in transverse flow between functional systems. Therefore systems should be considered separately in a higher detailed ship description.

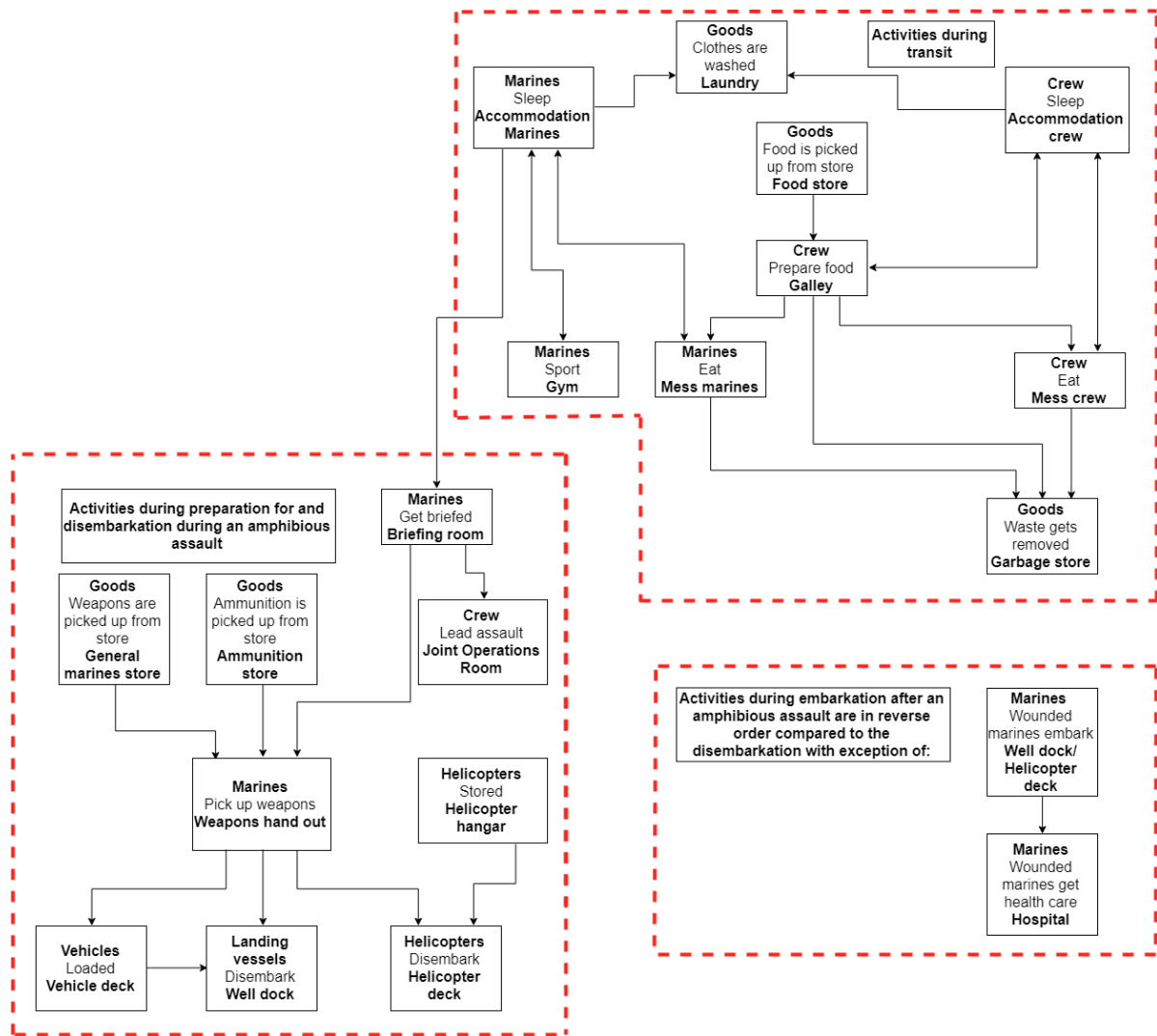


Figure 4.10: Functional systems involved in the different logistic activities in a LPD.

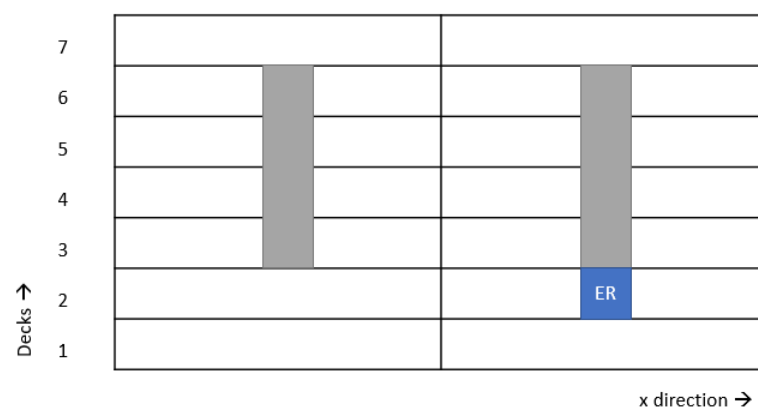


Figure 4.11: Decks three and six connected by a staircase, left, and a lift, right. The lift is driven by an engine in an engine room situated below the lift.

Thirdly, the helicopter lift size is based on the NH90 helicopter with folded rotor and tail, as shown in fig. 4.12. The helicopter lift is only required when the hangar is placed below the helicopter deck. The proposed path finding and selection method can come up with unfeasible solutions in which the helicopter hangar and lift are separated. Fitting a logistic systems to horizontally transport a helicopter through the ship in the concept definition phase is considered impossible, certainly when the required space is not included in the design. Therefore the helicopter lift was forced to be adjacent to the helicopter hangar.

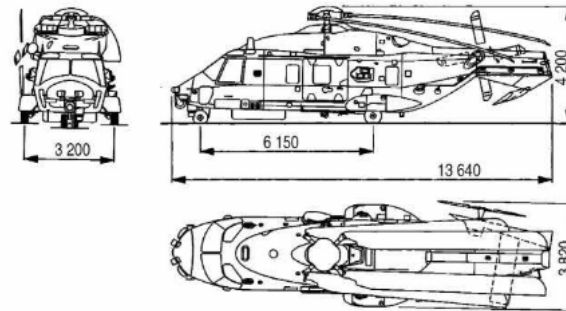


Figure 4.12: Dimensions of the NH90 maritime helicopter with folded rotor and tail, (Shulgin, 2015).

Moving Unit	Type	Standard width [m]	Standard length [m]	Width grow factor [m/extra path]
Marines	Staircase	2.8	2.8	0.3
Crew	Staircase	1.2	1.2	0.2
Goods	Lift	2.5	2.5	0.5
Vehicles	Lift/ramp	4	10	0
Helicopters	Lift	5	15	0

Table 4.5: An overview of the sizing parameters for logistic systems in a LPD.

4.6. Summary

In the previous sections the pre-configuration steps of the systems engineering V-diagram has been discussed for the design case of a LPD. Starting at the primary functions, followed by requirements setting and an analysis of the logistic processes, a set of support functions and functional systems has been developed. Based on the logistic processes and functional systems, a set of logistic system relations has been developed. Not much effort has been paid to detailed definition of the functional systems. This was considered appropriate as the LPD packing model is not developed to do concept exploration but to validate the Logistic Model. This validation is elaborated on in chapter 5.

The usefulness of the Logistic Model

The previous chapter elaborated on the design of a notional LPD which will serve as a test case for the LM. In general the Packing approach is used for concept exploration and vessel (characteristics) selection only, like demonstrated by Salvatori (2018) and Zandstra et al. (2015). In contrast, the focus in present research is to validate the LM. This explains the little effort paid to the modelling of functional systems.

True validation of a design tool in the sense of validation of a scientific theory is impossible, as explained by Pedersen et al. (2000). Therefore they describe validation of design tools as ‘a process of building confidence in usefulness’. The more effective (the tool provides designs correctly) and efficient (the tool provides correct designs) a design tool is, the more useful it is. The validation of the LM is done as follows:

1. *Assessment of effectiveness of the Logistic Model*

Assessment of the effectiveness of a model is the same as verification of a model. The aim is to ascertain the model has been build right. How the model should behave is described in chapter 3. In order to assess the effectiveness of the LM the following test cases are investigated:

First, test cases with a low number of logistic system relations are investigated in section 5.1.1. The LM should be able to place systems adjacent using the logistic system relations between these systems. The low number of logistic system relations enables local optimisation of system positions, which should be visible in the test case results.

Second, the behaviour of the logistic model in a test case involving a larger number of logistic system relations is investigated, section 5.1.2. It is expected that optimising logistic performance of the whole ship leads to less local optima as found in the previous test cases. Indeed, to improve the logistic performance of the whole ship compromises between system adjacency might be required, section 3.14.

2. *Assessment of efficiency of the Logistic Model*

To assess the efficiency of the LM the number of correct designs will be investigated and compared with the number of incorrect designs in section 5.2.

3. *Further assessment of the LM's usefulness in concept exploration.*

After the model has been verified by means of test cases, i.e. the effectiveness of the LM has been established, the usefulness of the model in the concept exploration of a logistic driven vessel is investigated in section 5.3. To find out if the LM actually adds to the concept exploration of logistic driven ships the impact of logistic systems on the size of a logistic driven ship is investigated. Therefore the LPD packing model created in chapter 4 is used. Contrary to the test cases used for the assessment of effectiveness, the Packing approach is given feasibility constraints to ensure that non-negotiable requirements are met, see section 3.14.3. Further the relation between logistic performance and size of concept designs is investigated. Finally representative designs are selected from the data set and investigated to find features that contribute to the design knowledge of a LPD.

5.1. The effectiveness of the Logistic Model

A proof of concept of the LM has been given in section 3.15. A further investigation of the effectiveness of the LM is provided in the current section. An effective model provides designs correctly. This means that the

designs generated are correct, i.e. the model performs as intended. The LM has been described in chapter 3. Given this description of the model the question to be answered in this section is:

Does the Logistic Model provide a set of correct logistic systems for each design?

To answer this question four test cases based on the LPD model developed in the previous chapter are investigated.

5.1.1. Small number of logistic system relations

The LM should be able to place logistically related systems close together and connect those by means of logistic systems. In ship design, see section 1.2, many compromises have to be made regarding the placement of systems. For instance, to improve the adjacency between one pair of systems the adjacency between another set of systems might be reduced. A few cases can be distinguished, which will be further explained below. To determine the effectiveness of the LM, only the LPM has been used as objective function. Indeed, the aim is to show that the LM is able to place systems close together as good logistic performance is defined as good system adjacency in section 3.14. The naval architectural aspects like stability and space utilisation (e.g. high packing density) are not taken into account in the test cases but are used in section 5.3. The following test cases are investigated:

1. Consider a few logistically connected systems, which are not restricted to certain locations. It is expected that the LM will cluster these systems. However, since the systems are not bound to certain locations these groups are either expected to be placed in several locations in the ship, or to be concentrated at certain locations due to the possible limited diversity of the Packing approach. Two sub cases are investigated.
 - (a) One system relation, automatically, involving one type of moving unit. It is expected that the Packing approach will place these systems closely together. Further, in the case a vertical connection is needed, one goods lift will be added as logistic system to provide the required vertical connection. In an exploration with a population of 20 designs and 50 generations¹ the best design found has

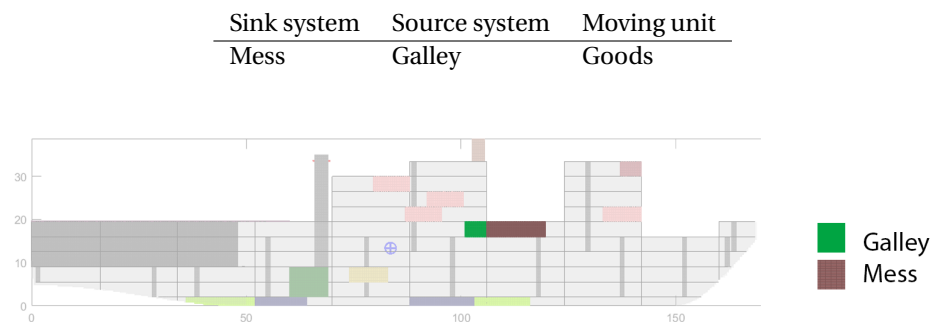


Figure 5.1: Side view of the design with lowest LPM score found for test case 1a, in which the galley is placed aft of the mess.

the galley and mess positioned horizontal adjacent, fig. 5.1, where the galley is positioned aft of the mess. This was also to be expected, because the distance between both systems is minimal in this case. Indeed, the galley is modelled as a smaller system than the mess. Since the positions of systems are defined as the aft lower corner of the system, positioning the galley aft of the mess will result in a smaller distance between the systems, and thus a lower LPM score. Depending on the size of the systems, designs with vertical adjacency between the galley and the mess could be more preferred than designs in which the galley is positioned in front of the mess. This preference is undesired since the order of systems does not play a role horizontal adjacency and therefore both cases should be scored equally. This issue is visualised in fig. 5.2. The results from the exploration support this explanation. Indeed, fig. 5.3 shows the relative horizontal position of the mess to the galley. In blue are all designs in which the galley and mess are positioned on the same deck. From

¹These numbers proved to give reliable results for test case 1 and 2 and made for a time efficient exploration. In test case 3 the number of generations was increased for improved convergence.

this figure it can be concluded that, indeed, for lower LPM scores the galley is positioned aft of the mess. Also, this figure shows the preference for ‘case 2’ over ‘case 3’. See chapter 7 for a possible solution for this issue.

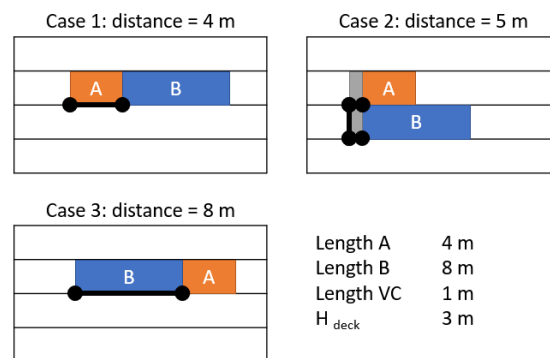


Figure 5.2: Example to illustrate the effect of system locations on optimisation to distance.

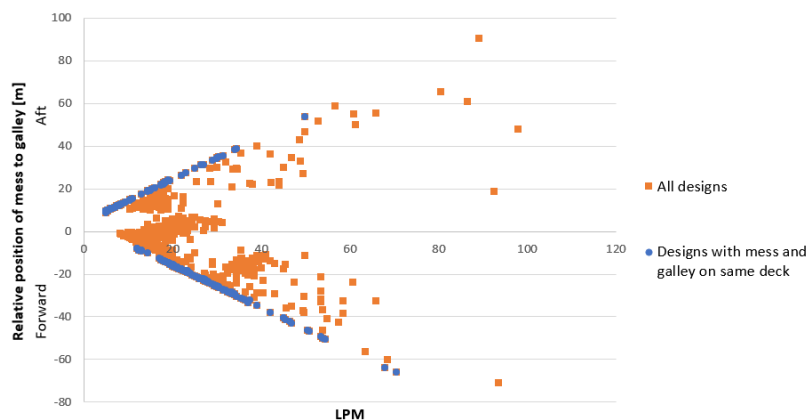


Figure 5.3: The relative longitudinal position of the mess to the galley, illustrating the effect described in fig. 5.2 can be observed in a whole data set as well.

An example design in which the galley and mess are positioned on different decks will be investigated. The design is selected based on the lowest LPM score and is shown in fig. 5.4. Since the mess and galley require a connection by a goods lift, this lift should be included in the design. Indeed, the LM added the required goods lift. Note the required engine room is correctly implemented as well.

Since the LM proves to provide reliable results for the case of one logistic system relation, the case of multiple system relations will be investigated next.

- (b) System relations involving multiple types of moving units. It is expected that the Packing approach will place these systems closely together because minimisation of the distance between systems minimises the LPM score. Further, in the case a vertical connection is needed, one or two goods lifts and/or a staircase for marines will be added as logistic systems to provide the required vertical connection.

In fig. 5.5 the design with the lowest LPM score found by the Packing algorithm in a search with a population of 20 designs and 50 generations is shown. This design indeed includes one staircase for marines to connect the briefing room with the weapon hand out. Further two goods lifts are included to connect both the ammunition store and the general marines store with the weapon

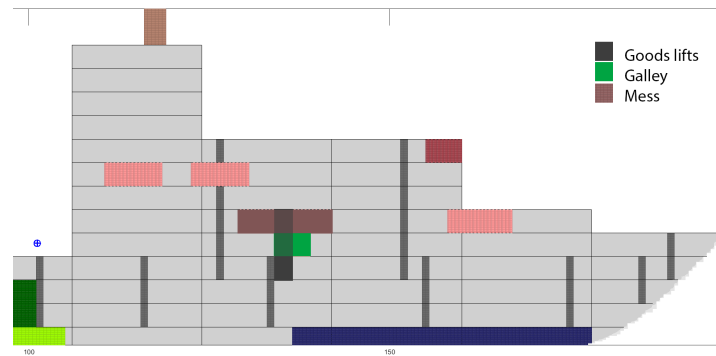


Figure 5.4: Side view of the design with lowest LPM score found for test case 1a, in which the galley is placed aft of the mess.

Sink system	Source system	Moving unit
Weapon hand out	Briefing room	Marines
Weapon hand out	Ammunition store	Goods
Weapon hand out	General marines store	Goods

hand out. Clearly the ammunition store and general marines store have been concentrated below the weapon hand out to minimise the LPM score. With regards to the left goods lift the following remarks can be made:

- This goods lift will be unused in the processes investigated as it can not be reached due to the watertight bulkhead, which is visible just right of the goods lift. These unused vertical connections lead to an overestimation of space required for logistic systems. However, considering more systems and logistic system relations, these excess connections might be used for connection in other logistic processes. Therefore no action is taken to remove possibly unused logistic systems.
- This goods lift has been included in the design due to the initial positions of the systems. Indeed, the initial position of the ammunition store is situated one compartment left of its final position. Due to the watertight subdivision an additional lift was needed. Once the initial position of the ammunition store is shifted to point between the bulkheads at $x = 88$ [m] and $x = 103$ [m], the left lift will be removed from the design. See fig. 5.6 for the initial and final positions of the four systems in consideration. The figure shows that the initial positions almost resemble the final positions.

This test case showed that the LM could overestimate the space required for vertical logistic systems. The source of this overestimation is the overlap management carried out by the packing algorithm. The overestimation is removed when the initial positions resemble the final positions. This is expected to when the number of generations in the exploration run is increased. The initial positions already match the final position quite well, as fig. 5.6 shows. Therefore this overestimation of space is accepted.

2. Consider a few logistically connected systems of which one system is restricted to a certain location. Only the case involving one moving unit will be presented as the LM proved to handle the case for multiple moving units well in the previous test cases. The three logistic system relations shown below are chosen. The well dock is obviously restricted to the aft of the ship. Considering these location limitations it is expected that the LM will place the systems just in front of the well dock to minimise the distance between the weapon hand out and the well dock. The ammunition and general marines store will be positioned close to the weapon hand out to minimise the distances for the latter two logistic system relations.

Again an exploration run with a population size of 20 and 50 generations was performed. The best scoring design is shown in fig. 5.7. The weapon hand out, the ammunition and general marines store are indeed restricted to their longitudinal lower bound of $0.4 \cdot LOA$. This results in unutilised space between these systems and the well dock.

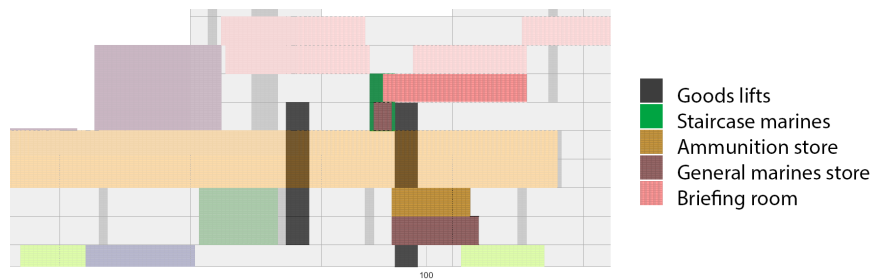


Figure 5.5: Side view of forward part of the design with lowest LPM score found for test case 1b.

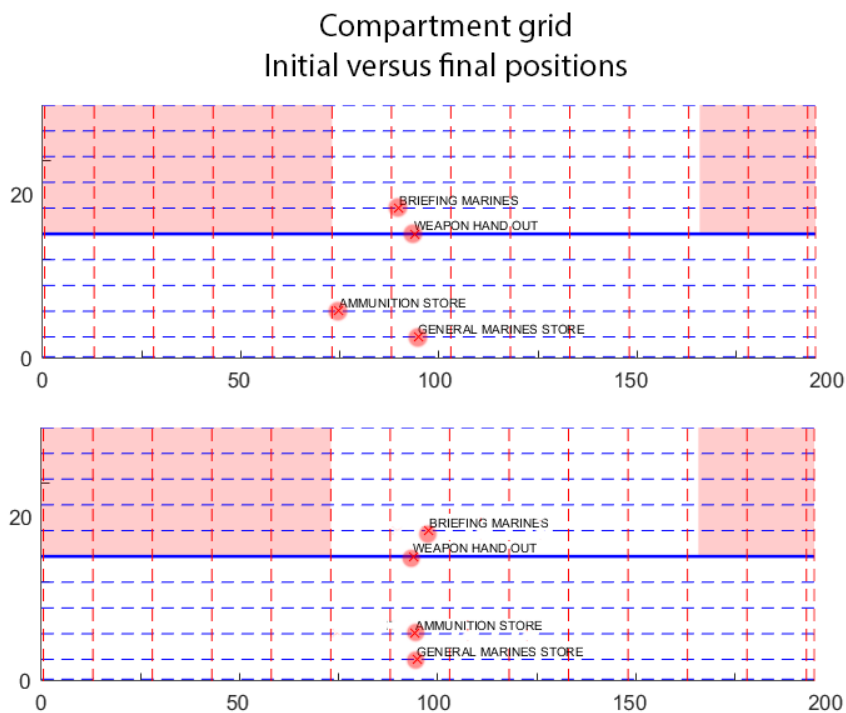


Figure 5.6: The initial (top) and final (bottom) positions of the four systems in consideration in test case 1b.

As expected, the weapon hand out is positioned at minimal distance to the well dock. The ammunition and general marines store are positioned as close to the weapon hand out as possible. Required vertical connection is indeed provided by a good lift positioned close to the weapon hand out and both stores. However, again a second good lift is included in the design as well. This lift is positioned in the compartment aft of the weapon hand out, as shown in fig. 5.7. Investigation of the initial positions of the systems and the subdivision of this design revealed that this goods lift is implemented because of the watertight subdivision. In fig. 5.8 the watertight subdivision of this design and the initial positions of the four systems are shown. Since the weapon hand out and the well dock are both initially located below the damage control deck, horizontal access between compartment 22 and 31 is not possible. Therefore an additional goods lift was required to provide access.

3. Consider a logistic system relation with multiple similar objects. In the test cases above each logistic system relation involved one object. This test case proves that the LM is able to handle logistic system relations that include multiple similar objects. In this case the accommodation exists of four objects. The mess, galley and food store are still modelled as single objects.

It is expected that the LM will place the accommodation objects close to the mess, while the mess

Sink system	Source system	Moving unit
Weapon hand out	Well dock*	Goods
Weapon hand out	Ammunition store	Goods
Weapon hand out	General marines store	Goods

* Remember the well dock is connected to other systems at the front of the well dock, see section 4.5.1.

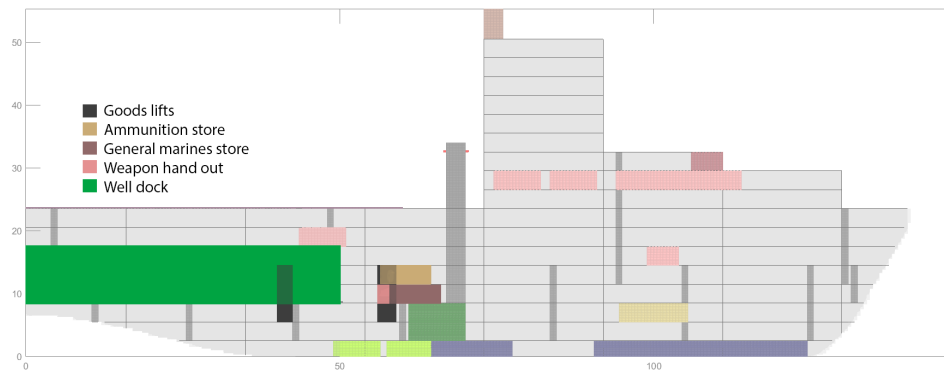


Figure 5.7: Side view of the design with lowest LPM score found in test case 2.

and food store in turn will be placed close to the galley. Required vertical connection will be provided by staircases for crew and good lifts. Again an exploration run involving a population of 20 designs and 50 generations is carried out. The design with lowest LPM score is given in fig. 5.9. The following remarks regarding this design can be made.

- One staircase provides vertical connection between upper three of the four accommodation blocks and the mess. Therefore three activities take place in the staircase between the upper three accommodation blocks and the mess. The size of this staircase is increased accordingly. This shows that the LM is able to transform a single logistic system relation to a set of logistic system relations between similar objects, as described in section 3.5.
- Further, this design shows that each watertight compartment and each zone is vertically connected as described in section 3.9.
- One goods lift provides vertical connection between the food store, galley and mess. Again, the engine room of this lift is modelled as intended.
- Intuitively it is noted that this design could be optimised further by positioning the upper three accommodation objects closer to the mess. Apparently the LM is not completely converged to an 'optimal' solution. Therefore the convergence of the exploration will be investigated.

The convergence plot of the exploration run in test case 3 is given in fig. 5.10. The exploration run seems to be converged to a large extend. However, given the potential for improvement in best design found so far and the trend of the convergence plot, it can be concluded that further convergence is possible. Therefore another exploration run is initiated, with a population size of 20 designs and 100 generations.

The second exploration run seems to be more converged, based on the trend of the convergence plot. However it is remarkable that the minimum LPM value found, 115, is higher than in the first run, 95. In particular this is due to the weights assigned to the moving units in this case. The MU 'Goods' is assigned weight 5, while 'Crew' is weighed 1. The actual total distance in both designs differs just four meters. Since the weights help to distinguish designs based on the performance on processes involving different moving units, a longer distance for a process involving an manoeuvrable entity, like a crew member, can be more acceptable than a longer distance for a process involving for instance a pallet with supplies.

Based on the results obtained in the test cases involving small amount of logistic system relations, it can be concluded that the LM performs as expected. As a result sufficient confidence in the effectiveness of the LM is gained. Therefore the behaviour of the LM in test cases with a large number of logistic system relations will be investigated in the next section to further increase confidence.

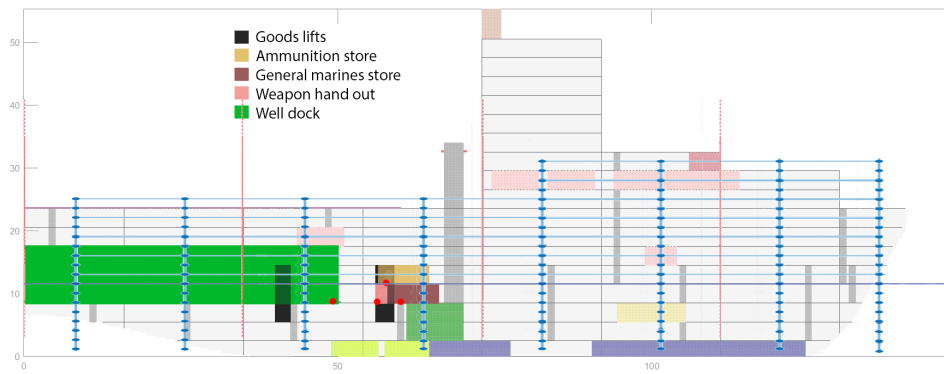


Figure 5.8: Side view of the design with lowest LPM score found in test case 2, with overlaying physical architecture visualising the watertight subdivision.

Sink system	Source system	Moving unit
Accommodation*	Mess	Crew
Galley	Mess	Goods
Galley	Food store	Goods

* Four accommodation blocks represent the accommodation space in the model.

5.1.2. Large number of logistic system relations

Since the LM proved to be able to deal with a small number of logistic system relations, the LM will be tested with a larger set of logistic system relations.

- For the fourth test case, test case two and three are combined. The set of logistic system relations is shown below. Since the systems in test case two are not connected to systems in test case three, it is expected that the LM will steer towards two clusters. The first cluster is the set of systems in test case two, which are expected to be placed close to the well dock. The second is the set of systems in test case three, which are expected to be placed in the superstructure.

Sink system	Source system	Moving unit
Weapon hand out	Well dock	Goods
Weapon hand out	Ammunition store	Goods
Weapon hand out	General marines store	Goods
Accommodation	Mess	Crew
Galley	Mess	Goods
Galley	Food store	Goods

It was expected that convergence in this test case is harder than in small test cases. Indeed, the previous test cases showed that the LM was less able to steer towards 'optimal' solutions when the number of logistic system relations is increased. Therefore a longer exploration run was carried out, involving 20 designs and 100 generations, instead of 50 generations. The best design found is presented in fig. 5.11. Clearly the two clusters can be distinguished. The food store (yellow) is not placed in the upper cluster as its vertical position is limited to deck five, where it is positioned in the design shown. The following notes on this design can be made:

- An unnecessary goods lift is included in the design around $x = 30$ [m], due to the initial position of the weapon hand out.
- The upper staircase aft of the exhaust extends one deck too high, due to the initial position of one of the accommodation objects, which was initially positioned at the bridge deck.
- The goods lift around $x = 70$ [m] serves both the process of transport of food from the food store to the galley as the transport of equipment from the general marines store to the weapon hand out. This shows the LM is able to correctly assess the use of vertical nodes and combine vertical connections needed for different logistic processes, as described in section 3.8.

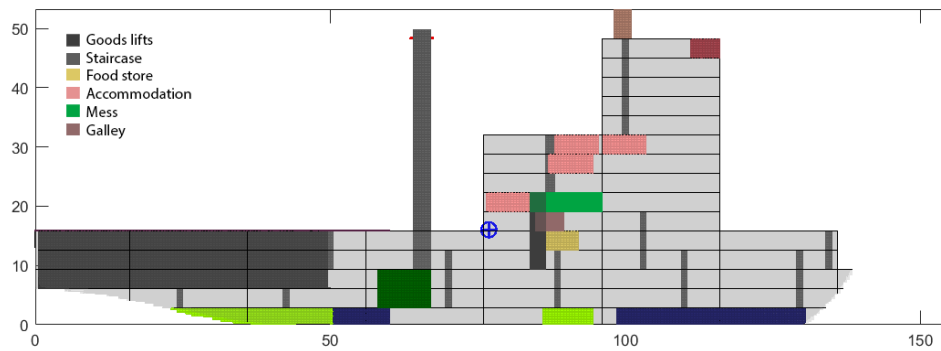


Figure 5.9: Design with lowest LPM score found in test case 3.

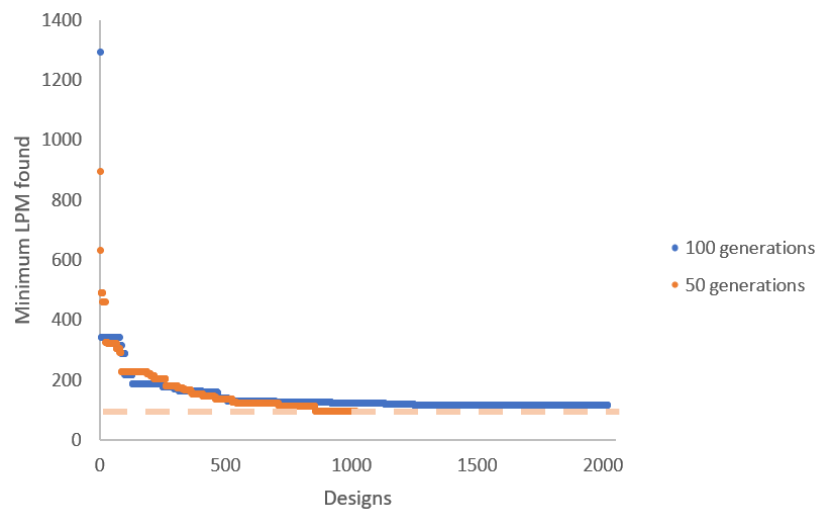


Figure 5.10: Convergence plot of the LPM for test case 3 for both exploration runs. Designs with disconnections have been filtered from this data set.

- Improved logistic performance could be achieved by placing accommodation related systems lower in the ship, for instance.

5.1.3. Conclusion

Four test cases have been presented to build confidence in the effectiveness of the LM. Based on different sets of systems and logistic system relations the behaviour of the LM has been assessed and compared to the intended behaviour as described in chapter 3. The LM has proven to give consistent correct logistic systems and the Packing approach was able to add these systems to the designs as expected. The question to be answered is:

Does the Logistic Model provide a set of correct logistic systems for each design?

Given the test cases, the Logistic Model provides indeed a set of correct logistic systems for each design. Therefore the results of the LM seem to be reliable.

5.2. The efficiency of the Logistic Model

The previous section pointed out that the LM provides correct designs, i.e. works as intended and described in chapter 3. In the previous section the issue of disconnection has not been discussed. The source of this issue is known, namely overlap management performed by the packing algorithm. Therefore designs which have disconnection are not seen as incorrect designs in the sense that the LM did provide wrong output. Instead these designs are seen as undesired. The following question needs to be answered:

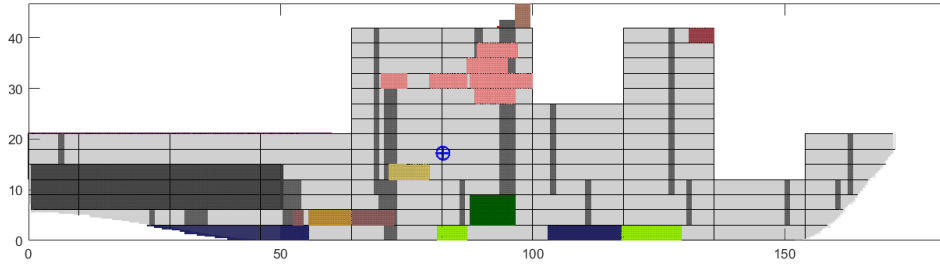


Figure 5.11: Most promising design found in test case 4.

Given the limitations of the Packing approach, does the Logistic Model provide designs correctly?

Since the LM performs as expected, each design is provided correctly. However, since some designs are undesired due to disconnection, the efficiency of the LM has been defined as eq. (5.1). To answer the question above the test cases, section 5.1, and the LPD exploration, section 5.3, have been investigated. The results of this analysis are presented in table 5.1. From this table can be concluded that the efficiency of the LM is high for the test cases. It should be noted that the low number of systems enables the Packing approach to place systems rather easily. However, when the number of systems and number of logistic system relations is increased the Packing approach moves systems significantly more during overlap management. Therefore the number of disconnections is also higher than in the test cases. In fig. 5.12 the percentage of designs with disconnection over the number of packed designs per generation in the exploration search is shown. With an average of approximately 23%, the number of disconnections varies a lot over the generations. The regression line indicates that the number of designs with disconnections reduce slightly over the generations. So this analysis shows that the NSGA-II is hardly able to steer away from disconnection. However, this is accepted as the NSGA-II is meanwhile able to find improved designs from a logistical point of view, as has been shown in section 3.14.3. The lower $LM_{\text{efficiency}}$ is therefore considered acceptable. To build further confidence the usefulness of the LM in a LPD design exploration test case will be assessed in section 5.3.

$$LM_{\text{efficiency}} = \frac{\text{number of correctly connected designs}}{\text{number of designs}} \quad (5.1)$$

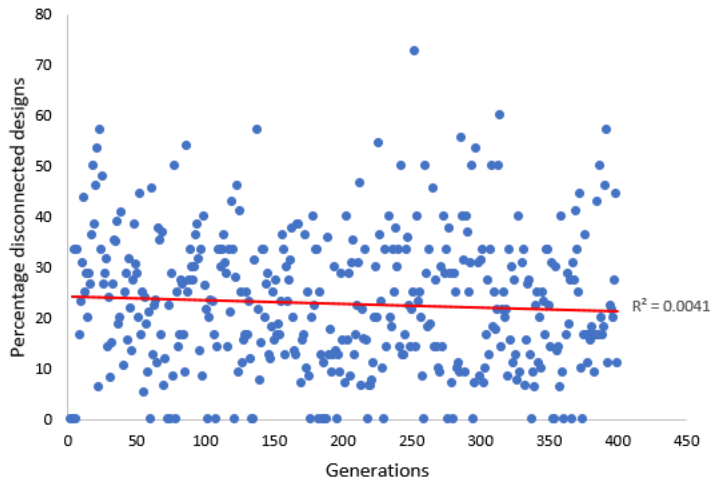


Figure 5.12: The number of design with disconnection over the number of packed designs per generation. On average 23% of the packed designs has at least one disconnection.

Logistic system relations	Number of designs	Number of designs with disconnection	Number of correctly connected designs	$LM_{\text{efficiency}}$
1	535	2	533	0.996
3	829	0	829	1.000
6	816	6	810	0.993
6	1626	3	1623	0.998
9	1811	0	1811	1.000
9	1727	29	1698	0.983
38	4993	1157	3836	0.768

Table 5.1: The efficiency of the LM in the test cases

5.3. Further assessment of the LM's usefulness during concept exploration

The previous sections concluded that the LM behaves as expected in test cases. In the current section the application of the LM to a LPD concept exploration will be investigated to build further confidence the LM's usefulness. Therefore the question to be answered in this section is:

Does the Logistic Model attribute to the concept exploration of a LPD?

To answer this question, first the concept exploration of a LPD will be described in section 5.3.1. Then the impact of logistic systems on the ship size will be investigated in section 5.3.2 in order to assess if the LM provides useful information in the concept exploration phase. In addition, section 5.3.3 describes the impact of LPM on the ship size. Finally a few promising designs will be selected from the data set in section 5.3.4. The layout of these concept designs will be further investigated in order to increase the design knowledge on logistic performance of LPDs.

5.3.1. LPD concept exploration

To answer the question posed above, an exploration run with 52 designs and 400 generations² was performed, and thus 20852 attempts to find feasible designs. This exploration run resulted in 5005 feasible designs, of which 1157 had at least one logistic disconnection. The set of connected designs to work with is therefore 3848 designs. Before investigating the impact of the logistic systems (section 5.3.2) and the LPM (section 5.3.3) on the ship size, a general overview of the range of the main dimensions of the designs found in the exploration is given in fig. 5.13.

5.3.2. Impact of logistic systems on ship size and logistic performance

Logistic systems utilise space in a ship. Since this research aims to improve the estimation of space required for logistic systems, the impact of logistic systems on the ship size is investigated. Where the LPM helps to steer towards logistically promising designs, are the ship size and performance driven by the logistic systems, as explained in section 1.2. The packing order of functional and logistical systems has been developed such that the logistic systems have minimal impact on the ship size, i.e. minimal void space is required to pack all systems, see section 3.13.3.

Given certain ship dimensions, ships with both functional and logistical systems will have more space occupation than ships with functional systems only. The impact of logistic systems on ship size is first investigated based on the volume occupation by logistic systems, in comparison to the volume occupation by functional systems. Space occupation can be calculated using eq. (3.7), as explained in section 3.14.3.

$$PD = \frac{\text{volume}_{\text{objects}}}{\text{volume}_{\text{ship}}} \quad (3.7 \text{ revisited})$$

The objects or systems in each design can be divided into two classes, chapter 1, namely in functional systems and logistic systems. So also the volume of the objects can be divided into these two classes.

²These values were suggested by DMO naval architects based on experience. Sufficient convergence was obtained for the purpose of this study.

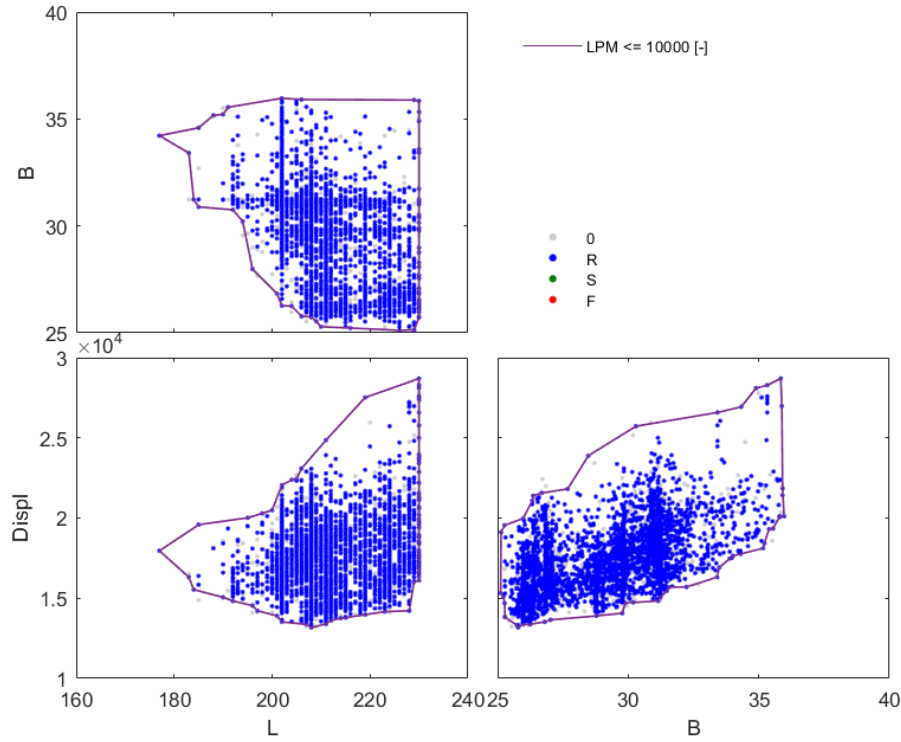


Figure 5.13: Range of main dimensions found in the exploration run performed

$$\text{volume}_{\text{objects}} = \text{volume}_{\text{functional systems}} + \text{volume}_{\text{logistic systems}} \quad (5.2)$$

Therefore, eq. (3.7) can be rewritten to:

$$\text{PD} = \frac{\text{volume}_{\text{functional systems}} + \text{volume}_{\text{logistic systems}}}{\text{volume}_{\text{ship}}} \quad (5.3)$$

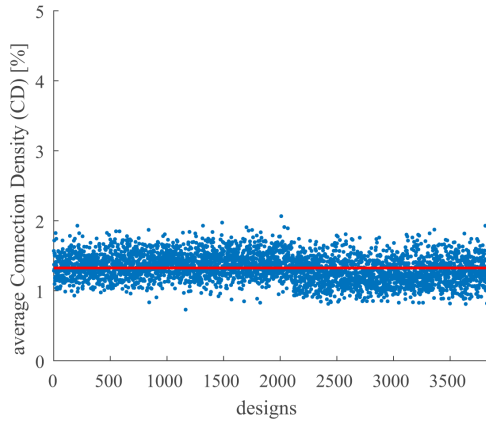
The volume occupation by logistic systems as function of the volume of the ship, or CD (connection density), has been defined eq. (5.4).

$$\text{CD} = \frac{\text{volume}_{\text{logistic systems}}}{\text{volume}_{\text{ship}}} \cdot 100[\%] \quad (5.4)$$

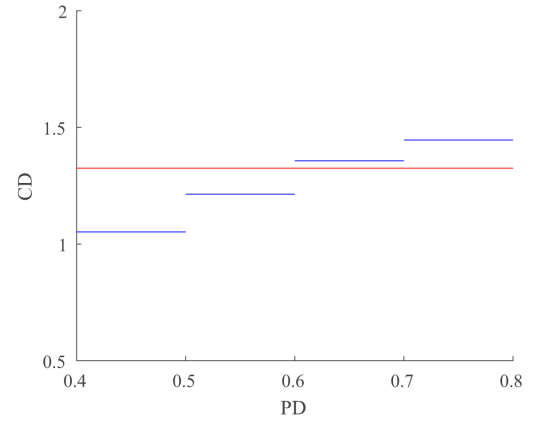
A plot of CD for each design is given in fig. 5.14a. The average is indicated by the red line. On average approximately 1.5% of the volume of the systems aboard a LPD is occupied by logistic systems. Note that the logistic systems required for vertical movement of vehicles neither the horizontal logistic systems have been included in this number, see section 4.5.3. Further the values used for the sizing of the logistic systems might be too low. Therefore the percentage in a more carefully modelled LPD with sufficient detail will likely be higher.

Further investigation revealed that the CD increases with increasing PD. This is shown in fig. 5.14b in which the average volume percentage of logistic systems for four intervals of PD and the overall average is given. This can be explained as the volume of the functional systems remains relatively constant³. Assuming a constant volume of the functional systems, both PD and CD will either increase if the volume of the ship reduces or the volume of the logistic systems increases.

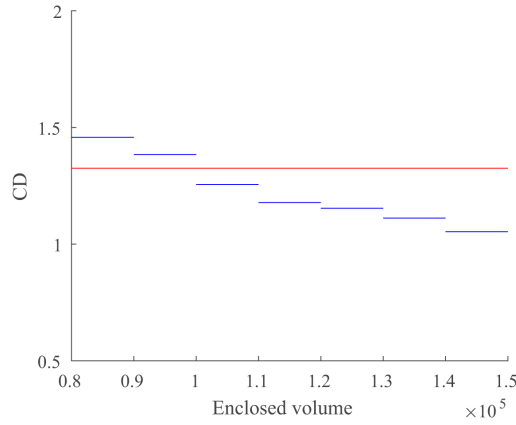
³A variation in the volume of functional systems is explained by some systems which are not necessary enclosed by the superstructure, like the hangar.



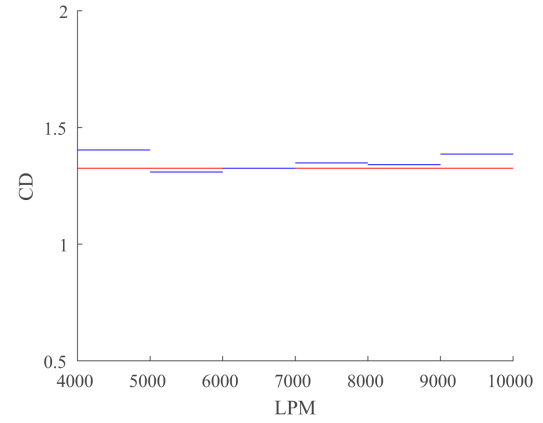
(a) Volume of logistic systems CD as percentage of volume of the ship. The red line indicates the average CD.



(b) Average volume percentage of logistic systems on PD intervals



(c) Average volume percentage of logistic systems on intervals of enclosed volume



(d) Average volume percentage of logistic systems on LPM intervals

Figure 5.14: Average CD for whole data set (in red) as well as CD related to PD, enclosed volume and LPM scores of designs

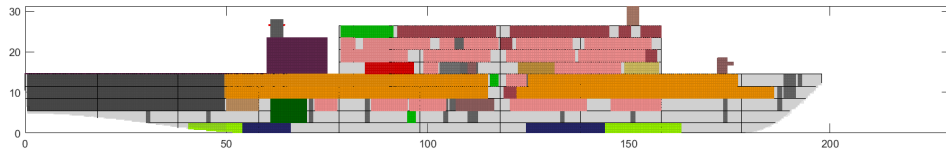
A similar trend is seen in fig. 5.14c, in which the average volume percentage of logistic systems for intervals of enclosed volume and the overall average is given. This was expected since PD and enclosed volume are negatively correlated, as is shown in section 3.14.

On the other hand, the relation between average CD and the logistic performance is less distinct, as shown in fig. 5.14d. Although some variation in the space required for logistic systems is apparent, the variation for different logistic performance scores is less than seen in fig. 5.14b. An explanation for this observation could be that the logistic performance of ships is less driven by the volume of logistic systems than it is by the configuration of functional systems. Another explanation could be that a slightly more voluminous design could have a logistically promising or a less promising configuration of systems. Because both volume and logistic performance are optimised, the Packing will converge to both smaller and logistically promising designs. Therefore the CD is high for logistically promising designs.

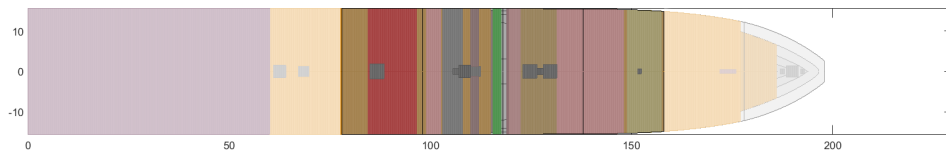
For one design the area occupied by logistic systems has been calculated for one deck. The design selected is the logistically most promising design in the data set with LPM = 4450, see fig. 5.15a. The deck selected is the first deck of the superstructure, as shown in fig. 5.15b. The total area of this deck is approximately 2500 m^2 , and the area occupied by logistic systems is approximately 50 m^2 . As a percentage approximately 2%

of the deck area is occupied by logistic systems. This is slightly higher than the volume occupation, but still rather low.

Although the space required for logistic systems has to be specifically added to each design, chapter 1, the impact of the logistic systems on the logistic performance appears to be low. Logistic systems provide required connection and have therefore to be taken into account. However with the same amount of logistic connections, both in terms of volume and number of connections, a wide range of logistic performance can be obtained. This is shown in fig. 5.16. Hence, it can be concluded that the arrangement of the functional systems is more important to the logistic performance of logistic driven ships. Therefore the relation between logistic performance and the ship size will be investigated next.



(a) The selected concept design



(b) The first deck of the superstructure. The grey objects on the centreline represent vertical connections.

Figure 5.15: Investigation of the area occupied by logistic systems on one deck

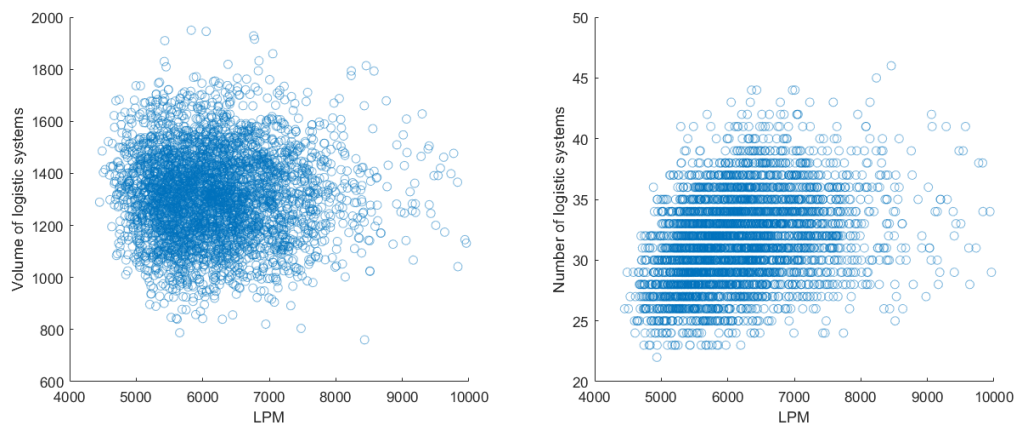


Figure 5.16: Logistic performance versus the number and volume of logistic systems in each design. Given the assumptions made, logistic performance is not driven by the amount of logistic systems.

5.3.3. Impact of LPM on ship size

The LPM score of a design is function of the x and z position of systems, see section 3.14. More specific the horizontal and vertical distance between logistically connected systems is scored in d_i . Therefore reducing the horizontal and vertical distance between systems will generally lower the LPM score. Since a shorter ship has shorter horizontal distances between systems generally, it is expected that shorter designs have better logistic performance. Note that the LPM score is also dependent of the available logistic systems. Indeed, the positions of the logistic systems are taken into account in d_i . In fig. 5.13 a slight negative trend between

Length and Width can be observed. Since it is expected that a shorter design will also result in a better logistic performance, two performance criteria are applied. The first criterion is $LPM < 5500$, which helps down selecting the set of 3848 designs to a set of 844 logistically acceptable designs. The minimum LPM score found in this concept exploration is 4450. For further down selection also the criterion $LPM < 5000$ was applied, resulting in 158 logistically promising designs. The dimensions of the logistically acceptable and promising designs in comparison with all designs is shown in fig. 5.17. As expected, the logistically promising designs are typically shorter and wider than the other designs in the data set.

Since the LPM score has been used as one of the objective functions, the NSGA-II searched for logistically promising designs. In section 5.3.2 it was found that logistic performance is driven by the configuration of functional systems, rather than by the implemented logistic systems. So indeed, the location of functional systems have impact on the logistic performance as well as on the size of the ship, as described in section 1.2. Two objective functions have been used to steer the exploration run, section 3.14.3. As expected, the multi-objective optimisation leads to a trade-off between enclosed volume and logistic performance. In fig. 5.18 the scores of each design regarding enclosed volume and logistic performance are plotted. Also the Pareto front is visualised. From this graph, and corresponding regression line, it can be concluded that the ship size in general has to increase to accommodate a logistically more promising configuration of systems.

The LPM provides a measure for logistic performance of logistic driven ships. It provides information on the total distance between logistically connected systems. Further, the performance of important, i.e. highly weighted, processes can be distinguished. However, the LPM does not inform the naval architect *why* a configuration is logistically promising. However, capturing this rationale is one of the aims of concept exploration, (Roth et al., 2017). Ideas for further research on this issue are given in chapter 7. In section 5.3.4 the configuration of a few designs will be manually analysed to further investigate the usefulness of the LPM in the concept exploration of logistic driven ships.

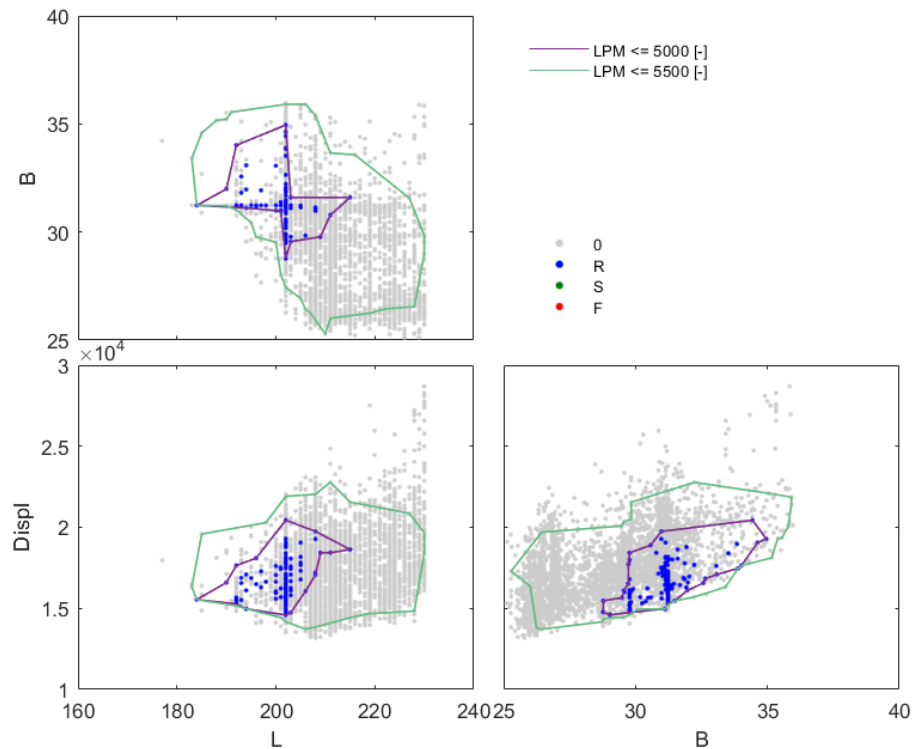


Figure 5.17: Down selection based on LPM to find a relation between LPM length and width

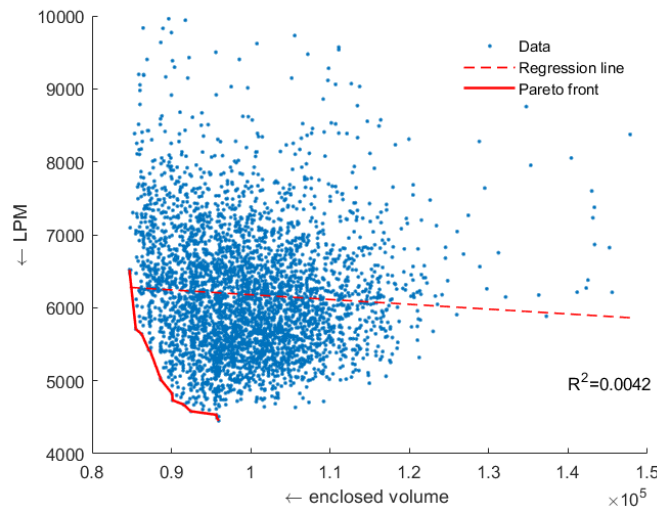


Figure 5.18: Objective scores for each design. The regression line indicates a larger ship is generally required to accommodate a logistically more promising configuration of systems.

5.3.4. LPD concept selection

In this section a few LPD concept designs will be selected. The configurations of these designs will manually compared for two reasons. First, the LPM is not able to give the reasons *why* a configuration is logistically promising. Manual analysis might reveal some rationale behind configurations or provide other useful insight. Further, manual analysis is used to further increase the confidence in the LM. The following designs have been selected for further analysis:

1. The logistically most promising design (ID 19181);
2. The logistically less promising on the Pareto front shown in fig. 5.18 (ID 19996);
3. Two random drawn logistically feasible designs (ID 4280 and ID 11217).

The main dimensions of the selected designs are given below. Also the logistic performance is given. The logistically less promising design on the Pareto front is the smallest design from an enclosed volume point of view. Note that this design indeed is longer than the logistically better performing designs, as has been pointed out in section 5.3.3.

The design with 4280 is generated relatively early in the exploration run. Although this design is slightly more slender than the first and last design selected, its logistic performance is slightly better than the fourth design. Note that the main dimensions of the first and last design are almost equal. The logistic performance of these designs is however significantly different. Therefore the layouts of these designs are compared next.

ID	LOA [m]	B [m]	T [m]	Displacement [m ³]	Volume	LPM	PD	GMt [m]
19181	202	31.23	5.13	16282	95962	4450	0.66	10.13
19996	215	25.28	5.05	13815	84720	6521	0.70	4.50
4280	206	29.83	5.32	16833	98351	5055	0.64	7.54
11217	203	31.23	5.13	16209	95925	5171	0.66	9.80

In fig. 5.19 the side views of both designs are shown. The upper design is the logistically most promising design in the data set. Two items will be pointed out:

1. The location of the hospital. The hospital is logistically connected to the helicopter deck and the well dock. Since the space in front of the well dock is occupied by the vehicle decks, the hospital has to be placed at another deck. In the upper design the hospital is placed on the same deck as the helicopter deck and close to the well dock, thus minimising the distance for both logistic system relations. A vertical connection is still needed for the transport of wounded marines from the well dock to the hospital. However, wounded marines flown in by helicopters can easily be transported to the hospital. In the lower design however, the hospital is moved up one deck compared to the previous design. This

increases the distance for both logistic system relations. Also additional vertical connection is required. Therefore the position of the hospital in design 19181 is considered preferable.

2. The food process involves the following functional systems: food store, galley, a mess for marines, a mess for crew and a waste store. The configuration of these systems in both designs is considered sub-optimal. In design 11217 these systems are positioned at three decks, compared to four decks in design 19181. The food store in design 19181 is positioned such that resupply can be done from the foredeck. In the other design the transport during resupply covers a larger distance. However, the distance between the galley and food store is minimal in the latter design. However, the distance between the galley and the messes is significantly larger, compared to design 19181. The position of the galley in the most promising design is strange and introduces excess vertical movement. Although the routing in the upper design is slightly harder because of the additional vertical movement due the fourth deck, the total distance for these processes is lower compared to the lower design.

The assessment of logistic performance might be source of the ‘imperfect’ clusters of functional systems observed in fig. 5.19. Instead of improving desired adjacency between systems, the total distance between logistically connected systems is minimised. Although this improves the layouts, it does not consider the required horizontal or vertical adjacency between systems. Further the issue found in section 5.1.1 regarding preference for vertical adjacency due to the positions of systems might play a role.

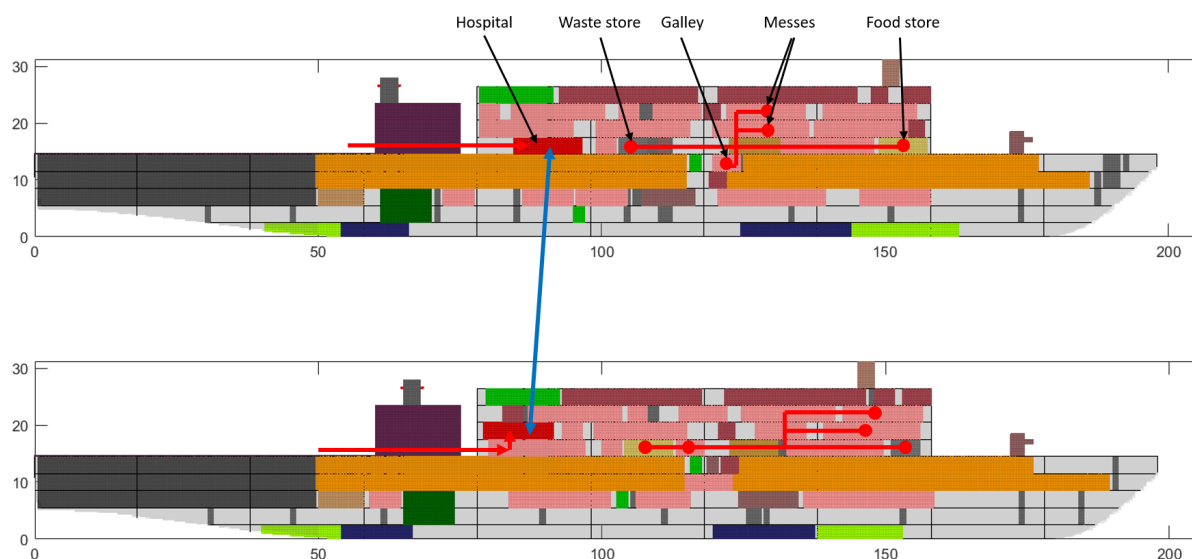


Figure 5.19: A comparison of system locations in design 19181 (top) and 11217 (bottom)

In fig. 5.20 design 19996 is shown. The logistic performance of this ship is low. One example of a bad configuration of systems is the adjacency between the food store and the galley.

1. The distance between the food store and the galley in this design is long. A more preferable location for the food store would be directly below the galley.
2. The networks used to determine d_i in the LPM calculation, section 3.14 do not take the watertight subdivision into account, section 3.14. Since the route between the galley and the food store crosses watertight bulkheads, this process can not take place. This design should therefore be penalised for the disconnection caused by overlap management. Therefore the LPM calculation needs to be further detailed, see chapter 7.

Finally design 4280 is investigated, see fig. 5.21. Similar to the first comparison the position of the hospital and the positions of the systems involved in the food process will be investigated. Further the position of the briefing room as well as the locations of the systems involved in the weapon hand out are investigated.

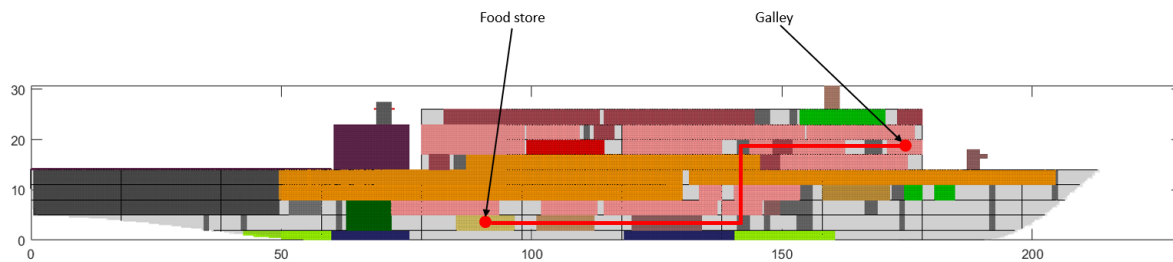


Figure 5.20: The design with minimum volume, 19996. The logistic performance of this design is bad, relative to the other designs in the data set. Also the route between the galley and the food store is visualised.

1. The hospital is located on the same deck as the helicopter deck, which is preferred. However, since the hospital is located approximately 30 meters forward of the hangar, wounded marines have to be transported through an accommodation block. This might be undesired from a hygiene perspective. Also, the accommodation block is logistically connected to systems positioned forward of the hospital, so logistic performance in this design could be improved by changing the order of the hospital and the accommodation block.
2. In this design the galley, messes and food store are all located horizontally adjacent on one deck. This seems a preferable configuration from a logistical point of view, although the order of systems might be changed to improve the flows between these systems. The waste store however is located low in the ship, and is disconnected from the available goods lift by a watertight bulkhead. This again underlines the importance of an improved LPM calculation.
3. The briefing room is situated forward and high in the superstructure. From a logistic point of view this seems a undesired location. Since the briefing room is logistically connected to the accommodation of marines, to the Joint Operations Room, and to the weapon hand out, see table 4.4, it is expected that a logistically more preferred configuration has a more centrally situated briefing room.
4. The weapon hand out is one of the most central systems in a LPD. Indeed it is connected to six functional systems, table 4.4. Since the logistic processes between the general marines store, the ammunition store and the weapon hand out involve the higher weighted moving unit 'Goods', minimisation of the distance between these systems improve the LPM score of the design significantly. Indeed, these systems are located close to the weapon hand out. Further the weapon hand out is located relatively close to the disembarkation stations, which could improve the flow in the ship during an amphibious assault.

The manual analysis of four designs revealed that the quality of the LPM calculation needs to be improved since disconnection caused by watertight bulkheads is yet not taken into account. Further the analysis showed again that the LM is able to steer towards some clustering of logistically related systems. On the other hand many less desired or undesired system configurations were found. Thus, analysis of created layouts helps to increase design knowledge by providing information on desired and undesired system locations. This knowledge can be used by the naval architect in later design phases. The final conclusions on the usefulness of the LM during concept exploration will be given in the next section.

5.3.5. Conclusion

To improve the confidence in the usefulness of the LM during concept exploration of logistic driven ships the packing model of the LPD created in chapter 4 has been used. The question to be answered was:

Does the Logistic Model attribute to the concept exploration of a LPD?

First, the impact of logistic systems on the size of logistic driven ships has been investigated. It can be concluded that the space required for logistic systems is relatively low, fig. 5.14. The actual configuration of systems is more important for the logistic performance of logistic driven ships.

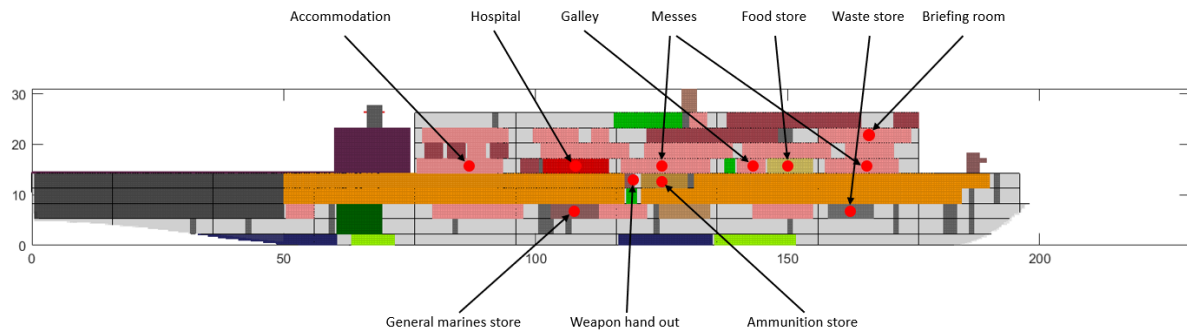


Figure 5.21: A randomly drawn design with ID 4280. The logistic performance of this design is bad, relative to the other designs in the data set. Also the route between the galley and the food store is visualised.

Further the impact of the LPM on ship size has been evaluated. It was shown that logistically promising designs are generally shorter and wider than logistically less promising designs in the data set. Although the LPM gives some measure regarding the logistic performance of concept designs, it gives no information on the actual configuration of systems.

Therefore the data set has been manually explored by selecting four designs. This analysis showed that the calculation of the LPM has to be further improved. On the other hand clusters of functional systems has been observed in logistically promising designs. This confirms that the LM itself works as intended.

Concluding, the LM does indeed contribute to the concept exploration of a LPD. First, it provides an estimation of the space required for logistic systems, and adds this space at specific locations to the concept designs. Second, it provides an indication of the logistic performance of concept designs and enables the Packing approach to steer towards logistically more promising designs. This completes this research. An elaborate conclusion will be given in chapter 6, followed by a discussion and recommendations for further research in chapter 7.

6

Conclusions

In this chapter conclusions will be drawn upon the research conducted and described in this report. First the problem background will be shortly recapitulated. Second the research questions will be answered.

Review of the research problem

The TU Delft Packing approach has been successfully applied to the design of various types of vessels. However, current estimations of the required space for logistic systems, like hallways and staircases, are based on a design margin. This approach (i.e. using a design margin) has proven insufficient and impractical in the design of surface combatants. An incorrect estimation for required space during concept exploration will lead to challenges, if not infeasible designs, in concept definition or later design phases. Applying the Packing approach to the design of logistic driven ships (e.g. cruise ships or Landing Platform Docks) will increase these challenges. Logistic driven ships are characterised by large and/or frequent amount of internal movement of entities, i.e. logistic processes. To accommodate these logistic processes, a sufficient number of adequately sized and placed logistic systems (e.g. staircases and hallways) needs to be included in the design. During concept exploration of logistic driven designs it is key to take the logistic process and their impact on the ship's performance into account. Indeed, carefully optimising the configuration of systems can reduce the space required for logistic systems and reduce the movement required to carry out the logistic processes. The estimation of required logistic systems and the assessment of logistic performance for concept designs of logistic driven ships are both hard and unsolved yet. These observations led to two research objectives, and subsequently two research questions, see chapter 1. These will be answered next.

Objective: To improve the estimate of space required for logistic systems and to allocate these logistic systems to low detail concept designs

The related research question is:

How to include sufficient space for logistic systems at the right location in a logistic driven ship concept design?

Three aspects are required to determine the required position and size of logistic systems for a concept design, see chapter 1:

1. *Known systems.* A ship requires functions to be fulfilled by functional systems. For instance sleeping and resting is covered by a functional system 'cabin' or 'day room'. In logistic driven ships operational processes require most functional systems to be logistically connected.
2. *Known logistic system relations.* Logistic processes aboard a logistic driven ship take place between (some of) the pre-defined functional systems. An analysis of logistic processes results in a set of logistic system relations which describe the adjacency required between logistically connected systems. Logistic systems have to fulfil the required connection described by the logistic system relations. Also the entities involved in the logistic processes and their requirements on sizing of logistic systems are captured by these relations.

3. *Known system locations.* To route logistic systems through a vessel the location of the source and sink systems need to be available. This information is not known before the systems are configured in a feasible design, and therefore the design of logistic systems before making a configuration, i.e. concept design, is hard.

To solve this problem a novel Logistic Model (LM) has been developed in this research. The LM uses initial positions of the functional systems provided by the TU Delft Packing approach to fill the gap in information identified. The integration of the LM and the Packing approach enables the pre-configuration definition of logistic systems and the addition of the required logistic systems to low detail concept designs. The routing of logistic system relations provided locations of required logistic systems. For this routing a network representation of the ship's structural subdivision and a novel path finding and selection method based on Yen's k-shortest path algorithm are used. The sizing of these logistic systems is based on the characteristics of the entities using these logistic systems and the number of processes in these logistic systems. Once the required logistic systems and their positions are determined, the logistic and functional systems are arranged into a feasible concept design by a packing algorithm. The logistic performance of this design is assessed and used to initiate a new, and possibly more promising, concept design. The model has been described in chapter 2 and chapter 3. Subsequently a test case was developed in chapter 4 and used to, successfully, validate the LM in chapter 5.

Hence it is concluded that the first research objective has been met.

Objective: To assess logistic performance of low detail concept designs of logistic driven ships

The related research question is:

How to assess the logistic performance of logistic driven ship concept designs?

To assess the logistic performance of concept designs of logistic driven ships a set of factors that influence the logistic performance of ships was identified in chapter 3. These factors could be summarised in four aspects, see section 3.14.1 for more detail.

1. Some logistic processes might be more important to the logistic performance of a logistic driven ship than others. The same applies for entities involved in the logistic processes.
2. A naval architect might want to vary the importance of processes and/or entities to find unexpected design solutions or to learn about their impact on the final design.
3. Required movement during logistic processes, the time required to complete a logistic process, and the mobility of entities are all related to the distance between systems.
4. The translation of systems compared to their initial positions during configuration by the Packing approach could lead to a change in logistic performance.

These four aspects were used in the new Logistic Performance Measure (LPM). The Logistic Performance Measure scores designs based on the travelling distance between systems, weights assigned by the naval architect and penalises designs in which some logistic processes can not take place after the configuration of systems.

Test cases indicate that the LPM can be used to assess the logistic performance of concept designs, such that logistically promising designs can be distinguished as well as to find more promising concept designs during exploration runs, see chapter 5. However, the LPM proved unable to provide detailed information on the relation between the logistic performance and the layout of the concept designs. The reason is that a single value can not provide information to distinguish between various aspects. To obtain this relations the naval architect has to manually assess the concept designs. Since finding these relations was not in the direct scope of the research performed and the LPM provides an indication of logistic performance of low detail concept designs, it can be concluded that the second research objective is also met.

In chapter 7 the work performed is shortly discussed and provides some guidelines and ideas for further research.

Discussion and future work

This chapter provides a discussion of the work performed in this thesis and gives some suggestions for further research. First, the LM will be discussed. Subsequently the analysis of low detail concept designs will be elaborated on. Further, style choices and related physical architectures are discussed. Finally some remarks on the design of LPDs are provided.

7.1. Improve the quality of the Logistic Model

One of the main contributions of the presented research is the development of the LM. The LM is able to provide a more educated estimation of the space required for logistic system during concept exploration. Further the LPM can be used to assess logistic performance of concept designs of logistic driven ships. However, various assumptions and simplifications have been made throughout the research. Further the level of detail available in the Packing approach proved to be a challenge. Hence the following remarks can be made regarding the LM and the Packing approach.

7.1.1. Path finding and selection

The path finding and selection approach developed in this thesis, see section 3.7, succeeds in finding and selecting a path for each logistic system relation. However, selecting paths with minimal directional switch only is a rough method. Especially in longer paths the number of directional changes could be allowed to be larger than one or two, for instance. On the other hand, the preference for less directional changes still holds. Further, a NSGA-II variable is available for final selection of paths, if needed. Combining these two thoughts, a fuzzy approach to path selection is proposed, where increasing paths with increased directional switch are penalised. That way the preference for less directional switch is taken into account. See fig. 7.1 for a visualisation of this penalty.

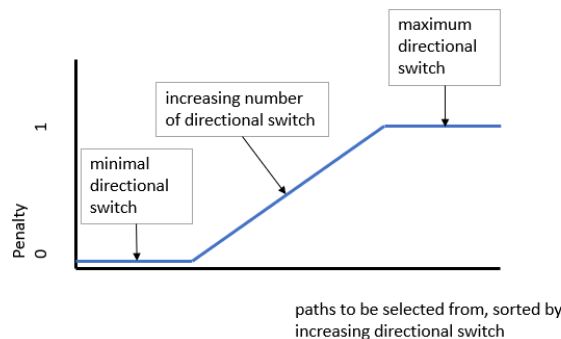


Figure 7.1: A fuzzy approach to path selection, similar to Nick (2008)'s Minimum Segment Width Fuzzy Utility.

7.1.2. Temporal aspects

Temporal aspects of logistic processes were kept outside the scope of this research, chapter 1. However, the importance of temporal aspects has been touched upon more than once in this report. For instance, knowledge on the temporal relations between logistic processes could help to separate these logistic processes. On the other hand the sizing of logistic systems could be improved when sequential and parallel logistic processes could be distinguished.

Separation of logistic processes thus touches upon temporal aspects. In this thesis only adjacency of functional systems has been used to find routes between these systems. However, some logistic processes may not be allowed to interfere each other. Therefore logistic processes might need to be *separated*, for instance to spread movement. Nick (2008); Gillespie et al. (2013) took separation of functional systems into account. Although this is different from separation of logistic processes, mentioned research might be helpful in the development of a refined path finding and selection method. Note that other reasons also could require separation of logistic processes, or restrict logistic processes to take place in certain locations. For instance the handling of waste cannot take place in the medical area for hygiene reasons.

7.1.3. Additional logistic systems

Due to limited detail available in the Packing approach both horizontal logistic systems and large vertical connections have been neglected in the concept designs. The following section will further discuss the level of detail of the Packing approach.

Since all logistic systems are important to provide logistic connectivity in the ship, all logistic systems need to be taken into account. This will also improve the estimation of the connection density. However, the addition of horizontal connections in a separated positioning slice in a higher detail Packing approach again reduces the amount of detail available for functional systems. Therefore the following approach is proposed.

Instead of adding each (horizontal and vertical) logistic system separately to a concept design, like done in this thesis, the pre-configuration development of a logistic systems network is expected to be promising. This logistic systems network is an hard packing object, representing all required logistic systems. The logistic systems network is to be positioned in centreline positioning slice in the 2.5D Packing approach. By pre-defining this object, multiple logistic systems can be defined next to each other. For example assume the following logistic systems are required in a ship, fig. 7.2a. The logistic systems network for this example is given in fig. 7.2b. Compared to the current situation, this approach only requires one positioning slice. This enables an increase in level of detail of logistic systems, while keeping two positioning slices available for functional systems. The challenge to be solved in this approach is the positioning of logistic systems inside a compartment. Should all logistic systems be positioned side by side, or should there also be longitudinal separation between logistic systems within a compartment? In turn, how to separate these systems?

7.1.4. Level of detail of the Packing approach

Increasing design knowledge as shown by Mavris and DeLaurentis (2000) appears to be difficult when the tool used does not provide the right level of detail. In this research it was shown that using the TU Delft Packing approach to increase the knowledge on the logistic performance of LPD concept designs required a reduction in the level of detail of the functional systems of these designs. Reducing the level of detail leads to the elimination of systems that are key in the logistic processes at some point. For example, the weapon hand out system is rather small, but is key in the process that takes place prior to disembarkation since it is involved in multiple logistic system relations. Therefore the weapon hand out system has to be taken into account in the logistic processes. This requires careful decisions by the naval architect on the modelling of functional systems. Also the space required for the smaller systems has to be included in the concept designs, even if these are not physically modelled.

The transverse detail of functional systems was very limited in this research, for two reasons. First, the 2D approach to logistic processes does not require much transverse detail of functional systems. Only the longitudinal and vertical position of systems is in that case important. The transverse direction has to provide sufficient information on the ship size, but is not taken into account in the LM. Second, the limited positioning space for functional systems reduced the transverse detail of systems as well.

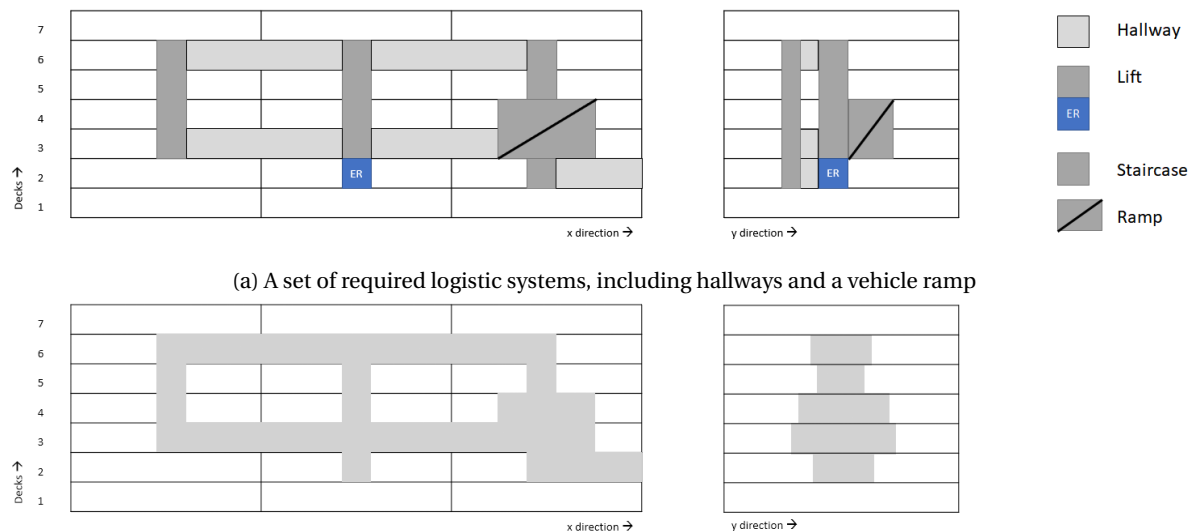


Figure 7.2: An example of a logistic systems network as one object to be packed a concept design.

To model more representative ship descriptions, an increase in the level of detail of the Packing approach might be required. The 2.5D approach currently used has three positioning slices. An increase to a 2.75D approach with five positioning slices, in combination with the logistic systems network presented earlier, is expected to improve the quality of the concept designs significantly. However, an increase in transverse detail also increases the transverse component of logistic processes. Therefore the level of detail of the logistic processes analysis has to be increased as well. Further, an increase in level of detail increases the complexity of path finding and selection for logistic systems as well as increases the computational effort required for concept exploration. On the other hand also the diversity of designs is expected to be increased, and therefore the effectiveness of concept exploration is also increased.

7.1.5. Storage of data in the Packing approach

One of the issues encountered using the Packing approach concerns the storage of data of concept designs. The Packing approach is limited to store only equally sized vectors. Therefore information on positions and sizes of a variable number of logistic systems, for instance, could not be stored for post processing. This limited the deducing of design rationale. Further the physical and logical architectures could not be stored per design. Also the networks used for the LPM calculation could not be stored for further analysis. To obtain and analyse these networks the naval architect has to assess individual designs. Therefore enabling the storage of variable data is expected to benefit the design of logistic driven ships, as additional design knowledge can be derived from the whole data set.

7.1.6. Improve LPM calculation

The test cases in section 5.1.1 and section 5.3 revealed some issues in the LPM calculation.

1. The watertight subdivision was not included in the networks used to calculate d_i . Therefore disconnection by watertight bulkheads is not found in the current LPM calculation. Disconnection by systems placed at another deck is indeed found, but the watertight bulkheads have to be included in the LPM calculation to improve the logistic performance calculation.
2. The actual top side shape is not taken into account in the LPM calculation. Therefore d_i is possibly calculated using routes through open space, as shown in fig. 7.3. Since these paths are infeasible, the actual top side shape of packed designs has to be taken into account.
3. In section 5.1.1 the preference of small systems to be placed aft of larger systems has been highlighted. Since this reduces diversity, this issue has to be solved. This could be done by using the centre of area instead of the most aft and lower position of systems as used in this thesis.

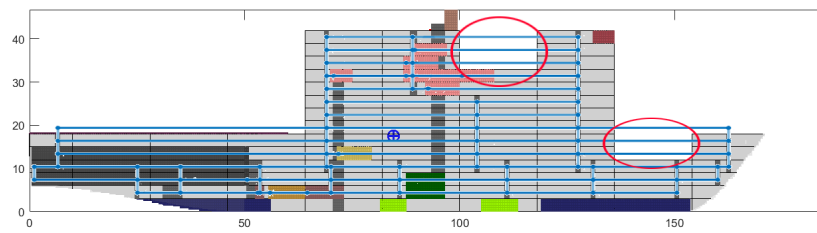


Figure 7.3: The current LPM calculation does not take the actual top size shape into account. This leads to infeasible paths through open space, as encircled in red.

7.2. Concept design arrangement assessment

This thesis pointed out that the LPM was not able to capture relations between locations of systems and the logistic performance of the concept design, see chapter 5. Individual and manual investigation of the created designs was required to obtain such relations. Besides the improvement of the data storage mentioned above, further investigation into layout assessment has to be conducted. Roth et al. (2017) used network theory, centrality measures and design rationale to analyse concept designs developed by the Packing approach. However, for logistic driven ships the travelling distance is found to be an important characteristic, and is therefore used in the LPM calculation. On the other hand, design rationale is important as well but not covered in present research. DeNucci (2012) developed a method to implement design rationale into the conceptual design phase. For the purpose of layout analysis of logistic driven ships it is proposed to develop a method which combines the LPM, design rationale and centrality measures. This may result in an automated qualitative analysis of the thousands of concept designs developed by the Packing approach during concept exploration. Further graphs like the one shown in fig. 7.4 could possibly be used to visualise congested areas or concentrations of logistic processes in designs. This figure shows the distribution of processes over a ship. The thickness of red lines indicate how often that edge, representing vertical or horizontal connections, is used.

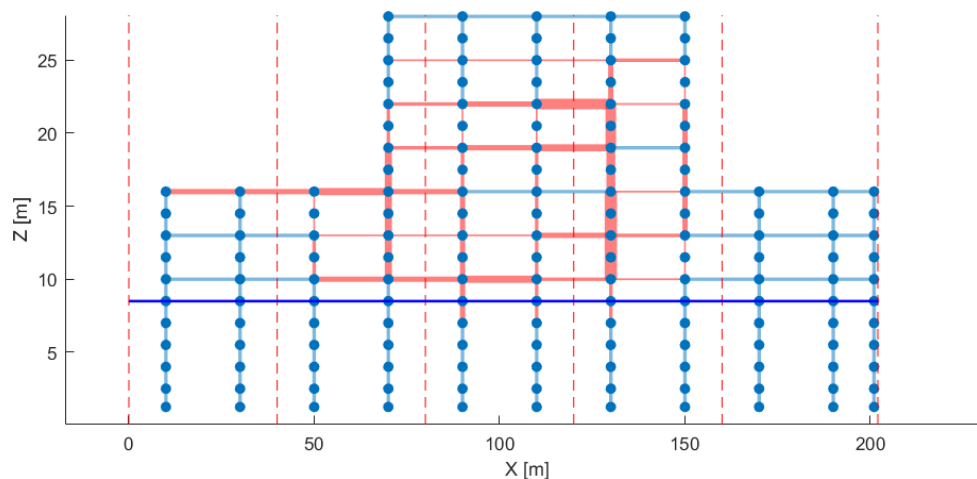


Figure 7.4: Distribution of processes over a ship, visualised by different sized, red, edges in a 2D physical architecture. Busy areas can be recognised by thick edges in this graph. Revisited fig. 3.4

7.3. Style choices and physical architectures

The physical architecture developed in this thesis was specifically applied to a LPD with an aft configuration of the helicopter deck. The 2D approach to logistic processes as described in section 3.3.1 is applicable to all ships involving logistic processes. The physical architecture is particularly suited to be applied to the design of ships that are symmetric at the centreline. This thesis provided the example for a LPD. But other vessel

types can be modelled as well. For instance, a logistic driven vessel like a cruise ship could be modelled by this generic description by removing the helicopter deck. On the other hand, the generic description could be applied to a merchant vessel type like a container ship as well. In the latter case the helicopter deck and foredeck would represent the cargo holds aft and fore the bridge subsequently. It is believed that the application of the LM to non-logistic driven ships will result in appropriate sized logistic systems. However, the LM will then be mainly a sizing tool since the number of possible locations of logistic systems is limited. Although connectivity is not expected to be a design driver, the use of the LM in the concept exploration of these ships could improve the space estimate for logistic systems, and thus reduce the effort needed to fit logistic systems in later design stages.

Regarding LPDs, two helicopter deck configurations can be distinguished as explained in section 3.3.2. First, LPDs can have a helicopter deck positioned aft of the superstructure (Class 1, fig. 7.5a) and, second, the helicopter deck can be positioned over the whole length of the ship with a starboard located superstructure (Class 2, fig. 7.5b). Note that the superstructure is not strictly located starboard, but is used most often. Reasons are flight operations as well as to provide an improved view for safe navigation. The previous chapters pointed out that the developed physical architecture can be used in the design of the first class of LPDs.



(a) LPD with helicopter deck positioned aft of the superstructure (Damen, n.d.).



(b) LHD with helicopter deck besides the superstructure. (Head, 2012)

Figure 7.5: Two LPD classes with a different topside style.

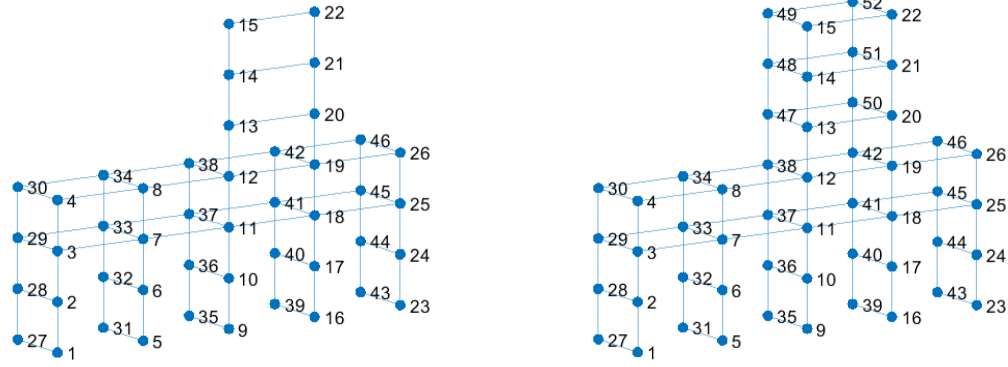
It is believed that a slightly adapted physical architecture can be used in the design of the second class of LPDs. However, this requires an increase in the level of detail of the Packing approach to five positioning slices, as discussed above. In fig. 7.6a an impression of a physical architecture is shown, which enables full routing below the helicopter deck and routing in the superstructure.

This model could also be implemented in the higher detail packing model of the first class of LPDs. Again a small adaption to the physical architecture is required, which enables full '2.5D' path finding, fig. 7.6b. Excessive modelling is yet required to use a more detailed physical architecture, mainly in step 7 and the implementation in the packing approach. Further path finding and selection issues have to be solved as well.

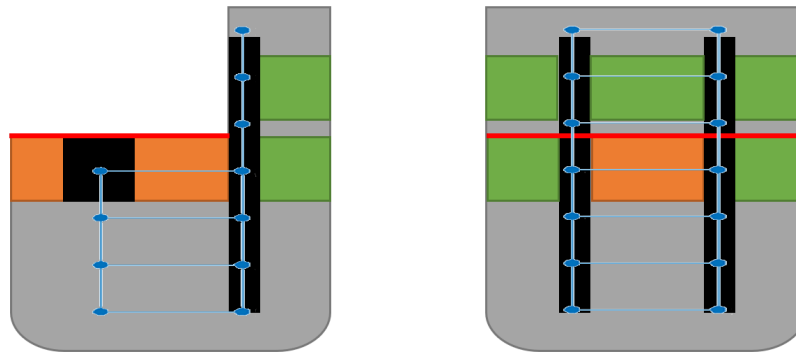
Both LPD types are shown as 2.75D models astern in fig. 7.6c. Also the corresponding physical architectures are shown as overlay. This shows both that a 2.75D packing model is required to model logistic driven ships and that the proposed physical architectures can be used to do path finding in higher detail designs.

The description of the topside of the ship by a helicopter deck, a bridge deck and foredeck, implies the implementation of style choices. Although style is hard to capture in numbers, it may have a significant impact on the results of the exploration, (Pawling et al., 2013). Indeed style choices made upfront might exclude some configurations. However, the choice for the topside description to refine the physical architecture has been justified for the following two reasons:

1. The refinement of the physical architecture enables more accurate path finding as no paths can be found through empty space above the helicopter and foredecks. This increases the performance of the LM.



(a) A new proposed physical architecture for higher detail designs of LPD class 2. (b) A new proposed physical architecture for higher detail designs of LPD class 1.



(c) Proof of concept for proposed physical architectures.

Figure 7.6: Two new proposed physical architectures for higher detail designs.

2. Currently, systems are prescribed to certain locations in the ship or adjacency between systems is coded by the naval architect. He relies on own knowledge and design insight. This means that the number of possible configurations can be restricted currently. Hence the effectiveness of concept exploration is also reduced.

However, the LM takes care of the required adjacency between systems. Hence the systems don't need to be restricted as much beforehand. The positioning of systems will be solved by the Packing approach.

Since the LM is able to develop more reliable logistic systems and enables a wider search for system configurations, the refinement of the physical architecture by adding style choices beforehand is considered acceptable.

7.4. The LPD ship description

With regards to the LPD packing model developed in chapter 4 the following recommendations can be given.

7.4.1. System definition

In this thesis little effort has been paid to correctly model detailed functional systems. Although this was not required for the scope of this research, a few limitations have been encountered. Small functional systems ended up with too high aspect ratios after overlap management and functional systems had to be combined into larger objects. This was caused by the reduced detail available due to the addition of logistic systems in the centreline positioning slice. For specific use of the model in the design of LPDs, functional systems have to be modelled more carefully. On the other hand, the sizing parameters for logistic systems also have to be tuned for a better estimation of the space required for these systems.

7.4.2. Ballasting for well dock operations

In this research the ballasting of LPDs has not been considered. LPDs with a submersible well dock require sufficient water ballast capacity to provide the required change in draft and trim for well dock operations. Depending on the well dock shape and the LPD's configuration of systems and hull shape, a minimum ballast water volume $V_{ballast}$ at a location $COG_{ballast}$ is required. In this section a first set of equations will be provided which can be used to determine the required ballast capacity of LPD concept designs. Refer to (Moore, 2010) for more theory on stability.

The initial trim of the packed and unballasted design is assumed to be 0 [m]. The subscript *ballast* indicates that the given parameter concerns the ballasted situation. Parameters without this subscript concern the unballasted situation. See fig. 7.7 for an indication of the following measures.

Assume the bottom of the well dock is located at z_{dock} , measured in meters from the keel. The draft aft T_{aft} is measured at the stern. For well dock operations a certain water level in the well dock is required, $T_{dock_{ballast}}$. The increase in draft at the stern is given by eq. (7.1).

$$\Delta T_{aft_{ballast}} = z_{dock} - T_{aft} + T_{dock_{ballast}} \quad (7.1)$$

$\Delta T_{aft_{ballast}}$ can be obtained by a change in water ballast, which could result in a change in draft, $\Delta T_{ballast}$, and/or a change in trim, $\Delta \theta_{ballast}$ [degree] or

$\Delta trim_{ballast}$ [m]. $\Delta T_{ballast}$ is given by eq. (7.2) and $\Delta trim_{ballast}$ is given by eq. (7.3).

$$\Delta T_{ballast} = \frac{\rho_{ballast\ water} \cdot g \cdot V_{ballast\ water}}{L \cdot B \cdot C_{wp}} \quad (7.2)$$

In which:

C_{wp} = the water plane area coefficient.

$V_{ballast\ water}$ = the required water ballast capacity.

$$\Delta trim_{ballast} = \frac{(LCF - COG_{ballast\ water}) \cdot \rho_{ballast\ water} \cdot g \cdot V_{ballast\ water}}{M_{m_{trim}}} \quad (7.3)$$

In which:

LCF = longitudinal position of the centre of floatation, measured from the stern.

$COG_{ballast\ water}$ = longitudinal position of the centre of gravity of the water ballast capacity.

$M_{m_{trim}}$ = Moment required for one meter trim.

The ballasted draft aft is given by eq. (7.4).

$$T_{aft_{ballast}} = T_{aft} + \Delta T_{ballast} + \Delta trim_{ballast} \quad (7.4)$$

Hence $\Delta T_{aft_{ballast}}$ can also be calculated by eq. (7.5). From this equation can be concluded that given a certain load of the LPD various combinations of ballast capacity and position of this capacity in the ship can provide the required draft in the well dock.

$$\begin{aligned} \Delta T_{aft_{ballast}} &= T_{aft_{ballast}} - T_{aft} = \Delta T_{ballast} + \Delta trim_{ballast} = \\ &= \frac{\rho_{ballast\ water} \cdot g \cdot V_{ballast\ water}}{L \cdot B \cdot C_{wp}} + \frac{(LCF - COG_{ballast\ water}) \cdot \rho_{ballast\ water} \cdot g \cdot V_{ballast\ water}}{M_{m_{trim}}} = \\ &= \left(\frac{1}{L \cdot B \cdot C_{wp}} + \frac{(LCF - COG_{ballast\ water})}{M_{m_{trim}}} \right) \cdot \rho_{ballast\ water} \cdot g \cdot V_{ballast\ water} \end{aligned} \quad (7.5)$$

While the overall draft of the ship is calculated in the Packing approach is currently calculated, the trim of each concept design is not calculated. The latter is required to find T_{aft} . Also the centre of floatation is not calculated currently.

During well dock operations the intact stability of the LPD reduces because the water plane area decreases due to the flooded well dock. Also ballast tanks might be partly filled, which adds a free surface effect and corresponding further reduction of intact stability. See (Leopold and Reuter, 1971) for a further elaboration

on well dock design. To ensure feasible concept designs of LPDs, the notions presented above need to be taken into account.

The research described in this thesis allows naval architects to take logistic processes into account during the concept exploration of logistic driven ships. This has never been done before. It would therefore be interesting to see how the method developed could be matured and applied to real ship design cases.

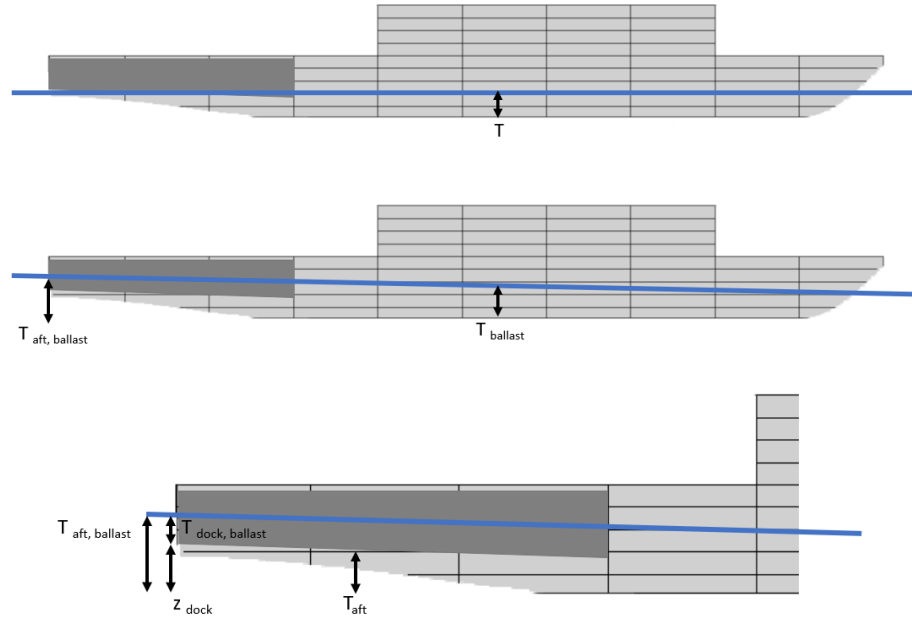


Figure 7.7: Various measures used in the calculation of the required ballast capacity.

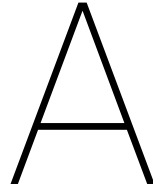
Bibliography

- D.J. Andrews. An integrated approach to ship synthesis. *Trans. RINA*, 128:73–102, 1986.
- D.J. Andrews and C.A. Dicks. The building block design methodology applied to advanced naval ship design. In *Proceedings of International Marine Design Conference*, pages 3–19, 1997.
- D.J. Andrews, E.A.E. Duchateau, J. Gillespe, J.J. Hopman, R. Pawling, and D.J. Singer. State of the art report: Design for layout. In *11th International Marine Design Conference*, pages 111–137, 2012.
- J. Bang-Jensen and G. Gutin. *Digraphs Theory, Algorithms and Applications*, 2000.
- BBC. Britains Biggest Warship S01E01, t=11m42s–12m35s, 2018. URL <https://www.dailymotion.com/video/x6i1kqg>.
- F. Bock, H. Kantner, and J. Haynes. *An algorithm (the r-th best path algorithm) for finding and ranking paths through a network*. Armour Research Foundation, 1957.
- D. Brefort, C. Shields, A. Habben Jansen, E. Duchateau, R. Pawling, K. Droste, T. Jasper, M. Sypniewski, C. Goodrum, M. A. Parsons, et al. An architectural framework for distributed naval ship systems. *Ocean Engineering*, 147:375–385, 2018.
- D.K. Brown. *The architecture of frigates*. 1987.
- BuildingCodeNYC.com. Exit Stair Width, n.d. URL <http://buildingcodenyc.com/sketches/exit-stair-width/>. Accessed: 2018-08-09.
- L. Casarosa. *The integration of human factors, operability and personnel movement simulation into the preliminary design of ships utilising the Design Building Block approach*. PhD thesis, UCL (University College London), 2011.
- J.S. Cieraad. *Generating conventional naval submarines for the preliminary design stage*. 2016.
- City of New York. NYC Building Code Chapter 10 - Means of egress, 2014. URL https://www1.nyc.gov/assets/buildings/apps/pdf_viewer/viewer.html?file=2014CC_BC_Chapte_10_Means_of_Egress.pdf§ion=conscode_2014. Accessed: 2018-08-09.
- S. Clarke, A. Krikorian, and J. Rausen. Computing the N best loopless paths in a network. *Journal of the Society for Industrial and Applied Mathematics*, 11(4):1096–1102, 1963.
- L. Cui, S. Kumara, and R. Albert. Complex networks: An engineering view. *IEEE Circuits and Systems Magazine*, 10(3):10–25, 2010.
- Damen. Landing Platform Dock "HNLMS ROTTERDAM". <https://products.damen.com/en/ranges/landing-platform-dock/landing-platform-dock--rotterdam>, n.d. Accessed: 2018-08-30.
- K. Deb. *Multi-objective optimization using evolutionary algorithms: An introduction*. 2011.
- T.W. DeNucci. *Capturing Design: Improving conceptual ship design through the capture of design rationale*. PhD thesis, Delft University of Technology, 2012.
- K. Droste, A.A. Kana, and J.J. Hopman. Process-based analysis of arrangement aspects for configuration-driven ships. In *Proc. of the 13th International Marine Design Conference (IMDC 2018)*, pages 327–337, 2018.
- E.A.A. Duchateau, P. de Vos, and S. van Leeuwen. Early stage routing of distributed ship service systems for vulnerability reduction. In *Proc. of the 13th International Marine Design Conference (IMDC 2018)*, pages 1083–1096, 2018.

- E.A.E. Duchateau. *Interactive evolutionary concept exploration in preliminary ship design*. PhD thesis, Delft University of Technology, 2016.
- J.H. Evans. Basic design concepts. *Naval Engineers Journal*, 71(4):671–678, 1959.
- T. Fujiyama and N. Tyler. An explicit study on walking speeds of pedestrians on stairs. Japan Society of Civil Engineers/Transportation Research Board, USA, 2004.
- J.W. Gillespie and D.J. Singer. Identifying drivers of general arrangements through the use of network measures of centrality and hierarchy. *Ocean Engineering*, 57:230–239, 2013.
- J.W. Gillespie, A.S. Daniels, and D.J. Singer. Generating functional complex-based ship arrangements using network partitioning and community preferences. *Ocean Engineering*, 72:107–115, 2013.
- M. Girvan and M.E.J. Newman. Community structure in social and biological networks. *Proceedings of the national academy of sciences*, 99(12):7821–7826, 2002.
- C.J. Goodrum, C.P.F. Shields, and D.J. Singer. Understanding cascading failures through a vulnerability analysis of interdependent ship-centric distributed systems using networks. *Ocean Engineering*, 150:36–47, 2018.
- W.E. Gortney. Department of Defense Dictionary of Military and Associated Terms. Technical report, Joint chiefs Of Staff Washington United States, 2010.
- J. Head. Wasp class. <https://www.jeffhead.com/worldwideaircraftcarriers/wasp7.jpg>, 2012. Accessed: 2018-08-30.
- C. Hölscher, T. Meilinger, G. Vrachliotis, M. Brösamle, and M. Knauff. Up the down staircase: Wayfinding strategies in multi-level buildings. *Journal of Environmental Psychology*, 26(4):284–299, 2006.
- R. Huang and Z.-R. Peng. Schedule-based path-finding algorithms for transit trip-planning systems. *Transportation Research Record: Journal of the Transportation Research Board*, (1783):142–148, 2002.
- T. Jaspers and A.A. Kana. Elucidating Families of Ship Designs using Clustering Algorithms. 2017.
- P.A. Jensen and J.F. Bard. *Operations research models and methods*, volume 1. John Wiley & Sons Incorporated, 2003.
- M. Kirchmer. Business Process Management: What Is It and Why Do You Need It? In *High Performance Through Business Process Management*, pages 1–28. Springer, 2017.
- H.K. Klein Woud and D. Stapersma. *Design of propulsion and electric power generation systems*. IMarEST, 2002.
- S. Knegt. Winning at sea: Developing a method to provide insight in early stage naval fleet design requirements. 2018.
- J.A Kratchman. *An investigation on the effects of firefighter counterflow and human behavior in a six-story building evacuation*. PhD thesis, 2007.
- T. Laverghetta and A. Brown. Dynamics of naval ship design: a systems approach. *Naval Engineers Journal*, 111(3):307–323, 1999.
- R. Leopold and W. Reuter. Three winning designs–FDL, LHA, DD-963: Method and selected features. Technical report, 1971.
- J.K. Liker. *The Toyota way*. Esensi, 2005.
- MATLAB. The MATLAB Users Guide, 1998.
- D.N. Mavris and D.A. DeLaurentis. Methodology for examining the simultaneous impact of requirements, vehicle characteristics, and technologies on military aircraft design. *Georgia Institute of Technology*, 2000.

- C.S. Moore. *Principles of Naval Architecture Series-Intact Stability*. Society of Naval Architects and Marine Engineers, 2010.
- NATO. Ergonomic Data For Shipboard Space Design In Nato Surface Ships, 1993.
- NATO. Logistics. https://www.nato.int/cps/ua/natohq/topics_61741.htm, 2017. Accessed: 2018-06-01.
- E.K. Nick. *Fuzzy optimal allocation and arrangement of spaces in naval surface ship design*. PhD thesis, University of Michigan, 2008.
- R. Pawling, D. Andrews, R. Piks, D. Singer, E. Duchateau, and H. Hopman. An integrated approach to style definition in early stage design. In *Proceedings of the 12th International Conference on Computer Applications and Information Technology in the Maritime Industries*, pages 248–263, 2013.
- R. Pawling, V. Percival, and D.J. Andrews. A Study into the Validity of the Ship Design Spiral in Early Stage Ship Design. *Journal of Ship Production and Design*, 33(2):81–100, 2017.
- K. Pedersen, J. Emblemstvag, R. Bailey, J.K. Allen, and F. Mistree. Validating design methods and research: the validation square. In *ASME Design Engineering Technical Conferences*, pages 1–12, 2000.
- M. Pollack. The k th Best Route Through a Network. *Operations Research*, 9(4):578–580, 1961.
- Neha Prajapat, Tony Waller, Joseph Young, and Ashutosh Tiwari. Layout optimization of a repair facility using discrete event simulation. *Procedia CIRP*, 56:574–579, 2016.
- D. Rigterink, R. Piks, and D.J. Singer. The use of network theory to model disparate ship design information. *International Journal of Naval Architecture and Ocean Engineering*, 6(2):484–495, 2014.
- M. J. Roth, K. Droste, and A. A. Kana. Analysis of General Arrangements Created by the TU Delft Packing Approach. In *Proceedings of the 16th Conference on Computer and IT applications in the Maritime Industries*, pages 201–211, 2017.
- L. Salvatori. Concept Design of a Damen Yacht-Support Vessel with the help of Packing. 2018.
- C.P.F. Shields, M.J. Sypniewski, and D.J. Singer. Characterizing general arrangements and distributed system configurations in early-stage ship design. *Ocean Engineering*, 163:107–114, 2018.
- D. Shulgin. French NH90 Caiman. <http://www.dmitryshulgin.com/tag/nh90-caiman/>, 2015. Accessed: 2018-08-08.
- B.J. Van Oers. *A Packing Approach for the Early Stage Design of Service Vessels*. PhD thesis, Delft University of Technology, 2011.
- B.J. Van Oers and J.J. Hopman. Simpler and Faster: A 2.5 D Packing-Based Approach for Early Stage Ship Design. In *11th International Marine Design Conference*, 2012.
- B.J. Van Oers, E. Takken, E.A.E. Duchateau, R.J. Zandstra, J.S. Cieraad, W. Van den broek de Bruijn, and M. Janssen. Warship concept exploration and definition at the Netherlands Defence Materiel Organisation. *Proceedings of the 2017 Workshop on Set-Based Design of ASNE*, 2017.
- M. Von Rosing, H. Von Scheel, and A-W Scheer. *The Complete Business Process Handbook: Body of Knowledge from Process Modeling to BPM*, volume 1. Morgan Kaufmann, 2014.
- K. Wagner, A. Wassink, B.J. van Oers, and J.J. Hopman. Modeling complex vessels for use in a 3d packing approach: An application to deepwater drilling vessel design. In *Proceedings of the 9th International Conference on Computer and IT Applications in the Maritime Industries (COMPIT'10)*, pages 259–272, 2010.
- M. Weske. Business process management architectures. In *Business Process Management*, pages 333–371. Springer, 2012.
- Wikipedia. Amphibious transport dock. https://en.wikipedia.org/wiki/Amphibious_transport_dock, n.d. Accessed: 2018-07-12.

- J. Y. Yen. Finding the k shortest loopless paths in a network. *Management Science*, 17(11):712–716, 1971.
- R.J. Zandstra, E.A.E. Duchateau, and B.J. van Oers. Concept exploration of a mine-countermeasures vessel using a packing-based ship synthesis model. In *Proc. of the 5th World Maritime Technology Conference (WMTC)*, pages 1–12, 2015.



Functional systems in a LPD

The 51 functional systems presented in table A.1 have been implemented in the ship description of a LPD. The order of the systems is the same as the packing order. The set with required logistic systems is packed after the 'Updowntakes shaft' is packed.

1	HELICOPTER DECK AFT	26	ACC CREW
2	BRIDGE	27	ACC CREW
3	PROPULSION PLANT	28	ACC MARINES
4	UPDOWNTAKES	29	ACC MARINES
5	UPDOWNTAKES SHAFT	30	ACC MARINES
-	<i>Set with required logistic systems</i>	31	ACC MARINES
6	WELLDOCK	32	ACC MARINES
7	WELLDOCK_FW	33	ACC MARINES
8	HANGAR	34	TECHNICAL STORE
9	LARGE VEHICLE DECK	35	FANROOM
10	SMALL VEHICLE DECK	36	LAUNDRY
11	SMALL VEHICLE DECK	37	FOOD STORE
12	RADAR MAST	38	GARBAGE STORE
13	GUN FRONT	39	AUXILIARY MACHINERY ROOM
14	OFFICES	40	AUXILIARY MACHINERY ROOM
15	JOR**	41	COMS ROOM
16	GENERAL MARINES STORE	42	COMS ROOM
17	AMMUNITION STORE	43	COMPUTER ROOM
18	WEAPON HAND OUT	44	COMPUTER ROOM
19	HOSPITAL	45	ADMINISTRATION ROOM
20	MESS CREW	46	ADMINISTRATION ROOM
21	MESS MARINES	47	SHIP SUPPLY STORE
22	BRIEFING MARINES	48	FUEL TANK
23	GALLEY	49	FUEL TANK
24	ACC* CREW	50	BALLAST TANK AFT
25	ACC CREW	51	BALLAST TANK FWD

* 'ACC' stands for 'Accommodation'. ** the 'JOR' is the Joint Operations Room from where an amphibious assault is coordinated.

Table A.1: List with functional and logistic systems in the ship description of a LPD.