Master of Science Thesis

Future ships

Design and cost analysis of unmanned ships

T. Frijters

January 9, 2017

Delft University of Technology

Challenge the future

Front cover: Illustration of an unmanned ship by Rolls Royce
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Master of Science Thesis

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T. Frijters

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Delft University Of Technology
Department Of
Ship Design, Production and Operation

The undersigned hereby certify that they have read and recommend to the Faculty of Mechanical, Maritime and Materials Engineering for acceptance a thesis entitled **"Future ships"** by **T. Frijters** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Preface

In this thesis, I have determined the change in design requirements of unmanned ships and their influence on weight and power. In addition I have determined the cost saving for unmanned shipping, which is the budget for additional equipment for unmanned shipping. The cost savings are not only dependent on ship design, but are also influenced by economics. Writing this thesis has allowed me to combine different aspects of my education and to apply them in a higher level of detail than before. I think that it is impossible to design ships or solve technical issues with only books and without practical experience.

Therefore, I would like to thank all who have shared their practical knowledge. Furthermore, I would like to thank my graduation committee for their support and supervision. Although you all had a key contribution to this project, and therefore my graduation, I would like to mention my daily supervisor from Delft University, Robert Hekkenberg, in particular. Thank you for supporting, advising and helping me on this stormy sea to graduation. It was you who gave me this interesting research topic about the influence of unmanned shipping on ship design. Furthermore, I would like to thank Alex Baenffer from RH Marine. Thank you for your support and the many discussions about graduating. Although Mart Hurkmans is no longer a committee member, I would like to thank you for pulling me on-board RH Marine and making it possible to carry out this research at RH Marine.

Of course, I have to thank my friends from Delft University, who have made the years at university so nice and fun. You all know what it is like to graduate and I could always ask for your help when necessary, thank you. Next, I want to thank my family and my girlfriend, Kim Nelemans. Thank you for your continuous support and that you have always been interested in what I was doing. I want to thank in particular my parents, Michel Frijters and Saskia Postelmans. Thank you for allowing me to go to university and for your continuous support. Thank you!

Delft, The Netherlands — T. Frijters
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Abstract

Unmanned ships are a new concept in the maritime sector. The concept of unmanned ships is driven by safety of life, cost and the shortage in seafarers. However, it is uncertain how the change from manned to unmanned ships influences the design and exploitation of the ship. Therefore, the influences on the ship will be researched in this thesis. The results from this thesis can be used by various organizations, researchers, and designers, to determine whether the concept of unmanned ships is feasible. The main question is:

What are the influences of unmanned shipping on the design considerations and what cost saving can be achieved by removing crew related equipment and the crew itself from merchant ships?

First, it has been researched how the design requirements change under international law. The design spiral has been used to identify the parts of the ship design that change, because of the changed requirements. These parts are: deadweight, lightweight, powering, machinery selection, general arrangement and costing.

To quantify the change in deadweight, lightweight and powering, a parametric study has been carried out and applied to different sized ships. Additionally, an analysis on what additional equipment should be installed on the ship, to make unmanned shipping possible, has been performed. Furthermore, a cost analysis has been carried out to quantify the cost savings associated with the removal of the equipment which is no longer needed for unmanned shipping. The change in cost is the budget for additional equipment required for unmanned shipping. For the cost analysis, building cost, maintenance cost, fuel saving, manning cost, insurance cost, depreciation cost and interest cost have been taken into account. The cost analysis has been applied to different sizes of ships.

Subsequently, the parametric study and cost analysis have been applied to a specific case. In addition the change in capacity, dimensions, trim, stability, seakeeping, general arrangement plan and tonnage have been analyzed. To check the sensitivity of the results, a sensitivity study for uncertain parameters has been performed. The different analyses showed that the change in weight and power is minimal, but that the saving in cost is significant. In conclusion, it can be stated that a significant cost reduction can be achieved by removing the accommodation and related systems from ships.

Contents

Nomenclature

Latin Symbols

A_e/A_0	=	Propeller disk ratio	$[-]$
A_{floor}	=	Total floor area of the accommodation	$[m^2]$
$A_{Pipe,Fifi,main}$	=	Cross sectional area of the main pipe of the firefighting system	$[m^2]$
$A_{Pipe,Fifi,sub}$	=	Cross sectional area of the subpipe of the firefighting system	$[m^2]$
$A_{Pipe,Fifi,vert}$	=	Cross sectional area of the vertical pipe of the firefighting system	$[m^2]$
A_{Pipe}	=	Cross sectional area of a pipe	$[m^2]$
$A_{Pipe,main}$	=	Cross sectional area of the main pipe	$[m^2]$
$A_{Pipe,main,supply}$	=	Cross sectional area of the main supply pipe for fresh water	$[m^2]$
$A_{Pipe,sub}$	=	Cross sectional area of the subpipe	$[m^2]$
$A_{Pipe,sub,supply}$	=	Cross sectional area of the subpipe for supply of fresh water	$[m^2]$
$A_{Pipe,vert}$	=	Cross sectional area of the vertical pipe	$[m^2]$
$A_{Pipe,vert,supply}$	=	Cross sectional area of the vertical supply pipe for fresh water	$[m^2]$
A_{WL}	=	Waterplane area	$[m^2]$
b	=	Beam of the accommodation	$[m]$
B	=	Beam	$[m]$
BM	=	Distance between center of buoyancy and the metacenter	$[m]$

BM'	=	Corrected distance between center of buoyancy and the metacenter	$[m]$
c_{Crew}	=	Specific crew cost	[€/year]
$c_{Fuel,acco}$	=	Fuel price for fuel accommodation	[€/ton]
$c_{Fuel,size}$	=	Fuel price for fuel main engine	[€/ton]
$c_{p,a}$	=	Specific heat at constant pressure of dry air	$[kJ/kg \cdot K]$
$c_{p,v}$	=	Specific heat at constant pressure of water vapor	$[J/kg \cdot K]$
$c_{Pipe,fresh,return}$	=	Specific cost for the return piping of the fresh water system	$[€/m]$
$c_{Pipe,Fifi,main}$	=	Specific cost for the main pipe of the firefighting system	$[€/m]$
$c_{Pipe,Fifi,sub}$	=	Specific cost for the sub pipe of the firefighting system	$[€/m]$
$c_{Pipe,Fifi,vert}$	=	Specific cost for the vertical pipe of the firefighting system	$[€/m]$
$c_{Pipe,main,return}$	=	Specific cost for the main return pipe of the fresh water system	$[€/m]$
$c_{Pipe,main,supply}$	=	Specific cost for the main supply pipe of the fresh water system	$[€/m]$
$c_{Pipe,sub,return}$	=	Specific cost for the sub return pipe of the fresh water system	$[€/m]$
$c_{Pipe,sub,supply}$	=	Specific cost for the sub supply pipe of the fresh water system	$[€/m]$
$c_{Pipe,vert,return}$	=	Specific cost for the vertical return pipe of the fresh water system	$[€/m]$
$c_{Pipe,vert,supply}$	=	Specific cost for the vertical supply pipe of the fresh water system	$[€/m]$
C_{adm}	=	Admiralty constant	$[\text{ton}^{\frac{2}{3}} \cdot kts^3/kW]$
$C_{Armature}$	=	Cost of one armature	[€]
C_B	=	Block coefficient	$[-]$
$C_{Building}$	=	Building cost	[€]
C_{cables}	=	Cost for cables and wires	[€]
C_{Dep}	=	Depreciation cost	[€]
C_{EntS}	=	Cost for the entertainment systems	[€]
C_{Fifi}	=	Cost for the firefighting system	[€]
$C_{Fifi,installation}$	=	Installation cost for the firefighting system	[€]
$C_{Fifi,material}$	=	Material cost for the firefighting system	[€]
$C_{Fifi,Pump}$	=	Cost for the pump of the firefighting system	[€]

C_{Fresh}	=	Cost for the fresh water system	[€]
$C_{Fresh,installation}$	=	Installation cost for the fresh water system	[€]
$C_{Fresh,material}$	=	Material cost for the fresh water system	[€]
$C_{Fresh,pump}$	=	Cost for the fresh water pump	[€]
$C_{Fuel,Trip}$	=	Cost of fuel per trip	[€]
$C_{Fuel,Trip,acco}$	=	Cost of fuel per trip for the accommodation	[€]
$C_{Fuel,Trip,size}$	=	Cost of fuel per trip for the main engine	[€]
$C_{Fuel,Year}$	=	Cost of fuel per year	[€]
$C_{Fuel,Year,acco}$	=	Cost of fuel per year for the accommodation	[€]
$C_{Fuel,Year,size}$	=	Cost of fuel per year for the main engine	[€]
$C_{gen,installation}$	=	Installation cost for the power generating systems	[€]
$C_{gen,material}$	=	Material cost for the power generating systems	[€]
C_{HVAC}	=	Cost for the HVAC system	[€]
$C_{H\&M}$	=	Cost for Hull and Machinery	[€/GT]
$C_{Insurance}$	=	Cost for insurance	[€/$year$]
C_{Int}	=	Interest cost	[€]
C_{IntCom}	=	Cost for the internal communication system	[€]
$C_{Joinery}$	=	Cost for the joinery	[€]
$C_{Joinery,installation}$	=	Installation cost for the joinery	[€]
$C_{Joinery,material}$	=	Material cost for the joinery	[€]
$C_{Lighting}$	=	Cost for lighting in the accommodation	[€]
C_M	=	Midship coefficient	[−]
$C_{Manning}$	=	Cost for manning	[€/year]
C_P	=	Prismatic coefficient	[−]
$C_{Piping,Fifi}$	=	Cost for piping of the firefighting system	[€]
$C_{Piping,Fifi,main}$	=	Cost for main pipes in the firefighting system	[€]
$C_{Piping,Fifi,sub}$	=	Cost for sub pipes in the firefighting system	[€]
$C_{Piping,Fifi,vert}$	=	Cost for vertical pipes in the firefighting system	[€]
$C_{Piping,Fresh,return}$	=	Cost for the return piping of the fresh water system	[€]
$C_{Piping,Fresh,supply}$	=	Cost for the supply piping of the fresh water system	[€]
$C_{Piping,main,supply}$	=	Cost for the main supply pipe of the fresh water system	[€]

$C_{Piping,sub,supply}$	=	Cost for the sub supply pipe of the fresh water system	[€]
$C_{Piping,vert,supply}$	=	Cost for the vertical supply pipe of the fresh water system	[€]
$C_{P\&I}$	=	Cost for Protection and Indemnity	[€/GT]
C_{st}	=	Cost for steel of the accommodation	[€]
$C_{st,installation}$	=	Installation cost for steel of the accommodation	[€]
$C_{st,material}$	=	Material cost for steel of the accommodation	[€]
C_{Window}	=	Cost for windows	[€]
$C_{Window,installation}$	=	Installation cost for windows	[€]
$C_{Window,material}$	=	Material cost for windows	[€]
C_{WP}	=	Prismatic waterplane coefficient	$[-]$
d_{Pipe}	=	Diameter of the pipe	$[m]$
$d_{Pipe,Fifi,main}$	=	Diameter of the main pipe of the firefighting system	$[m]$
$d_{Pipe,Fifi,sub}$	=	Diameter of the subpipe of the firefighting system	$[m]$
$d_{Pipe,Fifi,vert}$	=	Diameter of the vertical pipe of the firefighting system	$[m]$
$d_{Pipe,main}$	=	Diameter of the main pipe	$[m]$
$d_{Pipe,main,supply}$	=	Diameter of the main pipe for supply of fresh water	$[m]$
$d_{Pipe,sub}$	=	Diamter of the subpipe	$[m]$
$d_{Pipe,sub,supply}$	=	Diameter of the subpipe for supply of fresh water	$[m]$
$d_{Pipe,vert}$	=	Diameter of the vertical pipe	$[m]$
$d_{Pipe,vert,supply}$	=	Diameter of the vertical pipe for supply of fresh water	$[m]$
D	=	Depth	$[m]$
D_p	=	Diameter of the propeller	$[m]$
D_{Poop}	=	Depth poop deck	$[m]$
DWT	=	Deadweight tonnage	$[ton]$
f	=	Friction coefficient for pipe flows	$[s^2/m]$
GM_L	=	Longitudinal metacenter height	$[m]$
GM_t	=	Transverse metacenter height	$[m]$
h	=	Enthalpy	$[kJ/kg]$
h_{Acco}	=	Height of the accommodation	$[m]$
h_f	=	Head increase due to friction	$[m]$

$h_{f,Fifi,main}$	=	Head increase due to friction in the main pipe for the firefighting system	$[m]$
$h_{f,Fifi,sub}$	=	Head increase due to friction in the subpipe for the firefighting system	$[m]$
$h_{f,Fifi,vert}$	=	Head increase due to friction in the vertical pipe for the firefighting system	$[m]$
$h_{f,HVAC}$	=	Head increase due to friction in the HVAC system	$[m]$
$h_{f,HVAC,main}$	=	Head increase due to friction in the main pipe for the HVAC system	$[m]$
$h_{f,HVAC,sub}$	=	Head increase due to friction in the subpipe for the HVAC system	$[m]$
$h_{f,HVAC,vert}$	=	Head increase due to friction in the vertical pipe for the HVAC system	$[m]$
$h_{f,main}$	=	Head increase due to friction in the main pipe	$[m]$
$h_{f,sub}$	=	Head increase duo to friction in the subpipe	$[m]$
$h_{f,vert}$	=	Head increase due to friction in the vertical pipe	$[m]$
h_{Fan}	=	Head increase of the fan	$[m]$
h_j	=	Height of the accommodation above deck	$[m]$
h_m	=	Head increase due to minor loses	$[m]$
h_p	=	Head increase over the pump	$[m]$
$h_{Mixture}$	=	Enthalpy of the air mixture	$[kJ/kg]$
h_{Room}	=	Enthalpy of the air in the room	$[kJ/kg]$
i	=	Index	$[-]$
I_{Rate}	=	Interest rate	$[\%]$
I_T	=	Transverse moment of inertia of the design waterline	$[m]$
j	=	Index	$[-]$
k	=	Man-hours per ton of steel	$[h/ton]$
K	=	Structural weight coefficient	$[-]$
K_{losses}	=	Coefficient for minor losses	$[-]$
KB	=	Center of buoyancy height	$[m]$
KB'	=	Corrected center of buoyancy height	$[m]$
KG	=	Center of gravity height	$[m]$
KG'	=	Corrected center of gravity height	$[m]$
l	=	Length of the accommodation	$[m]$
l_j	=	Length of houses	$[m]$
L	=	Length over all	$[m]$

L_{PP}	=	Length between perpendiculars	$[m]$
$L_{Pipe,main}$	=	Total length of main pipe per deck	$[m]$
$L_{Pipe,main,return}$	=	Total length of main pipe per deck for return of sewage	$[m]$
$L_{Pipe,main,supply}$	=	Total length of main pipe per deck per supply of fresh water	$[m]$
$L_{Pipe,sub}$	=	Total length of subpipe per deck	$[m]$
$L_{Pipe,sub,return}$	=	Total length of subpipe per deck for return of sewage	$[m]$
$L_{Pipe,sub,supply}$	=	Total length of subpipe per deck per supply of fresh water	$[m]$
$L_{Pipe,vert}$	=	Total length of vertical pipe	$[m]$
$L_{Pipe,vert,return}$	=	Total length of vertical pipe for return of sewage	$[m]$
$L_{Pipe,vert,supply}$	=	Total length of vertical pipe per supply of fresh water	$[m]$
L_{Rate}	=	Loan rate	$[\%]$
L_{WL}	=	Length of the waterline	$[m]$
$m_{f,Trip,acco}$	=	Mass of fuel used on one trip for the accommodation	$[ton]$
$m_{f,Trip,size}$	=	Mass of fuel used on one trip for smaller unmanned ship	$[ton]$
$m_{f,Year,acco}$	=	Mass of fuel used in one year for the accommodation	$[ton]$
$m_{f,Year,size}$	=	Mass of fuel used in one year for smaller unmanned ship	
$\dot{m}$	=	Massflow	$[kg/h]$
$\dot{m}_f$	=	Massflow of fuel	$[kg/s]$
$\dot{m}_{Indoor}$	=	Massflow of the indoor air	$[kg/h]$
$\dot{m}_{Outdoor}$	=	Massflow of the outdoor air	$[kg/h]$
M_{st}	=	Stabilizing moment	$[Nm]$
M_{tr}	=	Trimming moment	$[Nm]$
n_i	=	Number of crew per device	$[-]$
N_{Amp}	=	Number of signal amplifiers for the entertainment system	$[-]$
$N_{Armature}$	=	Number of armatures	$[-]$
N_{Crew}	=	Number of crew	$[-]$
N_{Deck}	=	Number of decks	$[-]$
Ne	=	Rotations per minute of engine	$[rpm]$

N_{gen}	=	Rotations per minute of generator	$[rpm]$
N_i	=	Number of installed equipment of type i	$[-]$
N_p	=	Rotations per minute of propeller	$[rpm]$
N_{Ph}	=	Number of phone stations	$[-]$
$N_{Pipe,Fifi,sub}$	=	Number of subpipes per deck for the firefighting system	$[-]$
$N_{Pipe,main}$	=	Number of main pipes per deck	$[-]$
$N_{Pipe,main,supply}$	=	Number of main pipes per supply of fresh water per deck	$[-]$
$N_{Pipe,sub}$	=	Number of subpipes per deck	$[-]$
$N_{Pipe,sub,supply}$	=	Number of subpipes per supply of fresh water per deck	$[-]$
$N_{Pipe,vert}$	=	Number of vertical pipes	$[-]$
$N_{Pipe,vert,supply}$	=	Number of vertical pipes per supply of fresh water	$[-]$
N_{SatA}	=	Number of antennas	$[-]$
N_{SatRec}	=	Number of satellite receivers	$[-]$
N_{SF}	=	Number of seafarers	$[-]$
N_{TV}	=	Number of televisions	$[-]$
N_{TM}	=	Number of terminal modules	$[-]$
N_{Trip}	=	Number of trips	$[-/year]$
N_{User}	=	Number of users of fresh water in the accommodation	$[-]$
p	=	Atmospheric pressure	$[Pa]$
p_i	=	Pressure at position i	$[Pa]$
p_{sat}	=	Saturated vapor pressure	$[Pa]$
P	=	Power	$[kW]$
$P_{Armature}$	=	Power for one armature	$[W]$
P_B	=	Installed brake power	$[kW]$
P_D	=	Delivered power	$[kW]$
$P_{D,Manned}$	=	Delivered power manned ship	$[kW]$
$P_{D,Unmanned}$	=	Delivered power unmanned ship	$[kW]$
P_{EntS}	=	Power for the entertainment system	$[kW]$
P_{fresh}	=	Total power for the fresh water and sanitary system	$[kW]$
$P_{fresh,pump}$	=	Total power for the fresh water pump	$[kW]$

$P_{Fifi,pump}$	=	Power for the pump of the firefighting system	$[kW]$
P_{gen}	=	Installed generator power	$[kW]$
P_{Hotel}	=	Power consumption of hotel equipment	$[kW]$
P_{HVAC}	=	Power for the HVAC system	$[kW]$
$P_{HVAC,fan}$	=	Power of the fan for the HVAC system	$[kW]$
$P_{HVAC,heat}$	=	Power of the HVAC system for heat exchange	$[kW]$
P_i	=	Power of installed equipment of type i	$[kW]$
P_{IntCom}	=	Power for internal communication	$[kW]$
$P_{Lighting}$	=	The total power for lighting	$[kW]$
P_{Load}	=	Power load during the day	$[kW]$
P_{Peak}	=	The maximum power load during the day	$[kW]$
Q_{Fan}	=	Volumeflow through the fan	$[m^3/s]$
Q_{Pump}	=	Volumeflow through the pump	$[m^3/s]$
$Q_{Pump,Fifi}$	=	Volumeflow through the pump of the firefighting system	$[m^3/s]$
r_w	=	Evaporation heat of water	$[kJ/kg]$
R	=	Specific gas constant	$[J/kg \cdot K]$
R_{Acco}	=	Residual value accommodation	[€]
Re_d	=	Reynolds number for pipe flows	$[-]$
$scrap$	=	Percentage of scrap of steel	[%]
S	=	Distance	$[nm]$
S_{cables}	=	Total length of cables	$[m]$
S_A	=	Wetted surface	$[m^2]$
S_{Port}	=	Distance in port	$[nm]$
t	=	Trim	$[m]$
T	=	Draft	$[m]$
T_{Air}	=	Air temperature	$[K]$
T_{days}	=	Number of days	$[-]$
T_{Indoor}	=	Temperature of the indoor air	$[°C]$
T_{Int}	=	Loan period	$[year]$
$T_{Mixture}$	=	Temperature of the air mixture	$[°C]$
T_{off}	=	Days offhire	$[days/year]$
$T_{Outdoor}$	=	Temperature of the outdoor air	$[°C]$

T_{Port}	=	Time spend in port	$[h]$
T_{Trip}	=	Time for one trip	$[h]$
V_{Acco}	=	Volume of the accommodation	$[m^3]$
V_i	=	Speed at position i	$[m/s]$
V_{Pipe}	=	Speed in a pipe	$[m/s]$
V_S	=	Ship speed	$[kts]$
$V_{S,Port}$	=	Ship speed in port	$[kts]$
$\dot{V}$	=	Volumeflow	$[m^3/h]$
$\dot{V}_{Deck}$	=	Volumeflow per deck	$[m^3/h]$
$\dot{V}_{Pipe}$	=	Volumeflow in a pipe	$[m^3/h]$
$w_{Pipe,fresh,return}$	=	Specific weight of sewage pipe	$[kg/m]$
$w_{Pipe,main}$	=	Specific weight of main pipe	$[kg/m]$
$w_{Pipe,main,return}$	=	Specific weight of main pipe for sewage	$[kg/m]$
$w_{Pipe,main,supply}$	=	Specific weight of main pipe for supply of fresh water	$[kg/m]$
$w_{Pipe,sub}$	=	Specific weight of subpipe	$[kg/m]$
$w_{Pipe,sub,return}$	=	Specific weight of subpipe for sewage	$[kg/m]$
$w_{Pipe,sub,supply}$	=	Specific weight of subpipe for supply of fresh water	$[kg/m]$
$w_{Pipe,vert}$	=	Specific weight of vertical pipe	$[kg/m]$
$w_{Pipe,vert,return}$	=	Specific weight of vertical pipe for sewage	$[kg/m]$
$w_{Pipe,vert,supply}$	=	Specific weight of vertical pipe for supply of fresh water	$[kg/m]$
W_{Acco}	=	Weight of the accommodation	$[ton]$
W_{AC}	=	Weight of the air-conditioning unit	$[ton]$
$W_{Armature}$	=	Weight of one armature	$[kg]$
W_{cables}	=	Weight of cables and wires	$[ton]$
W_{CM}	=	Weight of the cooling machine	$[ton]$
$W_{C\&E}$	=	Weight of crew and effects	$[ton]$
W_{dh}	=	Structural weight deckhouse	$[ton]$
W_{DO}	=	Weight of the diesel oil	$[ton]$
W_{EntS}	=	Weight of the entertainment system	$[ton]$
W_{fresh}	=	Total weight of the fresh water and sanitary system	$[ton]$
$W_{fresh,pump}$	=	Total weight of fresh water pumps	$[ton]$

$W_{Fan,HVAC}$	=	Weight of the fan for the HVAC system	$[ton]$
W_{FW}	=	Weight of fresh water	$[ton]$
W_{Fifi}	=	Weight of the firefighting system	$[ton]$
$W_{Fifi,Pump}$	=	Weight of the pump for the firefighting system	$[ton]$
$W_{gen,50Hz}$	=	Weight of the generator for the 50 Hz generator	$[ton]$
$W_{gen,60Hz}$	=	Weight of the generator for the 60 Hz generator	$[ton]$
W_{Hotel}	=	Weight of hotel equipment	$[ton]$
W_{HVAC}	=	Weight of the HVAC system	$[ton]$
W_{IntCom}	=	Weight of internal communication	$[ton]$
$W_{Joinery}$	=	Weight of the joinery	$[ton]$
$W_{Lighting}$	=	Weight of the lighting in the accommodation	$[ton]$
W_M	=	Machinery weight	$[ton]$
W_{ME}	=	Weight of main engines	$[ton]$
$W_{Piping,Fresh,return}$	=	Total weight of sewage piping	$[ton]$
$W_{Piping,Fresh,supply}$	=	Total weight of piping for the supply of fresh water	$[ton]$
$W_{Piping,HVAC}$	=	Weight of the piping for the HVAC system	$[ton]$
$W_{Piping,main,supply}$	=	Total weight of main pipe per deck for the supply of fresh water	$[kg]$
$W_{Piping,vert,supply}$	=	Total weight of vertical pipe for the supply of fresh water	$[kg]$
$W_{Piping,sub,supply}$	=	Total weight of subpipe per deck for the supply of fresh water	$[kg]$
W_{rem}	=	Weight of remaining machinery	$[ton]$
$W_{st,gross}$	=	Gross steel weight	$[ton]$
W_{Store}	=	Weight of stores	$[ton]$
x	=	Humidity ratio	$[kg/kg]$
x_a	=	Center of gravity of the design waterline measured from ordinate 10	$[m]$
x_{Acco}	=	Horizontal center of gravity of the accommodation measured from ordinate 10	$[m]$
z_i	=	Height at position i	$[m]$

Greek Symbols

α	=	Pitch angle	$[°]$
β	=	Upper roll factor	$[-]$

δP_B	=	Delivered power reduction	$[kW]$
δT	=	Change in draft	$[m]$
δW	=	Ligthweight reduction	$[ton]$
ϵ	=	Roughness	$[m]$
η_{Fan}	=	Efficiency of the fan	$[-]$
η_{Pump}	=	Efficiency of the pump	$[-]$
η_{Light}	=	Luminous efficacy	$[lm/W]$
θ	=	Temperature	$[°C]$
μ	=	Viscosity	$[Ns/m^2]$
ρ	=	Density	$[kg/m^3]$
ϕ	=	Relative humidity	$[-]$
∇	=	Displacement	$[m^3]$
∇'	=	Displacement of the unmanned ship	$[m^3]$
Δ	=	Displacement	$[ton]$
ΔC_{gen}	=	Delta on generator cost	[€]
$\Delta C_{gen,installation}$	=	Delta on generator installation cost	[€]
$\Delta C_{gen,material}$	=	Delta on generator material cost	[€]
$\Delta_{Unmanned}$	=	Displacement of the unmanned ship	$[ton]$
$\Delta W_{gen,50Hz}$	=	Delta on generator weight for 50 Hz generator	$[ton]$
$\Delta W_{gen,60Hz}$	=	Delta on generator weight for 60 Hz generator	$[ton]$
Φ	=	Illuminance	$[lux]$

Abbreviations

AIS	=	Automatic Identification System	$[-]$
$COLREGS$	=	The International Regulations for Preventing Collisions at Sea	$[-]$
ECA	=	Emission Control Area	$[-]$
$FM-CW$	=	Frequency-Modulated Continuous-Wave	$[-]$
HFO	=	Heavy Fuel Oil	$[-]$
$HVAC$	=	Heating, Ventilation and Air Conditioning	$[-]$
LCB	=	Longitudinal Center of Buoyancy	$[m]$
LCF	=	Longitudinal Center of Floatation	$[m]$
LCG	=	Longitudinal Center of Gravity	$[m]$

LLC	=	Load Lines Convention	$[-]$
mlc	=	meter liquid column	$[-]$
$MARPOL$	=	The International Convention for the Prevention of Pollution from Ships	$[-]$
MCR	=	Maximum Continuous Rating	$[kW]$
MDO	=	Marine Diesel Oil	$[-]$
MGO	=	Marine Gas Oil	$[-]$
$MUNIN$	=	Maritime Unmanned Navigation through Intelligence in Networks	$[-]$
SFC	=	Specific Fuel Consumption	$[g/kWh]$
$SOLAS$	=	The International Convention for the Safety of Life at Sea	$[-]$
USV	=	Unmanned Surface Vehicle	$[-]$

Chapter 1

Introduction

1.1 Problem statement

Every day, thousands of manned ships sail the seas. This often goes well, but sometimes an accident happens. 85% of these accidents are caused by human error and often result in injury or even death [1]. A lot of research has been carried out on human factors that cause humans to make errors. These studies show, that the performance of people is dependent on the complexity of the system [2]. One could think of training people better for the task they have to perform. However, several studies on this topic show that this is not the solution to reducing the number of accidents caused by human error [2, 3, 4]. Research shows that vigilance, workload, stress and the ability to asses both the situation and the own performance are key parameters for human errors [2, 5, 6, 7, 8, 9, 10]. It can be said that humans are the weak link when it comes to the man-machine interaction. Removing people from ships can therefore contribute to less accidents and therefore safer shipping.

In addition, it is expected that there will be a shortage of seafarers in the near future due to the increasing transport volumes and the less interesting job of being a seafarer [11]. This is caused by the high degree of isolation from social life when working on seagoing ships. This has become worse since the time at sea has increased due to ecologic and economic considerations. A possible solution to both these problems is unmanned ships.

Something else that unmanned shipping could make interesting is cost reduction. By removing the crew from the ships and monitoring ships from shore, a great decrease in personnel cost and possibly a reduction in other cost like fuel cost and building cost can be achieved. In summary it can be said that the concept of unmanned ships is driven by safety of life, cost and the shortage in seafarers.

The goal for this thesis is to determine how ship design can change when the vessel is specially designed for unmanned shipping in deep sea. Furthermore, a goal of this thesis is to quantify for RH Marine, a maritime company which develops sensors and IT solutions for ships, the financial benefits associated with unmanned shipping as a function of vessel size. Only when there is a substantial benefit, will it be interesting for RH Marine to invest in unmanned shipping. To determine which research is required to reach these goals, Section 1.2 discusses the research and developments in the field of unmanned shipping.

1.2 Current developments

Unmanned and autonomous are two terms that are often used interchangeably. To make clear what the difference is between the two terms, a distinction needs to be made. The Oxford dictionary states that a vehicle is unmanned if it *"does not have or need a crew"* [12]. Furthermore the Oxford dictionary states that a vehicle is autonomous if it *"is able to do things and make decisions without the help from anyone else"* [13]. The definitions given by the Oxford dictionary are not precise enough and therefore do not make sufficiently clear the difference in terminology used in literature. The American National Institute of Standards and Technology gives a more precise explanation for the terminology. They define autonomous as: *“Operations of an unmanned system wherein the unmanned system receives its mission from either the operator who is off the unmanned system or another system that the unmanned system interacts with and accomplishes that mission with or without further human-robot interaction”*. And an unmanned system as: *“A powered physical system, with no human operator aboard the principal components, which acts in the physical world to accomplish assigned tasks. It may be mobile or stationary”* [14]. For the purpose of this thesis, the terminology as stated by the American National Institute of Standards and Technology will be used.

Shipping is not the only field in which unmanned vehicles are of interest. Other fields include cars and aviation. The developments in the aviation and the car industry show that is possible to have unmanned vehicles in busy areas. And since ships in general operate in far less busy areas, it should be possible to apply the similar technology to ships [15].

Research shows that the Unmanned Surface Vehicles, USVs, can be grouped according to the Carerock Laboratory using the following grouping [16]:

- Small ($<$ 1 ton)
- Medium ($<$ 100 ton)
- Large ($<$ 1000 ton)
- Extra-large ($>$ 1000 ton)

Most USVs developed until today have small or medium size and have about the size of recreational watercraft [16]. These USVs look very similar to their manned counterpart as can be seen in Figure 1.1. Furthermore a lot of research has already been carried out on the way USVs can avoid collisions with objects by using trajectory planning. The possible solution varies from the use of Kalman filters to the use of back propagation neural networks and everything in between [17, 18, 19, 20, 21, 22]. Therefore, no further research on trajectory planning is needed in this thesis. From the research on USVs, it can be concluded that it is possible to control USVs of small and medium size, but whether it is also possible for merchant ships is still unclear. In addition is further research on sensors that make unmanned shipping possible required as no literature on the topic was found.

Figure 1.1: Israeli Protector [16]

As mentioned before, have most developments focused on the small and medium sized crafts. On the other hand is the unmanned bridge project from Rolls Royce the first concept that applies unmanned technology to merchant ships. Rolls Royce has developed a virtual bridge which allows the operator to control the vessel from shore [23]. DNV-GL takes it even one step further and has developed a fully autonomous short sea shipping concept called ReVolt. The ReVolt concept, as shown in Figure 1.2, shows that slowing the sailing speed down influences the hullshape, machinery installation, capacity and the range of the vessel [1]. The concept is developed for a fixed route, between Oslo and Trondheim, on which multiple ships sail using the conveyor method. Sailing in the conveyor method means that multiple ships sail on the same route which consists out of multiple ports. The time between the arrival of two ships is fixed and when a ship leaves the final port, it sets sail to the first one. The effectiveness of the conveyor method is very dependent on the time in port and the infrastructure in the ports as a ship should be unloaded and loaded before the next autonomous ship arrives. When looking at the design of the vessel, it can be seen that the holds have been raised until container height. This allows to install cell guides which makes lashing unnecessary and does not require inspections during sailing. Furthermore, the ReVolt project has looked at the possibility to use composites as a construction material, which is lighter and would save fuel cost. However, ReVolt states that the weight that would be saved would cause a lower draft, which allows for smaller propellers that are less efficient. Using composites would therefore decrease the overall efficiency [1]. Hence, ReVolt states that the ship of the future is likely to be built in steel as it is a proven technology and less expensive. The ReVolt project also showed that rotating equipment requires the most maintenance and therefore DNV-GL tried to reduce this equipment as much as possible [1]. This is done by designing the vessel as fully electric with no generatorset, but batteries and no ballast system. The only rotating parts are the thrusters. DNV-GL also researched the possibility to use green technology such as solar panels, kites and Flettner rotors to reduce the environmental impact of the vessel. However, these technologies did not turn out to be cost effective for a full electric ship on short routes. Since ships sailing the deep sea requires even more energy, those green technologies are likely to be even less cost effective and therefore not applicable to ships sailing the deep sea.

Furthermore, DNV-GL says that the capital costs of the ReVolt are equal to a ship sailing on Heavy Fuel Oil, HFO, with the same capacity [1]. The cost for machinery, hotel and outfitting would be less, but the required battery pack is very expensive. However, they expect that the cost for the battery pack will go down in the future [1]. To test the feasibility of the ReVolt a scale prototype has been made. The prototype showed that it is possible for vessels to sail autonomously with current technology. The research did not show which sensors were used to allow autonomous sailing and how much money was spend on these sensors. In addition should one keep in mind that the concept is developed for a specific area which is close to shore and therefore the ships do not require large energy storage as will be the case for deep sea ships.

The research performed by ReVolt is sufficient in showing that design requirements can change when the vessel is specially designed for unmanned shipping and that it is possible to sail unmanned. However, research on sensors and the cost of technology which makes unmanned sailing possible is still required.

Figure 1.2: ReVolt[24]

On the other hand the MUNIN project, Maritime Unmanned Navigation through Intelligence in Networks project, which is a large project funded by the European Union did research on which sensors should be used for unmanned ships. Furthermore, MUNIN has researched the design of the shore stations that are required for monitoring unmanned ships [25]. In addition, MUNIN performed a lot of research on legal an liability issues and some research on ship design [25]. In their research on ship design MUNIN distinguishes two general approaches for production cost estimation: namely the top-down approach and the bottom-up approach. The top-down approach is a macro approach which relies on empirical or statistical relationships. It requires limited information and little effort, but is less precise than the bottom-up approach [25]. The bottom-up approach breaks the project into smaller units until a basic element is reached and estimates the cost for each unit. The total cost of the project is the sum of all the units [25]. The bottom-up approach gives quite accurate estimates but requires great effort and detailed information, something which is often not available in early design stages [25]. Due to this requirement for detailed information, MUNIN uses the top-down approach, resulting in a qualitative rather than a quantitative assessment for capital cost for the unmanned ship. In addition, MUNIN states that the following aspects of ship design should change when ships become unmanned. The accommodation and the supporting systems can be removed and preferably the ballast system too as both systems require many auxiliary systems that require maintenance [25, 26]. Maintenance is one of the topics that MUNIN looked at, but which requires more attention, especially in combination with the configuration of the engine room [25, 26]. The engine room must be reconfigured as more Emission Control Areas, ECAs, will arise where it is not allowed to sail on HFO. In these areas one should switch to a cleaner fuel such as Marine Gas Oil, MGO, or Marine Diesel Oil, MDO. Switching fuel can cause total black-outs and the number of black-outs in the ECA area of Long Beach and San Francisco increased by 120% since the introduction of the ECA area [26]. Therefore, one should look at other possibilities as there is nobody on-board to reset the system. In general, one should build in more redundancy into the design of the vessel to prevent total failure [25]. Building in this redundancy in combination with the required sensors will increase the capital cost for the vessel. MUNIN retrofitted a bulkcarrier in such a way that it can sail unmanned. However, it turned out that the vessel was no longer cost effective [25]. A specific reason why this was the case was not provided by MUNIN. Therefore one should research whether this is also the case when unmanned ships are designed from scratch for their intended purpose [25]. Research on MUNIN is sufficient when it concerns sensors and legislation, but needs elaboration on cost as cost are not quantified in MUNIN. Furthermore, MUNIN does not research the influence of size on ship design.

1.3 Research question

Research on USVs in Section 1.2 showed that it is possible to sail unmanned, but that further research on the technology used and the cost of that technology is required. One should note that USVs are probably not intended to interact with other traffic in the same way as merchant ships do. Therefore, the technology required to interact with other ships, and the influence of size, require further research as the design requirements may change. The ReVolt concept is sufficient in showing that design requirements can change when a ship is specially designed for unmanned shipping. However, one should keep in mind that the ReVolt concept is designed for short sea shipping in a very specific area and not for deep sea shipping. The ReVolt concept also needs some elaboration on sensors and cost of the concept. MUNIN is sufficiently clear on the required sensors and the states that ships should be specially designed for unmanned shipping, but needs elaborating on cost. Therefore one can conclude that the goals of this thesis, as set out in Section 1.1, are still valid.

This thesis will determine how ship design can change and what can be removed when the vessel is specially designed for unmanned shipping in deep sea in combination with an quantitative cost-benefit analysis as a function of vessel size using the bottom-up approach as this approach is more precise than the top-down approach. This will be done by answering the main question and subquestions given below. First, the design changes due to unmanned shipping will be researched with the help of legislation and ship design knowledge. Legislation will be used to determine the minimal requirements the unmanned vessel should have and the ship design knowledge will be used to determine what needs to be done to make the design economically feasible. Finally, a case study will be done to determine the possible cost benefit that can be made by using an unmanned ship compared to a conventional ship.

This thesis will not be about the design of the shore stations required for monitoring unmanned ships. Neither will this thesis determine quantitatively how maintenance in the engine room should take place and what should be done to optimize engine room equipment to sufficient reliability and minimal life cycle cost. Furthermore will this thesis not focus on the working principle of the IT system on-board the ship, nor perform a detailed analysis on the working principle of sensors and their applicability to unmanned shipping.

Main question:

What are the influences of unmanned shipping on the design considerations and what cost saving can be achieved by removing crew related equipment and the crew itself from merchant ships?

Subquestions:

1. What is the influence of unmanned shipping on the considerations in ship design?
   (a) What is the influence of legislation on the concept of unmanned shipping?
   (b) Which design requirements can be canceled, changed or added?
   (c) What are the advantages and disadvantages of the renewed design requirements?
2. What cost saving can be achieved by removing crew related equipment and the crew itself from conventional merchant ships?
   (a) How will removing crew and crew related equipment influence the capital cost?
   (b) How will removing crew and crew related equipment influence the operational cost?

1.4 Method

To answer the research questions, the approach as shown in Figure 1.3 will be used. First will be qualitatively analyzed in Chapter 2 how unmanned shipping influences ship design and what are the minimal requirements for a ship. Furthermore, it will be determined with this analysis which aspects of ship design require further analysis within this thesis. Based on the knowledge gained in the design analysis, will in Chapter 3 a model be developed which quantifies the change in ship design. Here it is determined what equipment can be removed and what reduction in weight and power can be achieved by removing this equipment. The results from the design model will be the input for the cost model, which will be developed in Chapter 4. The cost model will be used to determine the saving in cost as a result of the removal of crew and equipment. The result of the cost model is the available budget for systems that make unmanned shipping possible. The design model and the cost model will both give results for different sized ships. Hereafter, both the models will be applied to a specific ship and route in the case study in Chapter 5. The sensitivity of the results will be analyzed in Chapter 6. Finally, the conclusion will answer the research question in Chapter 7.

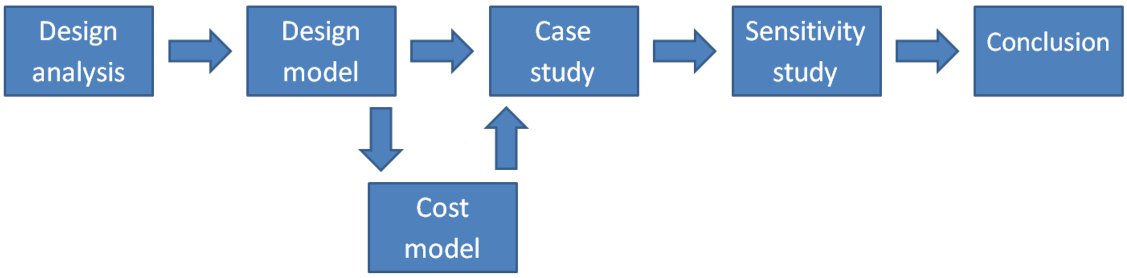


Figure 1.3: Research method

Chapter 2

The influence of unmanned shipping on ship design

It is the goal of this chapter to find the answer to the question: "*What is the influence of unmanned shipping on the considerations in ship design?*" as set out in Section 1.3. The results from this chapter determine the requirements for the design model in Chapter 3. To perform the design analysis, international legislation will be analyzed to determine the minimal requirements for unmanned ships. In Section 2.1 it will be researched how the design requirements change under international law. First it will be set out if unmanned ships should comply with international law and then to which legislation the unmanned ship must comply. Section 2.1 will end with which legislation could be of any hindrance when the ship is specially designed for unmanned shipping. In Section 2.2 it will be researched how the design requirements change with the help of the design spiral when the ship is specially designed for unmanned shipping. The design spiral will be used, because it shows the different steps in ship design. The analysis on the the design spiral will then be followed by an analysis of which of the legislation that could be of any hindrance, as defined in Section 2.1, is a true hindrance, based on the analysis of the design spiral, and which legislation can be argued to be inapplicable to unmanned ships. The chapter will end with a conclusion on the influence of unmanned shipping on ship design in Section 2.3. The structure of this chapter is shown in Figure 2.1.

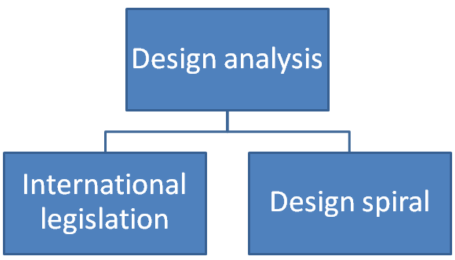


Figure 2.1: Structure of the design analysis

2.1 Design requirements under international law

Before setting out which technical regulations are applicable to an unmanned or autonomous ship, one should wonder if an unmanned ship is still a ship. If this is not the case, the question arises if it is governed by maritime law. As Bill Tetley once observed, the legal definition of 'ship' and 'vessel' varies from one international maritime convention to another, because they are *"very much a function of the subject matter concerned"* [27, 28]. In the law of the sea the term is also not strictly defined [27, 29]. The term ship is even not defined in the UN Convention on the Law of the Sea which uses the terms 'ship' and 'vessel' interchangeably [27, 30]. However according to van Hooydonk most commentators on the description undoubtedly rightly assume that for the purpose of the law of the sea that unmanned ships must be regarded as ships [27, 31, 32, 33]. The rules of the Law of the Sea Convention, which define the rights and duties of states in relation to international shipping therefore also apply to the operation of unmanned ships [27]. Since unmanned ships are defined as ships, all conventions and laws which apply to conventional ships, also apply to unmanned ships. However a distinction in legislation will be made in this section between legislation to which unmanned ships must comply and legislation that unmanned ships ought to comply with. Legislation to which unmanned ships must comply will directly affect the design of the unmanned ship and will be discussed in Section 2.1.1. Legislation the unmanned ship ought to comply with, but of which it is arguable if the unmanned ship should truly comply with, due to the absence of humans, will be discussed in Section 2.1.2. The ship for example needs, according to Rule 5 of the COLREGs, always a proper look-out by both sight and hearing. This is nowadays done by the eyes and ears of the crew, but those will need to be replaced. The removal of the crew has a direct effect on the required equipment. On the other hand, the MARPOL Convention requires that ships must have a sewage system. When ships become unmanned one can argue if the presence of a sewage system is still a valid requirement. Finally a conclusion on the construction, design and equipment requirements under international law will be given in Section 2.1.3.

2.1.1 International law unmanned ships must comply with

As mentioned before, will the legislation, to which unmanned ships must comply, be discussed in this section. Of the conventions and regulations discussed in this section, only the parts will be discussed that are relevant for the design of an unmanned ship. The unmanned ship should also comply with the others parts of the conventions and regulations, but these parts will not influence the design of unmanned ships in a different way than they do for manned ships. In general, one can say that the legislation that influences the design of the unmanned ship the most, is legislation that dictates the tasks and duties of the crew who need to be replaced by technology, because all other legislation will remain applicable for both manned and unmanned ships. The legislation and regulations that will be discussed are the SOLAS Convention, MARPOL Convention, Load Lines Convention, COLREGS and the Class Rules.

SOLAS Convention

The International Convention for the Safety of Life at Sea, SOLAS, has no chapters that are specifically written for unmanned ships. This is logic, as the convention was written in 1974 when unmanned ships were not even a possibility. Therefore, the convention is written with manned vessels in mind. However, the convention also points out duties of the master that need to be replaced by technology when the ship is unmanned. The first duty of the master that needs to be replaced by technology is the masters duty to warn for certain dangers encountered as described in Chapter V, Regulation 31 [34]. This requires the unmanned ship to have systems on board that can asses the weather, ice forming on the superstructure and to communicate this to other vessels in the area. The second duty of the master that needs to be replaced is the duty that when a master receives a distress signal, and he is in the position to provide assistance, the master should do so or give a reason in the logbook for not doing so according to Chapter V, Regulation 33 [34]. To comply with this regulation the ship must be able to deploy life-rafts or other lifesaving appliances and be able to function as a relay station in communication. Or one could argue that unmanned ships are by definition not in the position to provide assistance. The absence of humans on-board allows to discard much of SOLAS, but this will be discussed in Section 2.1.2.

MARPOL Convention

The International Convention for the Prevention of Pollution from Ships, MARPOL, is the main international convention that covers the prevention of pollution of the marine environment by ships from operational and accidental causes. It was adopted in 1973 [35]. Back then, unmanned ships were inexistend and therefore the convention was framed with manned vessels in mind. The result is a convention with no specific requirements for unmanned ships. Unmanned ships must therefore comply with the same regulations as manned ships. However for some regulations it can be argued whether unmanned ships must comply with them. These regulations will be pointed out in Section 2.1.2.

Load Lines Convention

The Load Lines Convention, LLC, is the convention that recognizes the limitations of draft to which a ship may be safely loaded. The convention prescribes the required freeboard height and is adopted in 1966 [36]. Since unmanned and manned ships both will be loaded with cargo, the convention also applies to unmanned ships. However the convention states no special requirements for unmanned ships. This is again caused by the non-existence of unmanned ships when the convention was written.

COLREGS

The International Regulations for Preventing Collisions at Sea, COLREGS, is the convention that prescribes the traffic regulations at the sea [37]. The convention was adopted in 1972 and even though unmanned ships did not exist yet, unmanned ships are required to comply with the Collision Regulations. Although the convention has been framed with manned ships in mind, it has influence on the design of the unmanned vessel as duties prescribed in the convention that are performed by humans need to be replaced by technology [25, 27]. Rule 5 from this convention states:

"Every vessel shall at all times maintain a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision." [38].

The rule states that there should always be somebody at the bridge by both sight and hearing. In other words: One should always have two resources of information for judging the current situation. For manned ships this is done by looking through the window and using radar as a tool for sight. Hearing is done with human ears and mainly applicable when sight is bad due to for example fog. Unmanned ships will also need a proper look-out to be aware of the situation around the vessel. Therefore equipment should be installed on the ship that can replace the human eyes and ears and then act accordingly to the situation. Furthermore Rule 33 from the convention states:

"A vessel of 12 metres or more in length shall be provided with a whistle, a vessel of 20 metres or more in length shall be provided with a bell in addition to a whistle, and a vessel of 100 metres or more in length shall, in addition, be provided with a gong, the tone and sound of which cannot be confused with that of the bell. The whistle, bell and gong shall comply with the specification in Annex III to these regulations. The bell or gong or both may be replaced by other equipment having the same respective sound characteristics, provided that manual sounding of the required signals shall always be possible." [25, 39].

The rule states that vessels should have equipment for sound signals dependent on their size. However the most important words of the rule are in the end which state that it should always be possible to manual sound the equipment. When ship become unmanned their will be nobody on-board to manually operate the equipment. Therefore one can conclude that equipment for sound signals should be redundant.

Class Rules

Class Rules are regulations written by a Classification Society. There are different Classification Societies which all have their own rules. Despite nonuniform rules, they have in common that ships, that have been classified by them, are considered safe. Until now, Classification Societies do not have rules specific for unmanned ships, but rules that are applicable to manned ships must also be complied to by unmanned ships. The rules often show that ships must comply with the rule or the designer must prove that a different solution is just as safe or safer for a certain application. Therefore, one can say that unmanned ships are accounted for in a certain way in the rules of Classification Societies. The rules from Bureau Veritas state for the design requirements of automation that:

"*All control systems essential for the propulsion, control and safety of the ship shall be independent or designed such that failure of one system does not degrade the performance of another system.*' and '*Failure of any part of such systems shall not prevent the use of the manual override.*" [40].

From these lines it is possible to conclude that automation systems should be built redundant and that those systems should both have an automatic and a manual way to operate them. However it is arguable if the manual way is still useful when there is nobody on-board to operate the system manually. Therefore it is better to follow the philosophy of the rules instead of following the rules literally.

2.1.2 International law unmanned ships ought to comply with

In this section the legislation will be discussed to which unmanned ships ought to comply with, but of which it is arguable if the unmanned ship truly should. Of the conventions and regulations discussed in this section, only the parts will be discussed that are relevant for the design of an unmanned ship. The unmanned ship should also comply with the others parts of the conventions and regulations but these parts will not influence the design of unmanned ships in a different way than they do for manned ships. In general one can say that the legislation that sustains human presence has the most influence on the design. The legislation and regulations that will be discussed are the SOLAS Convention, MARPOL Convention and Load Lines Convention. The COLREGS and the Class Rules do not have special regulations for the presence of humans on-board that influence the design of unmanned ships in different way than they do for manned ships and are therefore these two conventions are left out of this analysis on legislation to which unmanned ships ought to comply with.

SOLAS Convention

The International Convention for the Safety of Life at Sea, SOLAS, has no chapters that are specifically written for unmanned ships, as mentioned before. Therefore, the regulations written in the convention are framed with manned ships in mind. Hence, it contains regulations which are difficult to comply with and unnecessary for unmanned ships. The first regulation which would be unsuitable for unmanned ships is Regulation 16 of Chapter I, which states that all certificates must be available on-board for examination at all times [25, 41]. It is not difficult to arrange a space where these certificates can be maintained but it also requires that authorities can access the vessel at any time. This is not a problem as long as only authorities access the vessel, but if criminals access the vessel this can turn into safety problems for the ship and its cargo. Therefore, one should try to find a different solution to this problem. This can either be by storing the certificates digitally in such a way that they are always accessible, or discard unmanned ships from this requirement. The next regulations assume that there is human presence on ships and are focused on the safety of both ship and crew. These regulations are:

- Damage control information must be readily available on the bridge, just as the position of doors and flooding indicators (Regulation 25, Chapter II-1)[25, 42].
- The steering gear must be controllable from both bridge and steering gear control room (Regulation 29, Chapter II-1) [25, 42].
- It is required to have at least two independent ways of communication between the navigation bridge and the machinery space (Regulation 37, Chapter II-1) [25, 42].

- It is required to have a radio phone and radio transponders on ships. Furthermore must flares be kept at the bridge and are ships required to have on-board communication and alarm systems (Regulation 6, Chapter III) [25, 43].

The regulations named above have in common that they all name the bridge of the vessel. However the bridge is likely to disappear, as it is there to accommodate crew for their task of sailing the vessel. When ships become unmanned, the bridge is likely to be replaced by an automatic system, making it hard to comply with these requirements. However, one could argue that the bridge becomes an onshore control room from which someone can intervene. Since this thesis will only look at the ship itself, it will be left out of this thesis if the onshore control room complies with the legislation named above. The next regulations are also focused on the safety of both ship and crew, but are more focused on an emergency situation.

- The requirements for emergency source of electrical power and the duration requirements for emergency lighting and power to certain parts of the vessel (Regulation 43, Chapter II-1) [25, 42].
- The requirements for materials and the hazards those can produce in the form of smoke and toxic products during a fire in spaces where persons work or live (Regulation Chapter II-2) [25, 44].
- It is required to have a life-jacket for every person on board. (Regulation 7 Chapter III) [25, 43].
- Every ship shall carry at least one lifeboat (Regulation 31, Chapter III) [25, 43].

When humans will be removed from ships most requirements stated in the regulations mentioned above will become useless. Except for the requirements for emergency electrical power. These are still valid for the case that the unmanned ship encounters a black-out. But the requirements for emergency lighting can be argued about since the lighting has no longer a purpose for the safety of humans. By not complying to the regulations that guard the safety of humans, money can be saved that can be invested in unmanned technology.

MARPOL Convention

The International Convention for the Prevention of Pollution from Ships, MARPOL, has no chapters specifically written for unmanned ships, as mentioned before. Therefore the convention is framed with manned ships in mind. Since crew will be removed from ships one can argue whether unmanned ships ought to comply with the convention. Annex IV of the convention, which contains the regulations for the prevention of pollution by sewage from ships, states that whether a ship ought to comply with, or not, is dependent on its size [25, 45]. However unmanned ships will not produce any sewage and therefore it is pointless to comply with Annex IV. The same holds true for Annex V which contains the regulations for the prevention of pollution by garbage from ships [25, 46]. It is stated in Annex V that all ships should comply with it, but since unmanned ships will not produce any garbage, it is again pointless to comply with Annex V.

Load Lines Convention

The Load Lines Convention, LLC, has no special regulations for unmanned ships, as mentioned before. The convention is framed with manned ships in mind and this reflected in the requirements. Regulation 25 of Chapter II states that ships should have sufficient accommodation and freeboard, and have guardrails on the superstructure and open decks to protect the crew [25, 47]. One can argue whether it is still required to comply with this regulation as the crew will be removed from the vessel when ships become unmanned.

2.1.3 Conclusion on design requirements under international law

Based on the analysis of international law, one can state that the influence of international law is limited on the change in design requirements for unmanned ships. The various legislation analyzed, mainly the SOLAS Convention and the COLREGS, make demands that need to be solved by technology. The international legislation has mainly influence when the tasks and duties of crew on-board need to be replaced by equipment. The legislation prescribes that equipment should make sure of full situational awareness by using sensors. In addition it is required to have equipment for life saving appliances in order to be able to help other manned vessels in distress. However, the most important requirement prescribed by international law is that critical and automatic systems should be redundant. Finally, there is a set of requirements set in the legislation that unmanned ships ought to comply with, but of which it is very likely that unmanned ships should not due to the absence of humans on-board. From the analysis of international law it can said that equipment that guards the full situational awareness of the vessel needs further attention. Therefore situational awareness will be analyzed further in Chapter 3.

2.2 Design requirements under the design spiral

Next to the requirements that come from international law as analyzed in Section 2.1, there are requirements that come from analyzing the design spiral. The design spiral is chosen as a tool among different analysis tools to analyze the change in design requirements, because it shows the different aspects of ship design as shown in Figure 2.3. Therefore the design spiral is a clear method to analyze the change in ship design. Another analysis tool that could be an option to analyze the change in design requirements is the v-diagram of system engineering which looks at ship design in a more abstract way. The v-diagram for system engineering is shown in Figure 2.2. However, the v-diagram for system engineering does not take into account the interactions between the different aspects of ship design in the way the design spiral does. Therefore, the design spiral will be used to analyze the change in the design requirements. The analysis will be performed in Section 2.2.1. Section 2.2.2 discusses which legislation with which the unmanned ship ought to comply, should actually be taken into account. Finally, the conclusion on the design requirements under the design spiral will be given in Section 2.2.3.

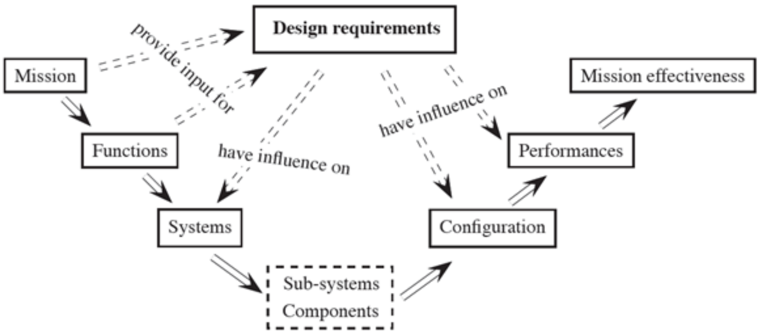


Figure 2.2: V-diagram for system engineering [48]

2.2.1 How unmanned shipping changes the design requirements

In this section it will be analyzed how the design requirements change when ships become unmanned. This is done with the help of the design spiral for merchant ships, which is given in Figure 2.3 [49]. Every step in the design spiral will be analyzed on whether the part is directly affected when ships become unmanned. This analysis answers the question if the change in ship design is caused by unmanned shipping or that the change in ship design is caused by choices made elsewhere. The parts of the design that are not directly affected by unmanned shipping will not be further analyzed. When the change in ship design is directly caused by unmanned shipping, then that part of the design will be further analyzed in this section, based on the impact unmanned shipping has on the design and the required effort to achieve reliable results. This impact and required effort will be assessed as either high or low. When the impact on ship design is high and the required effort is low or high, but low enough to be addressed adequately in the context of this thesis or when the impact on ship design is low and the required effort is low, then that part of the design will be analyzed in this thesis. When the impact on ship design is high and the required effort is too high, then that part of the design will not be treated in a scenario analysis. A summary of the requirements, which determine if further analysis of that part of the design is required in this thesis, is given in Table 2.1. In Chapter 5, a scenario analysis on cost will be performed based on a transport case. The result from this analysis will be an available budget for modifications, that need to be made to the ship in order to make unmanned shipping possible. The modifications caused by the parts of the design that have a high impact, but which require too much effort, also draw this budget. The analysis of the design requirements with the help of the design spiral is given below.

Directly affected by unmanned shipping	**Impact on ship design**	**Required effort to change part of the design**	**Further analysis required**
Yes	High	Low	Yes
Yes	Low	Low	Yes
Yes	High	High	Case sensitive
Yes	Low	High	No
No	-	-	No

Table 2.1: Summary of the requirement for analysis

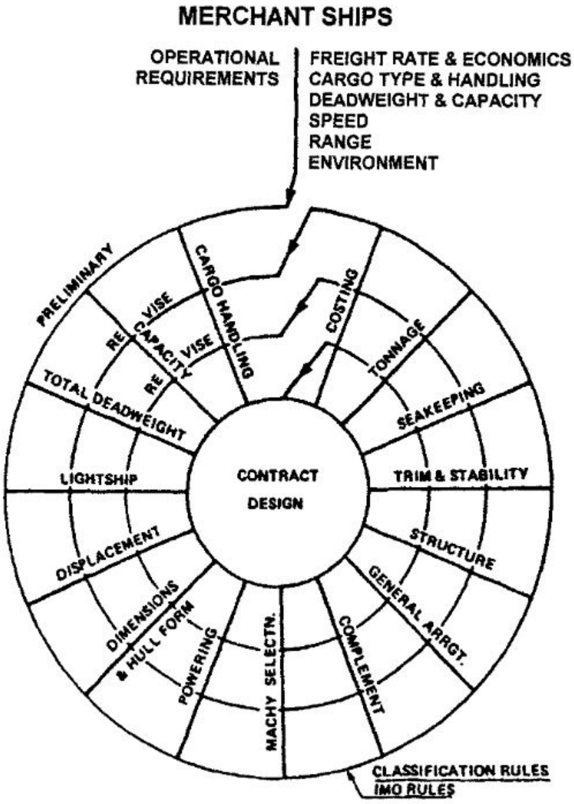


Figure 2.3: Design spiral [49]

Cargo handling

Cargo handling is highly standardized and therefore it is very unlikely that cargo handling will change due to unmanned shipping. Furthermore, cargo handling is done in port where there are other workers than the crew of the ship who can take over the duties of the crew with respect to cargo handling. Therefore, the influence of cargo handling on the design of unmanned ships will be limited.

Capacity

The capacity of the vessel is dependent on two aspects. The first is the expected amount of cargo that needs to be transported annually between two ports, the distance between the ports and the handling time in the ports. The optimal capacity for the vessel will be result of a business study performed by the future ship owner. When the first aspect is leading, the dimensions of the vessel will become smaller and the amount of cargo that needs to be transported remains the same. The second aspect that determines the capacity of the ship, is the infrastructure the ship encounters on its journey. In the case the capacity of the ship is limited by, for example, locks, the free space or weight, as a result of the removal of spaces for human presence, will be used for cargo capacity. From these two aspects one can conclude that the capacity is case dependent and therefore the capacity will not be further analyzed at this stage, but it will be given as a result in the case study in Chapter 5.

Total deadweight

The total deadweight is a measurement for the amount of mass a ship can carry. The things that make up the total deadweight are [49]:

- Cargo deadweight
- Crew and effects
- Stores of all sorts
- Fuel for main engines
- Diesel oil for generators
- Sundry tanks
- Fresh and feed water

When ships become unmanned, the crew, the fresh water, stores and a part of the diesel oil for the generators are no longer needed. These items and the cargo deadweight, which is case dependent, as has been described under capacity, are directly affected by unmanned shipping. Since these items are directly affected by unmanned shipping, one can say that the total deadweight is directly affected bu unmanned shipping. The impact of this will have on the ship design is low, as the items that make up the major part of the total deadweight, are still present. Furthermore, it will cost little effort to calculate the change in the items that make up the total deadweight. The change in the items that affect the total deadweight can be calculated with Equations 2.1 to 2.4 [50].

$$W_{DO} = SFC * MCR * (S/V_S) * 10^{-6} * margin \quad [ton] \tag{2.1}$$

In this equation is SFC the specific fuel consumption of the engines in g/kWh, MCR the maximum continuous rating of the engines in kW, S the length of the route in nautical miles and V_S the speed traveled in knots. A margin is applied to make sure that the ship has sufficient diesel oil for the journey.

$$W_{FW} = 0.17 * N_{SF} * T_{days} \quad [ton] \tag{2.2}$$

The deadweight for fresh water is dependent on the number of seafarers on-board and the number of days that is takes to make the journey. The deadweight for the stores is also dependent on these parameters, as those items are the supply for the crew.

$$W_{Store} = 0.01 * N_{SF} * T_{days} \quad [ton] \tag{2.3}$$

$$W_{C\&E} = 0.17 * N_{SF} \quad [ton] \tag{2.4}$$

The deadweight for the crew and effects is only dependent on the number of seafarers as it is the weight of the crew and their luggage.

Lightweight

The lightweight is the weight of the empty ship. When ships become unmanned the accommodation, bridge and other systems that are required for human presence can be removed from the ship. On the other hand, systems that replace the tasks and duties of the crew will need to be added, together with more redundancy in propulsion, generators, electrical systems et cetera. Removing and adding equipment will change the lightweight of the ship. It is estimated that the total lightweight will not change significantly. The removal of the accommodation and the bridge with equipment will reduce the lightweight, while adding the required additional equipment will result in extra weight. For example, replacing an engine with 6000kW power by two engines of 3000kW, thus increasing redundancy, will not double the weight, but it will be heavier than one single engine [51]. The same can be proven with Equations 2.5 to 2.7 [50] for the machinery weight.

$$W_M = W_{ME} + W_{rem} \quad [ton] \tag{2.5}$$

The machinery weight can be divided into the weight of the main engines and the weight of the remaining machinery.

$$W_{ME} = \sum_i 12.0 * (MCR_i/Ne_i)^{0.84} \quad [ton] \tag{2.6}$$

In this equation is MCR the maximum continuous rating in kW and Ne_i the engine speed in rpm. The index i is used to distinguish different engines. The weight of the remaining machinery is only dependent on the maximum continuous rating.

$$W_{rem} = 0.69 * (MCR)^{0.70} \quad [ton] \tag{2.7}$$

These equations will also be used for the generators and the equipment that replaces the tasks and duties of the crew. Removing systems that are no longer needed will result in a weight loss while requirements for additional equipment and applying redundancy will result weight gain. The true impact on ship design, due to the change in systems, will be further analyzed in the case study in Chapter 5.

Displacement

The displacement of the vessel is the direct result of both the total deadweight and the lightweight which have already been discussed. Therefore, this part of the design does not require specific research.

Dimensions

The dimensions of the ship are the result of the required displacement, block coefficient and the capacity in combination with the restrictions caused by infrastructure like port drafts, port facilities, locks and sailing area which have been discussed before. Therefore the change in dimensions will be discussed in the context of the case study in Chapter 5.

Hull form

The hull form can change if one wants to remove the ballast system, because the ballast system requires multiple pumps, which have rotating parts, and MUNIN showed that rotating equipment requires the most maintenance [26]. Most of this maintenance is done by the crew during voyages. This will not be possible when the ship becomes unmanned. Therefore, creating a hull form that does not require a ballast system would have an high impact on ship design. It would require quite some effort to design a hull form that does not need a ballast system for all loading conditions and still have a sufficient fuel efficiency [52, 53, 54]. However, there are easier ways to circumvent a failing ballast pump, like making the system redundant with an additional ballast pump.

Powering

Powering is calculating the required power for both propulsion and electrical systems by setting up a power balance. The required power for electrical systems will change as the power used by the crew can be removed from the balance, but the additional equipment required for unmanned shipping will increase the required electrical power. How this power balance will change is hard to predict as it is case dependent. Therefore it will be discussed in the context of a case study in Chapter 5. The way powering will be calculated is the same for both manned and unmanned ships and therefore one can say that the required effort is low.

Machinery selection

After the powering has been completed, the way this power is generated must be selected. As stated by MUNIN, the amount of equipment with rotating parts should be reduced as this equipment requires the most maintenance [26]. This affects the machinery selection and therefore one should look at other possibilities that need less rotating parts. In addition, one should look at the way redundancy can be built into the power system as there is nobody on-board that can do repairs when the ship is out to sea. This will have major influence on the ship design. Building the power system more redundant will require more equipment, which will result in extra cost. The required technology already exists, but how it will influence the design and the cost is uncertain. This thesis will focus on what equipment can be removed and the cost associated with that equipment in the case study in Chapter 5. Determining what equipment can be removed will require low effort as it is the equipment which is present for the crew.

Complement

The complement part of the design will by definition change significantly as it is about the crew arrangement. When ships become unmanned, will there no longer be any crew on-board. This will have large influence on the design of the ship as can be seen in the other parts of the design. Removing the crew itself from the ship does not take much effort, but it takes a lot of effort to research the design consequences of this removal. This is discussed in the other parts of the design. Therefore one can say that the influence on ship design is high and that the required effort is high too.

General arrangement

The general arrangement is the arrangement of all the systems and spaces that need to be present on the ship. When ships become unmanned, the general arrangement will change as spaces and systems that are required for human presence are no longer required and other systems that are required to sail the ship without crew need to have a space on-board. These changes in spaces and equipment will significantly change the general arrangement plan. Although the general arrangement will change when ships become unmanned, the process of setting up the general arrangement will not change. Therefore the required effort to change this part of the design will be low as will be addressed in Chapter 5.

Structure

The primary objective of the structural design is to design a structure that will withstand all the forces acting on it. The most important forces are the bending moments and the shear forces which stem from the waves which the ship encounters and the loading by the cargo carried [49]. This will be the same for both the manned and the unmanned ship. The building material and building method are not likely to change when ships become unmanned [1]. Therefore one can conclude that the structure is not directly affected by unmanned shipping.

Trim and stability

The trim and stability of the vessel are mainly determined by the main dimensions and the way the vessel is loaded. The trim and stability is roughly equal for both manned and unmanned ship and therefore does this part of the design not require an in-depth study at this stage. The actual trim and stability of a specific unmanned ship will be discussed in the case study in Chapter 5.

Seakeeping

The seakeeping of vessel includes the motions and the accelerations of the vessel acting on both crew and cargo. These accelerations can cause people to get seasick and cargo to fall overboard. The motions and accelerations are determined by the main dimensions, hull shape, cargo, lightship, sea state and the center of gravity of the vessel. If the limit in accelerations is determined by the crew on board, then the limit in accelerations can change. In order to determine if the limit in accelerations is limited by the crew, the next approach is used. First the roll period of a large heavy lift vessel with a large beam and without cargo was calculated. The calculation showed that the roll period was very short, which means high accelerations for the crew. Then a ship owner, Holwerda Shipmanagement B.V., was interviewed to understand if the accelerations that are expected during the voyage have any influence on the way the vessel is loaded. From this interview it became clear that the loading capacity of the vessel is limited by the minimum stability and not by accelerations. A low stability means a long period which results in low accelerations. Therefore one can conclude that the limit in accelerations is determined by the cargo and not by the crew. Since the cargo will remain on-board, the limit in accelerations will likely be similar and therefore seakeeping does not require an in-depth study at this stage. The seakeeping of a specific unmanned ship will be discussed in the case study in Chapter 5.

Tonnage

The tonnage is a direct result of dimensions and is calculated with a fixed formula based on the total volume of the enclosed spaces. The result of this calculation forms the basis for manning regulations, safety rules, registration fees and port fees. Since the result of the calculation is the direct result of choices made earlier in the design process, this part does not require specific research. The tonnage of a specific unmanned ship will be discussed in the case study in Chapter 5.

Costing

The costing of a ship are all the costs that need to be made in order to have a ship and sail it over the oceans. This includes both building cost and operational cost. For an unmanned ship, the costing will be significantly different than for a manned ship as unmanned ships require extra equipment that fulfills the tasks and duties of crew. On the other hand, can some equipment be removed from the ship saving money, just as the crew will be removed, thus saving loans. It is the goal of this thesis to quantify the cost for the unmanned ship and compare those to manned ship. This quantification will be performed in a case study in Chapter 5 for a specific ship. The principles that can be used for determining the cost are the same, only the result will be different and therefore the required effort will be low. Furthermore, costing itself not have an influence on the design of the ship, but it is clear that costing is directly affected by unmanned shipping as the change in costing is the consequence of changes in the design. Since it is clear that costing will significantly change when ships become unmanned, the impact is set to high.

Part of design	Directly affected by unmanned shipping	Impact on ship design	Required effort to change part of design
Cargo handling	No	-	-
Capacity	No	-	-
Total deadweight	Yes	Low	Low
Lightweight	Yes	High	Medium high
Displacement	No	-	-
Dimensions	No	-	-
Hull form	Yes	High	High
Powering	Yes	High	Low
Machinery selection	Yes	High	Low
Complement	Yes	High	High
General arrangement	Yes	High	Low
Structure	No	-	-
Trim and stability	No	-	-
Seakeeping	No	-	-
Tonnage	No	-	-
Costing	Yes	High	Low

Table 2.2: Analysis of the design requirements for the design spiral

Summary

The summarized results of the analysis made in this paragraph can be seen in Table 2.2. Whether a part of the design should be further analyzed will be determined on the basis of the requirements as set in Table 2.1. In the cases that a part of the design will not be further analyzed in this thesis, analysis on that part will be left as a recommendation for further research. The parts that will be further analyzed are: total deadweight, lightweight, powering, machinery selection, general arrangement and costing. These items, except for Costing, will be further analyzed in Chapter 3. Costing will be further analyzed in Chapter 4

2.2.2 International law that is a hindrance to the design of the unmanned ship

The three conventions of which it was shown that they could be of any hindrance to the design of the unmanned ship are the SOLAS Convention, MARPOL Convention and the Load Lines Convention, see Section 2.1.2. These conventions will be analyzed below on whether these conventions are a true hindrance to the design of the unmanned ship.

SOLAS Convention

The unmanned ship must, as stated in Section 2.1 comply with the SOLAS Convention. Every cargo ship must according to Chapter I, Regulation 12 have a Cargo Ship Safety Construction Certificate and a Cargo Ship Safety Equipment Certificate. Those certificates are issued when there is satisfactory compliance with Chapters II-1, II-2, III and IV of the convention. Section 2.1.1 showed to which requirements the unmanned ship must comply and Section 2.1.2 showed to which requirements the unmanned ship should comply. As shown in Section 2.1.2 it can be hard to comply with the requirements as stated in the SOLAS Convention. However Regulation 4 permits the Administration to exempt any ship which embodies features of a novel kind from any of the provisions of chapters II-1, II-2, III and IV of the SOLAS Convention [25, 41]. This allows for a discussion with the Administration on which regulations the unmanned ship should truly comply. Since it is not the goal of this thesis to find an answer to the legal issues concerned with unmanned ships and there is a possibility to ask for exemptions at the Administration, it is concluded that the regulations of the SOLAS Conventions that could be of any hindrance are not a true hindrance to the design of the unmanned ship.

MARPOL Convention

The MARPOL Convention, as stated in Section 2.1, is on of the conventions the unmanned ship must comply with. Although the convention has no regulations that directly affect the design of the unmanned ship, it has two annexes that could be of hindrance to the design of the unmanned ship as stated in Section 2.1.2. These annexes contain the regulations for the prevention of pollution by sewage and garbage. When ships become unmanned, sewage and garbage are no longer produced on the vessel and therefore not present. Therefore, the sewage and garbage systems on the vessel can be removed, but this is not allowed by the MARPOL Convention as it states no exemptions. One could conclude that the MARPOL Conventions is a true hindrance to the design of the unmanned ship, but one could also come up with a smart solution. Design the unmanned vessel with a sewage and garbage system that has a capacity of zero. In this way ones complies to the convention and at the same time no space is lost to unnecessary systems.

Load Lines Convention

Unmanned ships must, as stated in Section 2.1, comply with the Load Lines Convention. Although there are no regulations specifically written for unmanned ships, there are regulations to which the unmanned ship should comply but of which it can be argued that the unmanned ship truly should. This is set out in Section 2.1.2. Here it is stated that according to Regulation 25 of the convention every ship should have sufficient accommodation and freeboard. Since the accommodation will be removed when the ship is specially designed for unmanned shipping, the ship is no longer complying to the Load Lines Convention. Therefore Regulation 25 could be a hindrance to the design of the unmanned ship. However Regulation 6 of the Load Lines Convention permits the Administration to exempt any ship which embodies features of a novel kind from any of the provisions the Load Lines Convention states as long as the safety of the ship is ensured. Removing the accommodation of the ship will not endanger the safety of the ship and therefore Regulation 25 is not a true hindrance to the design of the unmanned ship.

2.2.3 Conclusion on design requirements under the design spiral

Conclusively, it can be stated that the influence of unmanned shipping on the requirements for the ship is significant, because the design changes for a large part when ships become unmanned. The impact on ship design is high and it often requires low to medium high effort to change a part of the design. These parts, which will be further analyzed in this thesis are: total deadweight, lightweight, powering, machinery selection, general arrangement and costing. Furthermore, the international law that could be of any hindrance for the design of unmanned ships has been further analyzed in this section. From this analysis it can be concluded that the legislation, in combination with the results from the analysis of the design spiral, will not be of any hindrance to the design of the unmanned ship, because international law allows for exemptions as long the safety of the vessel is guarded.

2.3 Conclusion

It is the goal of this chapter to find the answer to the question: "What is the influence of unmanned shipping on the design of a ship?" as set out in Section 1.3. This has been done by analyzing the influence of international law and the design spiral on the design requirements for the unmanned ship.

Based on the analysis of international law one can conclude that the influence of international law is limited on the change in design requirements for unmanned ships, because of all the various legislation analyzed, only the SOLAS Convention and the COLREGS make demands that need to be solved by technology. The analysis shows that international law has mainly influence when the tasks and duties of the crew on-board need to be replaced by equipment. It is prescribed in the legislation that the equipment should make sure of full situational awareness. In addition, it is required to have equipment for life saving appliances in order to be able to help other manned vessels in distress, but it can be argued that unmanned ships should be discarded from this obligation. However the most important requirement prescribed by international law is that critical and automatic systems should be redundant. Furthermore, there is a set of requirements in the legislation that unmanned ships ought to comply with, but of which it is very likely that unmanned ships should not, due to the absence of humans on-board. From the analysis on international legislation it can be concluded that systems and parts of the vessel that are required to facilitate human presence on-board and equipment that guards the full situational awareness of the vessel both need to be further analyzed.

From the analysis on the design spiral it can be concluded that the influence design requirements for the unmanned ship is significant because the design changes for a large part for unmanned ships. The impact on ship design is generally high in these parts of the design and it mostly requires low to medium high effort to change those part of the design. From the analysis of the design spiral it can be concluded that the part that need to be further analyzed are: total deadweight, lightweight, powering, machinery selection, general arrangement and costing. Furthermore, the international law that could be of any hindrance for the design of the unmanned ship has been further analyzed with respect to the design spiral. From this analysis it can be concluded that the legislation will not be of any hindrance to the design of the unmanned ship, because international law allows for exemptions as long the vessel is still concerned to be safe.

Chapter 3

Design model

In Chapter 2 it has been concluded that next to costing, which will be further analyzed in Chapter 4, total deadweight, lightweight, powering, machinery selection, situational awareness and general arrangement require further analysis. How these are influenced by unmanned shipping will be determined with the help of a design model. The results from the design model will be the input for the cost analysis and a specific case in the case study as can be seen in Figure 3.1. First will be analyzed in Section 3.1 what can be removed from the ship at the user side. This will be quantified with the help of a parametric study in order to estimate the change in lightweight, machinery selection and powering, which in its turn influences the total deadweight. The results from this analysis will be the input for what can be removed from the vessel at the power supplier and how that influences the fuel consumption, which will be determined in Section 3.2. In Section 3.4 it will be determined what equipment should be added to make unmanned shipping possible and to guarantee sufficient situational awareness. Finally a conclusion to the chapter will be given in Section 3.5. The structure of this chapter is shown in Figure 3.2. Since the required situational awareness equipment will not be determined in this thesis for different sized ships, the situational awareness equipment is dotted to the design model in Figure 3.2.

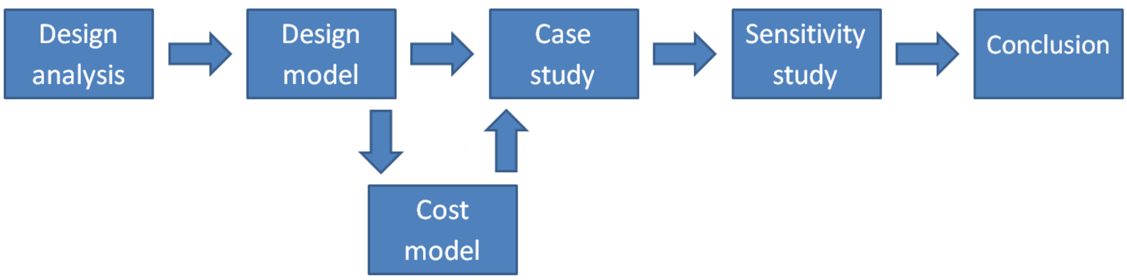


Figure 3.1: Position of the design model in the total thesis

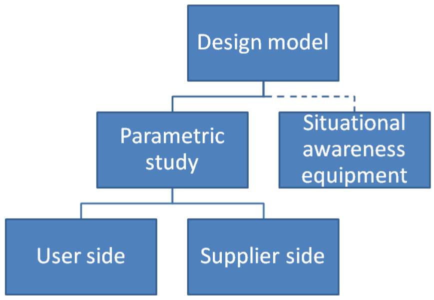


Figure 3.2: Structure of the design model

3.1 Removed user equipment

In this section it is analyzed what parts of the ship can be removed when the ship becomes unmanned with the help of the Uniform Administration for Shipbuilding. This breakdown structure of the ship is provided in Appendix A. The result of the analysis of the Uniform Administration for Shipbuilding is a new breakdown structure which contains all the systems on a ship that are present to support life on-board. This breakdown structure for life support is shown in Figure 3.3. The codes in this breakdown structure refer to the codes used in the Uniform Administration for Shipbuilding. The breakdown structure for life support will be used as a basis for a parametric study on the change in lightweight and power use in this section. In Section 3.1.1 the hull and outfitting will be discussed. Then Section 3.1.2 will look at the primary ship systems, followed by the electrical systems in Section 3.1.3. Then the deck equipment will be discussed in Section 3.1.4 and then the secondary ship systems in Section 3.1.5. The joinery and arrangement of the accommodation will be discussed in Section 3.1.6 followed by the nautical, navigation and communication equipment which will be discussed in Section 3.1.7. Finally the parametric study will be compared for different sizes of ships in Section 3.3.

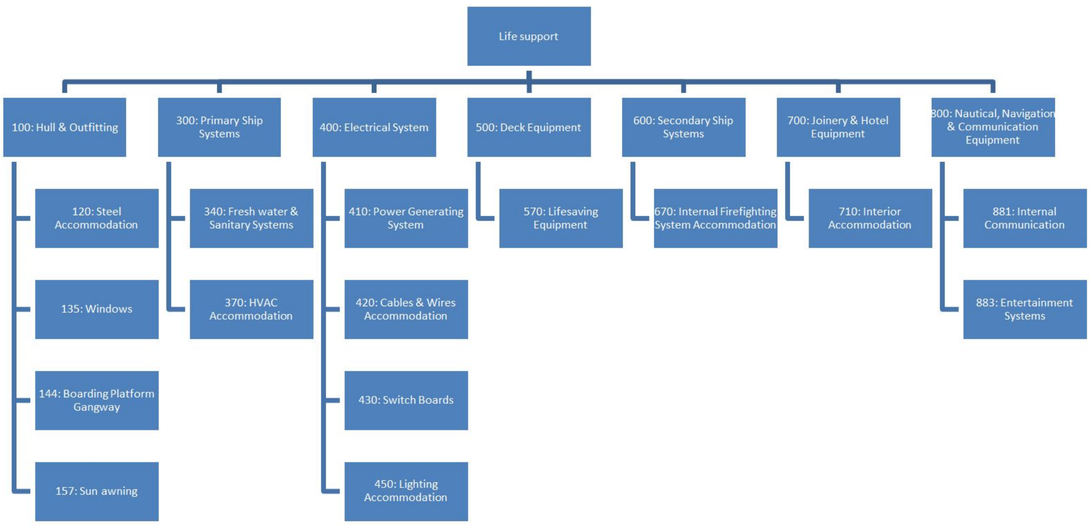


Figure 3.3: Breakdown structure for life support

3.1.1 Hull and outfitting

The items that make up the hull and outfitting are the steel of the accommodation, the windows, the boarding platform gangway and the sun awnings. These items will be analyzed in Sections 3.1.1.1 to 3.1.1.4.

3.1.1.1 Steel of the accommodation

Removing the steel of the accommodation will affect the lightweight of the ship. The structural weight for the accommodation can be estimated with the unit area weights of all surfaces of the accommodation. For the front of the accommodation one can take 0.10 ton/m², for accommodation sides, top and back 0.08 ton/m² and for decks inside the accommodation 0.05 ton/m² [50]. Applying the discussed numbers, the structural weight of the accommodation of can be estimated with Equation 3.1 [50].

$$W_{dh} = 0.18 \cdot b \cdot h_j + b \cdot l \cdot (0.05 \cdot N_{Deck} + 0.08) + 0.16 \cdot h_j \cdot l \quad [ton] \tag{3.1}$$

In this equation is b the breadth of the accommodation in meter, l the length of the accommodation in meter, h_j the height of the accommodation above deck and N_{Deck} the number of decks in the accommodation. Based on this and the particulars of the accommodations of a containerfeeder and a large ocean liner container vessel, which are given in Table 3.1, the structural weight of an accommodation could weigh 60 ton on a containerfeeder and 500 ton on a large ocean liner container vessel. The steel weight has no influence on the use of electrical power.

	Containerfeeder	**Ocean liner container vessel**
l [m]	8.1	15.8
b [m]	10.4	34.4
h_j [m]	11	30.4
h_{Acco} [m]	13.3	30.4
N_{Deck} [-]	5	8
N_{Crew} [-]	10	34

Table 3.1: Particulars accommodations [55] [p39;p47]

3.1.1.2 Windows

To determine the effect of windows on the lightweight of the ship, the following approach is used: the weight of the windows is dependent on the number of windows and the size of each window. Since this is still uncertain in the early design stage, the surface of windows of different ships has been determined with the help of the general arrangement plan of these ships. Since it was unknown what the exact weight of the windows is for those ships, it is assumed that the ships have 2 cm thick glass with a steel strip along the edges. Based on the density of glass and steel and the required steel for the strip, it is estimated that weight of the windows is 0.1 ton/m² of window surface. When one applies this number to various accommodations, one finds that the weight for windows is approximately 3%

of the steel weight for the accommodation. The weight for windows will be about 2 ton on a containerfeeder and 15 ton on a large ocean liner containervessel.

3.1.1.3 Boarding platform gangway

It is very uncertain if the boarding platform for the gangway can truly be removed from the ship when ships become unmanned, as the platform might be required when people need to be on-board to do repairs or maintenance work. When the platform will be removed from the ship, one assumes that human presence is never required on-board the ship. Since it is unlikely that this will be the case, the boarding platform gangway will be left out of the parametric study.

3.1.1.4 Sun awnings

The number of sun awnings is dependent on the number of windows present on the ship. The weight for the sun awnings will be low compared to other weights. Therefore the influence of sun awnings will not be taken into account in determining the lightweight. Furthermore,sun awnings have no influence on the used power and the fuel consumption. Therefore, the parametric study on sun awnings will be canceled.

3.1.2 Primary ship systems

The items that are affected by unmanned shipping and that make up the primary ship systems are the fresh water and sanitary systems and the HVAC of the accommodation. These items will be analyzed in Section 3.1.2.1 and Section 3.1.2.2.

3.1.2.1 Fresh water and sanitary systems

Among the ship systems that are present on ships to support life are the fresh water and sanitary systems. However, these systems can also be removed when ships become unmanned. Therefore the weight reduction and power consumption of these systems will be estimated. First the total length and the diameter of the piping will be estimated with the help of a piping lay-out, resulting in a weight for piping. This piping lay-out will then be used to determine the required power for the pump. However, total piping length is dependent on the arrangement of the accommodation, which is unknown in early ship design. Therefore, assumptions on the number of users per deck and the size of the pipes at the user side will be assumed for this calculation. It will be assumed that each user requires a hot and a cold water supply and one combined sewage pipe. Based on personal experience, the nominal diameter of the piping for supply will be 0.5 inch at the user end and the pressure at the end will be 2 bar. This equals the situation as present in homes [56]. Per supply the following approach is used: the piping to the end user is called the subpipes. The subpipes for one deck are connected to a larger pipe which is called the main pipe. The main pipes from different decks are connected to a larger pipes which connects the different decks. A conceptional drawing of this principle is shown in Figure 3.4. When one applies this principle to multiple decks and a larger accommodation, the piping per supply will look like as shown in Figure 3.5. Since it is unlikely that all users will request water at the same time, but that is possible that different users at the same floor request for water, the ratio as defined in Equation 3.2 is used. The ratio is based on the piping in flats.

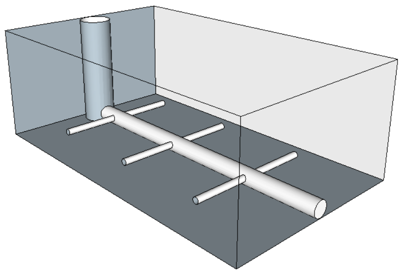


Figure 3.4: Single deck block

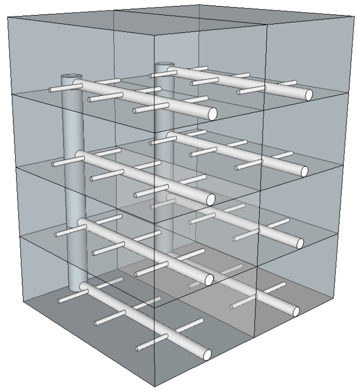


Figure 3.5: Multiple deck blocks

$$1.5 \cdot \sum A_{Pipe,vert,supply} = \sum A_{Pipe,main,supply} = \sum A_{Pipe,sub,supply} \quad [mm^2] \tag{3.2}$$

With the given ratio as defined in Equation 3.2, the nominal diameter of piping for the subpipes and the assumption that the speed is equal in all pipes, one can calculate the nominal diameter of the main pipes for each deck with Equation 3.3. This diameter is required to determine the specific weight of the pipe.

$$d_{Pipe,main,supply} = \sqrt{N_{Pipe,sub,supply} \cdot d_{Pipe,sub,supply}{}^{2}} \quad [mm] \tag{3.3}$$

with

$$N_{Pipe,sub,supply} = N_{User} \quad [-] \tag{3.4}$$

In Equation 3.3 is $d_{Pipe,main,supply}$ the diameter of the main supply pipe, $d_{Pipe,sub,supply}$ the diameter of the subpipe for supply that goes to the user and $N_{Pipe,sub,supply}$ the number of subpipes that equal the number of users, N_{User}, as defined in Equation 3.4. In a similar way one can calculate the diameter of the vertical pipes for supply with Equation 3.5.

$$d_{Pipe,vert,supply} = \sqrt{\frac{N_{Deck} \cdot d_{Pipe,main,supply}{}^{2}}{1.5}} \quad [mm] \tag{3.5}$$

with

$$N_{Pipe,main,supply} = N_{Pipe,vert,supply} = round\left(\frac{l}{6}\right) \quad [-] \tag{3.6}$$

In Equation 3.5 is $d_{Pipe,vert,supply}$ the diameter of the vertical supply pipe, $d_{Pipe,main,supply}$ the diameter of the main supply pipe and N_{Deck} the number of decks. It will be assumed that there will be one main supply pipe for every 6 meters of length for the accommodation which is connected to a vertical pipe that connects the different decks, as defined in Equation 3.6. Since the diameter of the different supply pipes is known, one can determine the specific weight of these pipes in Table 3.2 [57]. Before one can calculate the weight for piping per supply, the total length of piping for the different types of piping per deck should be determined. It is assumed that it will take on average 8 meter of subpipe to get from the main pipe to the user because the subpipe has to follow the internal walls in the accommodation and will enter the cabin at a position close to the hallway while the user might be at the other side of the cabin. Furthermore is it assumed that each main pipe will run over the entire breadth of the accommodation. The users of the water will be close to the floor of each deck and therefore the pipes will also run close to the floor. This will result in the length of the vertical supply pipes being shorter than the height of the accommodation. Furthermore, every vertical supply pipe connects one set of main pipes. Applying these assumptions, the length of the different types of pipe can be calculated with Equation 3.7 to Equation 3.9.

$$L_{Pipe,sub,supply} = 8 \cdot N_{Pipe,sub,supply} \quad [m] \tag{3.7}$$

$$L_{Pipe,main,supply} = N_{Pipe,main,supply} \cdot b \quad [m] \tag{3.8}$$

$$L_{Pipe,vert,supply} = \frac{N_{Deck} - 1}{N_{Deck}} \cdot h_{Acco} \cdot N_{Pipe,vert,supply} \quad [m] \tag{3.9}$$

The weight of the piping for the fresh water supply can now be calculated with Equation 3.10. In this equation is N_{Deck} the number of decks in the accommodation, are $W_{Piping,main,supply}$, $W_{Piping,sub,supply}$, $W_{Piping,vert,supply}$ the total weight of piping in kg for the different types of pipe which can be calculated with Equations 3.11 to 3.13 which are dependent on the total length of pipe per deck and the specific weight of the pipe which can be can be found in Table 3.2 [57]. As mentioned before, every user will have one hot supply and one cold supply of fresh water. Therefore the piping must be doubled and this is accounted for in Equation 3.10 by multiplying by two.

$$\begin{aligned} W_{Piping,Fresh,supply} \quad = \quad & \frac{2}{1000} \cdot (N_{Deck} \cdot (W_{Piping,main,supply} + \\ & W_{Piping,sub,supply}) + W_{Piping,vert,supply}) \quad [ton] \end{aligned} \tag{3.10}$$

with

$$W_{Piping,main,supply} = L_{Pipe,main,supply} \cdot w_{Pipe,main,supply} \quad [kg] \tag{3.11}$$

$$W_{Piping,sub,supply} = L_{Pipe,sub,supply} \cdot w_{Pipe,sub,supply} \quad [kg] \tag{3.12}$$

$$W_{Piping,vert,supply} = L_{Pipe,vert,supply} \cdot w_{Pipe,vert,supply} \quad [kg] \tag{3.13}$$

Once the water has been provided to the user, it is returned to the sewage tank on manned ships. However this return also requires some piping. For the return piping the same principle as shown in Figure 3.4 and Figure 3.5 will be used and it is assumed that the disposable water from sinks, toilets and other water using equipment in the accommodation is combined and that the diameter of this pipe does not change in diameter further from the user. Since the distance to the user is equal to the distance from the user, one can say that the total length of subpipes for the return equals approximately the total length of subpipes for the return. The same holds true for the main pipes and the vertical pipes and is mathematically shown in Equations 3.14 to 3.16.

$$L_{Pipe,sub,return} = L_{Pipe,sub,supply} \quad [m] \tag{3.14}$$

$$L_{Pipe,main,return} = L_{Pipe,main,supply} \quad [m] \tag{3.15}$$

$$L_{Pipe,vert,return} = L_{Pipe,vert,supply} \quad [m] \tag{3.16}$$

Since the diameter will not change over distance for the return pipe, the specific weight of the different sections will remain equal. This is mathematically shown in Equation 3.17. For the return pipe it is assumed that the nominal diameter is 5 inch. This is approximately the diameter of the sewage piping in houses used too. The specific weight for this pipe can again be found in Table 3.2 [57]. By rewriting Equation 3.10, the weight for the return piping can be estimated with Equation 3.18.

$$w_{Pipe,sub,return} = w_{Pipe,main,return} = w_{Pipe,vert,return} = w_{Pipe,fresh,return} \quad [kg/m] \tag{3.17}$$

$$\begin{aligned} W_{Piping,Fresh,return} = & \frac{w_{Pipe,fresh,return}}{1000} \cdot (N_{Deck} \cdot (L_{Pipe,main,return} + \\ & L_{Pipe,sub,return}) + L_{Pipe,vert,return}) \quad [ton] \end{aligned} \tag{3.18}$$

The total weight for piping for the fresh water system varies between 10 ton for a containerfeeder and 55 ton for a ocean liner container vessel. This includes a margin of 40% of the fresh water piping weight for flanges and brackets.

d_{Nominal} [inch]	d [mm]	w [kg/m]
0.5	15.7	1.27
0.75	20.9	1.68
1	26.6	2.50
1.5	40.9	4.05
2	52.5	5.44
3	77.9	11.30
4	102.3	16.10
5	128.1	21.80
6	154.1	28.30
8	202.7	42.50
10	254.4	60.30
12	304.9	73.80
14	336.6	81.30
16	387.4	93.30
20	489.0	117.00

Table 3.2: Sizes and weight of piping for fresh water and sanitary systems [57]

The power consumption and weight of the pump are dependent on the volumeflow and the head increase of the pump [58]. Since the calculation of the head increase and the pump power is very basic, the calculation is given in Appendix B. Then a pump is chosen based on the head increase and the volumeflow trough the pump. Since this is very case dependent, the weight of the pump is also very case dependent. Therefore will there be a pump chosen for this thesis that is in general sufficient for pumping fresh water to the different users in the accommodation. The pump is a Wärtsilä Hamworthy centrifugal pump of model CM with a capacity between 5 and 40 m^3/h and a head increase over the pump between 10 and 50 mlc, meter liquid column [58]. The capacity range is shown in Figure 3.6 [58]. The weight of the pump is approximately 260 kg [58]. Since one pump for the cold supply and one pump for the hot supply is needed, the total weight of pumps, $W_{fresh,pump}$, is approximately 520 kg. The total weight of the fresh water and sanitary system can be calculated with Equation 3.19.

$$W_{fresh} = W_{Piping,Fresh,supply} + W_{Piping,Fresh,return} + W_{fresh,pump} \quad [ton] \tag{3.19}$$

The weight of the fresh water and sanitary systems will be about 10 ton for a containerfeeder and 55 ton for a large ocean liner container vessel. Furthermore, the required power for the fresh water and sanitary system will be about 6 kW for a containerfeeder and 8 kW for a large ocean liner container vessel.

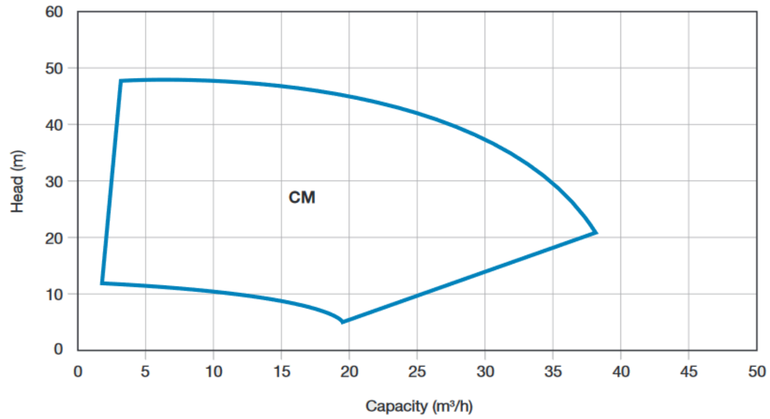


Figure 3.6: Capacity range of Wärtsilä Hamworthy centrifugal pump model CM [58]

3.1.2.2 HVAC accommodation

HVAC stands for heating, ventilation and air conditioning. This thesis will only look at the HVAC in the accommodation, as the HVAC that is installed elsewhere in the ship cannot be removed when the ship is made unmanned, as it is needed in the case of maintenance or repairs in the engine room. For the design of HVAC systems in the accommodation, the norm ISO7547 is used [59]. This norm puts out the design condition as shown in Table 3.3. The result from applying the norm is the number of air changes per hour the HVAC system has to perform in order to maintain the design condition for a given caseload. However, from experience it is known at RH Marine that 10 air changes per hour are sufficient for the accommodation and therefore this number will be used in this thesis. Taking 10 air changes per hour is a conservative approach as the result from the norm ISO7547 is in general lower. Of the defined volumeflow, 40% is fresh air from outside and 60% is reused air from the accommodation [59]. A schematic representation of the system is shown in Figure 3.7.

	Winter	**Summer**
$T_{Outdoor}$ [°C]	-20	35
$\phi_{Outdoor}$ [%]		70
T_{Indoor} [°C]	22	27
ϕ_{Indoor} [%]		50

Table 3.3: Design conditions HVAC [59]

$$\dot{V} = 10 \cdot V_{Acco} \quad [m^3/\mathrm{h}] \tag{3.20}$$

Based on the design conditions shown in Table 3.3 and the experience of RH Marine with HVAC systems, a distinction will be made between the winter and the summer calculation of the required power and the associated parameters of air [59]. The formulas that will used are equal, but sometimes need to be rewritten to find the required parameter. The formulas used in this calculation form the basis of the Mollier diagram [60]. The Mollier diagram is shown in Appendix D. First the winter condition will be explained and then the summer condition.

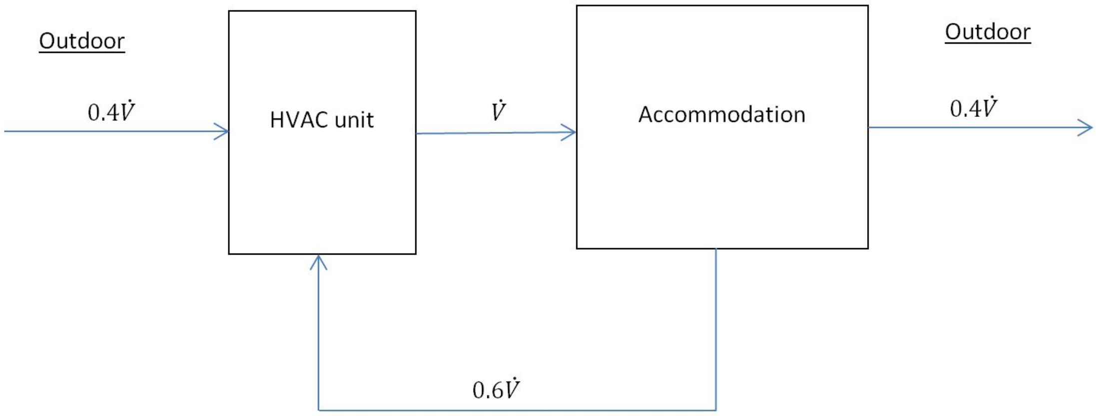


Figure 3.7: Schematic respresentation of the HVAC system

Winter The winter condition is different from the summer condition, as defined in Table 3.3, as the summer condition sets limits on the relative humidity while the winter condition does not. First the size of the volumeflow of both the outdoor flow and the indoor flow from the accommodation needs to be determined. 40% of the volumeflow will be fresh air from outside and 60% will be reused air from the accommodation [59]. Since the temperature is different for both of these flows, the density of the flow has to be taken into account. The density of the air in both flows can be calculated with Equation 3.21. In this equation is p the atmospheric pressure of 101325 Pa, R the specific gas constant for dry air of 287.058 J/kgK and T_{Air} the air temperature in Kelvin. The density of the two flows is required to calculate the massflow of the two flows. This can be done with Equation 3.22.

$$\rho = \frac{p}{R \cdot T_{Air}} \quad [kg/m^3] \tag{3.21}$$

$$\dot{m} = \rho \cdot \dot{V} \quad [kg/h] \tag{3.22}$$

Then the two flows can be mixed according to the ratio in massflow, resulting in a mixture with one new temperature. The temperature of the mixture can be calculated with Equation 3.23. In winter, the temperature of the air blown into the accommodation will needs to be higher than 22 °C. This based on experience at RH Marine and temperature losses during transport of the air. The required air temperature after the HVAC system is 30 °C according to RH Marine. This is higher than the temperature of the mixture according to the design conditions and therefore the air of the mixture needs to be heated to 30 °C. This will require power which can be calculated with Equation 3.24 [61]. In this equation $\dot{m}$ is the total massflow in kg/h and h the enthalpy of respectively the mixture and the flow that goes to the accommodation in kJ/kg.

$$T_{Mixture} = \frac{\dot{m}_{Indoor} \cdot T_{Indoor} + \dot{m}_{Outdoor} \cdot T_{Outdoor}}{\dot{m}_{Indoor} + \dot{m}_{Outdoor}} \quad [C] \tag{3.23}$$

$$P_{HVAC,heat} = \frac{\dot{m}}{3600} \cdot (h_{Room} - h_{Mixture}) \quad [kW] \tag{3.24}$$

The enthalpy of non saturated air can be calculated with Equation 3.25. In this equation $c_{p,a}$ is the specific heat at constant pressure of dry air, which is 1.004 kJ/kgK, θ the air temperature in °C, x the humidity ratio in kg/kg, r_w the evaporation heat of water which is 2,500 kJ/kg and $c_{p,v}$ the specific heat at constant pressure of water vapor which is 1.83 kJ/kgK [62]. However the humidity ratio will not change in the winter condition as the air will not be humidified before it is blown into the room. Therefore, the humidity is left open in the design conditions in Table 3.3.

$$h = c_{p,a} \cdot \theta + x \cdot (r_w + c_{p,v} \cdot \theta) \quad [kJ/kg] \tag{3.25}$$

When one sticks to the design conditions prescribed by the norm ISO7547, the temperatures of the flows are fixed which result in fixed densities and fixed enthalpies. The number of air changes is a chosen constant which results in the massflow being dependent on the volume of the accommodation. Since the enthalpies are fixed, the required power to fulfill the requirements of the design conditions is dependent on the volume of the accommodation. Applying these fixed numbers to the different formulas results in a power requirement of 94.3 W/m^3. This can also be seen in the rewritten formula for power heat exchange which is given in Equation 3.26.

$$P_{HVAC,heat} = 9.43 \cdot 10^{-2} \cdot V_{Acco} \quad [kW] \tag{3.26}$$

The power consumption of the HVAC system for the winter condition is about 110 kW for a containerfeeder and 1,600 kW for a large ocean liner container vessel.

Summer The summer condition takes, differently from the winter condition, the relative humidity into account as can be seen in Table 3.3. The first steps of the process are equal to the winter condition. First, the the size of the volumeflow of both the outdoor flow and the indoor flow from the accommodation need to be determined. Based on experience of experts at RH Marine, the number of air changes per hour will be fixed and set to 10 air changes per hour. 40% of the total volumeflow will be drawn from outside and 60% from the accommodation. Since the two flows have a different temperature, the density of the flow has to be taken into account. The density of the flows can be calculated with Equation 3.21. Then one can calculate the massflow of both flows with Equation 3.22. This can then be followed by the calculation of the enthalpies for both of the flows. The enthalpy can be calculated with Equation 3.25. However the humidity ration in this equation is not zero for the summer condition. The humidity ration can be calculated with Equation 3.27 [62].

$$x = 0.622 \cdot \frac{\phi \cdot p_{sat}}{p - \phi \cdot p_{sat}} \quad [kg/kg] \tag{3.27}$$

In this equation p is the athmospheric pressure in bar, ϕ the relative humidity as a number between 0 and 1, and p_{sat} the saturated vapor pressure in bar. The saturated vapor pressure is dependent on temperature and given in steam tables. The saturated vapor pressure of water as a function of temperature is shown in Appendix E [61]. For the calculation of the saturated vapor pressure of temperatures between the data points, linear interpolation is used.

Then one can mix the two flows according to the ratio in massflow, resulting in a mixture with new temperature, humidity ratio and enthalpy. The temperature of the mixture can be calculated with Equation 3.23, the humidity ratio with Equation 3.28 and the enthalpy of the mixture with Equation 3.29. The relative humidity does not change to the ratio of the massflow, but can be calculated with Equation 3.30. In summer, the temperature of the air after the HVAC system should be 14°C and have a relative humidity of 90% based on experience at RH Marine. This is lower than the temperature of the mixture according to the design conditions and therefore the air of the mixture needs to be cooled to 14°C. This will require power and the amount of power can be calculated with Equation 3.24 [61]. However, cooling is done with the help of a coolant and therefore one should take into account the coefficient of performance, COP. This coefficient results in a lower electrical power requirement for the same HVAC power requirement.

$$x_{Mixture} = \frac{\dot{m}_{Indoor} \cdot x_{Indoor} + \dot{m}_{Outdoor} \cdot x_{Outdoor}}{\dot{m}_{Indoor} + \dot{m}_{Outdoor}} \quad [kg/kg] \tag{3.28}$$

$$h_{Mixture} = \frac{\dot{m}_{Indoor} \cdot h_{Indoor} + \dot{m}_{Outdoor} \cdot h_{Outdoor}}{\dot{m}_{Indoor} + \dot{m}_{Outdoor}} \quad [kJ/kg] \tag{3.29}$$

$$\phi = \frac{x}{x + 0.622} \cdot \frac{p}{p_{sat}} \quad [-] \tag{3.30}$$

When one follows the design conditions prescribed by the norm ISO7547, the temperatures of the flows are fixed which result in fixed densities, humidity ratios, relative humidity and fixed enthalpies. The number of air changes is a chosen constant based on experience, which results in that the mass flow being dependent on the volume of the accommodation. Since the enthalpies are fixed, the required power to fulfill the requirements of the design conditions is dependent on the volume of the accommodation. Applying this fixed numbers to the different formulas and setting the Coefficient of Performance to 5, results in a power requirement of 22.4 W/m^3 [63]. This can also be seen in the rewritten formula for power which is given in Equation 3.31.

$$P_{HVAC,heat} = 2.24 \cdot 10^{-2} \cdot V_{Acco} \quad [kW] \tag{3.31}$$

The required power can now be calculated for different conditions. The power consumption in the summer condition is about 25 kW for a containerfeeder and 370 kW for a large ocean liner container vessel. The equipment that consumes the power has a certain weight that can be removed when ships become unmanned. The weight for the HVAC can be calculated with Equation 3.32. In this equation is W_{AC} the weight of the air-conditioning unit, W_{CM} the weight of the cooling machine with the coolant, $W_{Piping,HVAC}$ the weight of the piping in the accommodation for the HVAC system and $W_{Fan,HVAC}$ the weight of the fan in the system that moves the air.

$$W_{HVAC} = W_{AC} + W_{CM} + W_{Piping,HVAC} + W_{Fan,HVAC} \quad [ton] \tag{3.32}$$

The weight of the air-conditioning unit is analyzed in Figure 3.8 as a function of volumeflow [64]. The result of this analysis is an estimation of the weight of the air-conditioning unit which is given in Equation 3.33.

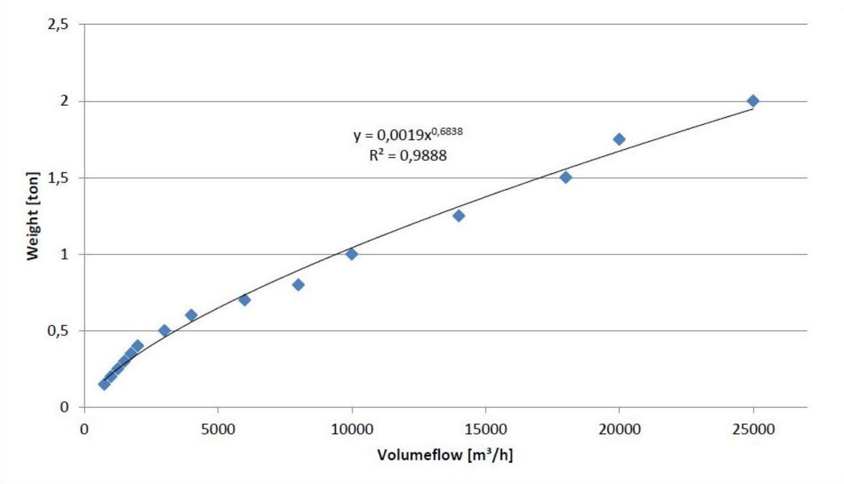


Figure 3.8: Analysis AC-unit weight [64]

$$W_{AC} = 1.9 \cdot 10^{-3} \cdot \dot{V}^{0.6838} \quad [ton] \tag{3.33}$$

The weight of the cooling machine is analyzed in Figure 3.9 as a function of the cooling capacity [63]. The cooling machine is more closely positioned to the engine room while the AC-unit is closely positioned to the accommodation. In this way, one saves on piping and loss of heat. The result of this analysis is an estimation of the weight of the cooling machine which is given in Equation 3.34.

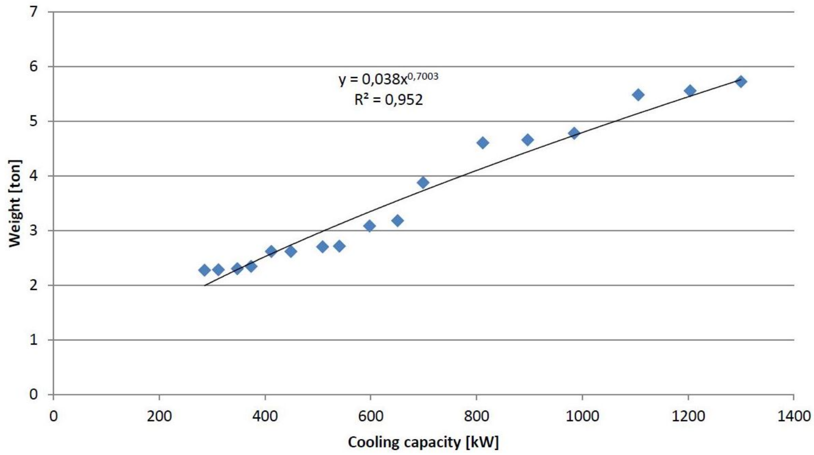


Figure 3.9: Analysis cooling machine weight [63]

$$W_{CM} = 3.8 \cdot 10^{-2} \cdot P_{HVAC}^{0.7003} \quad [ton] \tag{3.34}$$

The weight of the piping for the HVAC system is dependent on the number of decks, the size of the accommodation and the number of air changes per hour. It is assumed that the number of air changes is fixed as mentioned earlier in this section. In order to estimate the total piping weight of the HVAC system, the accommodation is assumed to be divided into equally sized decks. It is assumed for every deck that it requires 10 air changes per hour to fulfill the requirements as stated in Table 3.3. The volumeflow for one deck can be calculated with Equation 3.35.

$$\dot{V}_{Deck} = \frac{\dot{V}}{N_{Deck}} \quad [m^3/\text{h}] \tag{3.35}$$

In this equation, $\dot{V}$ is the total volumeflow of the accommodation, which can be calculated with Equation 3.20, and N_{Deck} the number of decks in the accommodation, including the bridge deck. For the calculation of the piping, the accommodation is assumed to be a block with length l in the longitudinal direction of the ship, b the breadth of the accommodation in the transverse direction and h_{Acco} the height of the accommodation. It is assumed that the HVAC systems has a main pipe at every deck with a distance of 6 meter between the main pipes. The number of main pipes on one deck can be calculated with Equation 3.36. The number is rounded, because it is impossible to have for example 1.3 pipes. The main pipes run across the entire width of the accommodation. The main pipe is connected to smaller subpipes that transport the air to the different spaces on a deck. It is assumed that the distance between the subpipes is 3 meter. The number of subpipes on one deck can be calculated with Equation 3.37. The main pipes are also connected to a vertical pipe, that connects the different decks with each other. It is assumed that the number of vertical pipes is equal to the number of main pipes per deck. The number of vertical pipes can be calculated with Equation 3.38.

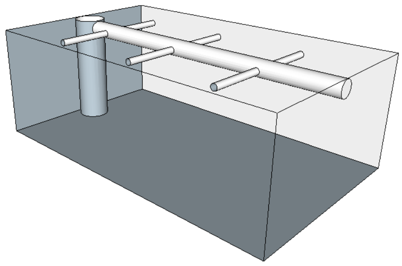


Figure 3.10: Single deck block

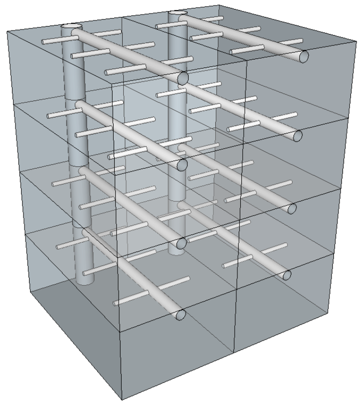


Figure 3.11: Multiple deck blocks

$$N_{Pipe,main} = round\left(\frac{l}{6}\right) \quad [-] \tag{3.36}$$

$$N_{Pipe,sub} = 2 \cdot round\left(\frac{b}{3}\right) \quad [-] \tag{3.37}$$

$$N_{Pipe,vert} = N_{Pipe,main} = round\left(\frac{l}{6}\right) \quad [-] \tag{3.38}$$

The number of required pipes can now be calculated. However, the three different pipes all have different diameters. The volumeflow in pipe is dependent on the cross sectional area of the pipe and the speed of the air in the pipe, as can be seen in Equation 3.39. When one applies this equation to the main pipe and assumes that the pipe has a circular cross-section and that it transports the air for the entire deck, one can rewrite Equation 3.39 into Equation 3.40 for the diameter of the main pipe. This diameter is required to determine the weight per meter of pipe. The specific weight of spiro piping, the type of piping used for HVAC systems, is given in Table 3.4 [57].

$$\dot{V}_{Pipe} = 3600 \cdot A_{Pipe} \cdot V_{Pipe} = \frac{\dot{V}_{Deck}}{N_{Pipe,main}} \quad [m^3/\mathrm{h}] \tag{3.39}$$

$$d_{Pipe,main} = \frac{1}{30} \cdot \sqrt{\frac{\dot{V}_{Deck}}{\pi \cdot V_{Pipe} \cdot N_{Pipe,main}}} \quad [mm] \tag{3.40}$$

It is known what the diameter of the main pipe has to be, but a similar calculation should be performed for the subpipes and the vertical pipes. It is assumed that the speed in all the pipes is equal, resulting in the volumeflow of the pipe being only dependent on the cross sectional area of the pipe. Hence, the sum of the cross sectional areas of the vertical pipes equals the sum of the cross sectional areas of the main pipes, which equals the sum of the cross sectional areas of the subpipes. This is mathematical represented in Equation 3.41. Rewriting Equation 3.41 for the subpipes and the vertical pipes results in Equation

3.42 and Equation for the pipe diameter 3.43. The specific weight of the spiro pipes can then again be taken from in Table 3.4 [57].

$$\sum A_{Pipe,vert} = \sum A_{Pipe,main} = \sum A_{Pipe,sub} \tag{3.41}$$

$$d_{Pipe,sub} = \sqrt{\frac{{d_{Pipe,main}}^2}{N_{Pipe,sub}}} \quad [mm] \tag{3.42}$$

$$d_{Pipe,vert} = \sqrt{N_{Deck} \cdot {d_{Pipe,main}}^2} \quad [mm] \tag{3.43}$$

The number of required pipes and the specific weight of the pipes is known, but the required length still needs to be determined. The main pipe is assumed to run over the the full breadth of the accommodation. Therefore one can determine the total length of main pipes per deck with Equation 3.44. Furthermore, it is assumed that the subpipes run 3 meter perpendicular to the main pipe in two directions. The total length of subpipes per deck can therefore be determined with Equation 3.45. For the vertical pipes it is assumed that these run over the entire height of the accommodation. Therefore one can calculate the total length of vertical pipes with Equation 3.46.

$$L_{Pipe,main} = N_{Pipe,main} \cdot b \quad [m] \tag{3.44}$$

$$L_{Pipe,sub} = 3 \cdot N_{Pipe,sub} \quad [m] \tag{3.45}$$

$$L_{Pipe,vert} = N_{Pipe,vert} \cdot h_{Acco} \quad [m] \tag{3.46}$$

The weight of the piping for the HVAC system can now be calculated with Equation 3.47. In this equation, N_{Deck} is the number of decks in the accommodation, $L_{Pipe,main}$, $L_{Pipe,sub}$, $L_{Pipe,vert}$ are the total length of the different types of pipe and $w_{Pipe,main}$, $w_{Pipe,sub}$, $w_{Pipe,vert}$ are the specific weights of the different types of pipe which can be taken from Table 3.4. An additional margin of 10% is included in the formula for mounting brackets.

$$\begin{aligned} W_{Piping,HVAC} \quad = \quad & \frac{1.1}{1000} \cdot (N_{Deck} \cdot (L_{Pipe,main} \cdot w_{Pipe,main} + \\ & L_{Pipe,sub} \cdot w_{Pipe,sub}) + L_{Pipe,vert} \cdot w_{Pipe,vert}) \quad [ton] \end{aligned} \tag{3.47}$$

d [mm]	w [kg/m]
80	0.99
100	1.23
125	1.54
150	1.85
160	1.97
200	2.47
250	3.08
300	4.44
315	4.66
400	5.92
500	9.86
630	12.43
800	19.73

Table 3.4: Sizes and weight of duting for HVAC [57]

Although the weight of the piping is known, one still has to determine the weight of the fan that moves the air. Therefore an analysis on box-shaped fans is performed. The results of the analysis is shown in Figure 3.12 [65]. The analysis shows the relationship between the capacity of the fan and the weight of the fan. From the analysis it can be seen that the influence of the fan on the total system is very limited. The weight of the fan can be estimated with Equation 3.48. In this equation is Q_{Fan} the volumeflow through the fan in m^3/s. The volumeflow presented in the graph is maximum volumeflow the fan can produce.

$$W_{Fan,HVAC} = 4.02 \cdot 10^{-2} \cdot Q_{Fan}^{0.7078} \quad [ton] \tag{3.48}$$

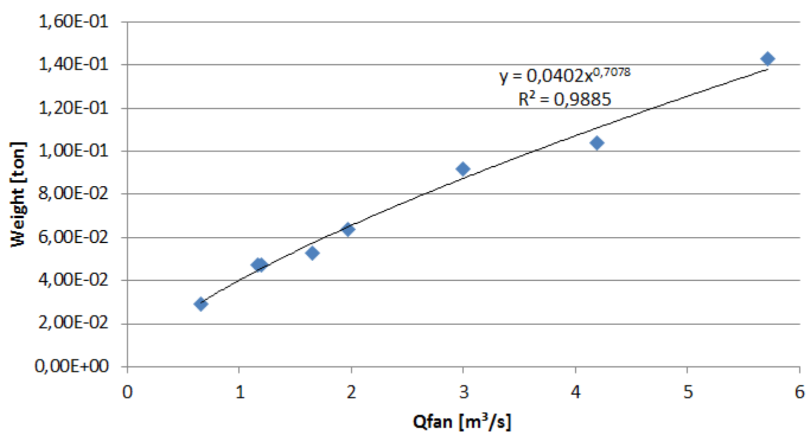


Figure 3.12: Analysis fan weight [65]

Once the weight of the fan is determined, one has to determine the true power used by the fan. This is a very standard calculation and therefore one can find the calculation of the fan power in Appendix B.

The weight of the HVAC system is about 2 ton for a containerfeeder and 20 ton for a large ocean liner container vessel. Furthermore, the maximum required power for the HVAC system is about 110 kW for a containerfeeder and 1,600 kW for a large ocean liner container vessel.

3.1.3 Electrical system

The items that are affected by unmanned shipping and that make up the electrical system are the power generating systems, cables and wires in the accommodation, switch boards and the lighting in the accommodation. Cables, switch boards and lighting will be analyzed in Section 3.1.3.1 to Section 3.1.3.3 while the power generating system will be analyzed in Section 3.2 when the peak load, which is required to determine the weight saving, is known as it is dependent on the result of other sections of this chapter.

3.1.3.1 Cables and wires accommodation

The accommodation is full of all sorts of cable and wires. These cables and wires distribute the power from the generators in the engine room to the different users in the ship, but also deliver data from sensors to the systems that process that data. In this thesis, only the cables in the accommodation will be treated, as a large portion of these cables is no longer needed when ships become unmanned. In order to determine the amount of cables and wires in the accommodation, the following approach is used: First the total length of cables in an accommodation will be determined, then the length of cables associated with spaces in the accommodation that can be removed for unmanned ships will be determined. The total length of cables that can be removed will then be related to the floor area of the removed spaces, resulting in a cable length per m^2.

RH Marine has performed the electrical installation of two ships, which were later named Fjord and Fjell by Dockwise. The vessel Fjell is shown in Figure 3.13. Since RH Marine performed the electrical installation, they have a clear view on the amount of cables used in every space of the vessel Fjell. However, before this information about the electrical installation can be used, it should first be checked whether the vessel Fjell is a valid vessel to use as a reference for cables and wires. Most merchant ships have their accommodation and engine room at the stern while the vessel Fjell has it's accommodation at the bow. When the accommodation is placed at the bow and the engine room at the stern, then the cables run across the full length of the ship, making an comparison with most merchant ships invalid. However, in Figure 3.13 it can be seen that the smoke stack is next to the accommodation, proving that the engine room is at the bow and therefore proving that the vessel Fjell is a valid vessel for analyzing the cables and wires in the accommodation. This can also be seen in the general arrangement plan of the vessel which is given in Appendix G. RH Marine installed approximately 215 km of cables in the vessel, but only 40 km can be removed if the ship would become unmanned as not all spaces can be removed. The spaces that can be removed have been colored yellow in Appendix G and have a total floor area of approximately 1400 m^2. This results in 28.6 m of cable per square meter. The total length of cables and wires in the accommodation can be estimated with Equation

3.49. The weight of a cable is about 0.2 kg per meter of cable [66]. Multiplying the specific weight of the cable with the length of the cable and including a margin of 50% for cable trays results in an estimation for cable weight as a function of floor area. The total weight of the cable can be estimated with Equation 3.50. In this equation is A_{floor} the floor area in m^2 and $8.6 \cdot 10^{-3}$ the weight of cable in ton/m^2.

$$S_{cables} = 2.86 \cdot 10 \cdot A_{floor} \quad [m] \tag{3.49}$$

$$W_{cables} = 8.6 \cdot 10^{-3} \cdot A_{floor} \quad [ton] \tag{3.50}$$

The weight of cables and wires is about 4 ton on a containerfeeder and 38 ton on a large ocean liner container feeder.

Figure 3.13: Dockwise Fjell [67]

3.1.3.2 Switch boards

The effect unmanned shipping will have on the number of and size of switch boards will be limited, as most users of the switch board will remain the same. Most generators, pumps and lighting will remain present, only equipment in the accommodation that is there for human support will be removed. This includes galley equipment, lighting in the accommodation, entertainment systems, computer monitors at the bridge and power reserved for power sockets for general hotel use. However, these users of the switch board are relatively small users. Therefore, according to experts at RH Marine, will the size and amount of switch board not significantly change. What could happen according to these experts is that fewer local distribution boards will be needed. However, these local distribution boards weigh about 200 kg and will therefore have very little impact on the lightweight. Since the impact on lightweight is very limited, this thesis will not analyze the switch boards any further.

3.1.3.3 Lighting accommodation

The lighting in the accommodation affects both the lightweight of the vessel and the power consumption. This distinction will also be used in this section. First will the effect of lighting in the accommodation on power consumption be discussed and then the effect of lighting on the lightweight.

The power consumption of lighting is dependent on the type of lighting, the required illuminance and the area that needs to be covered. The required illuminance for different tasks is prescribed in norms like the Dutch NEN1890 [68]. The illuminance requirements for different tasks are given in Appendix H. In this appendix a table is given which contains both the standard illuminance and the design value for illuminance. When one designs the lighting for a space, one should use the design value for the calculations in order to maintain the standard illuminance value at all times. This is required as the light intensity of an armature reduces over time. The power consumption for lighting can be calculated with Equation 3.51 when one assumes that the accommodation is one open space.

$$P_{Lighting} = \frac{\Phi \cdot A_{floor}}{10^3 \cdot \eta_{Light}} \quad [kW] \tag{3.51}$$

In this equation is Φ the illuminance in lux, A_{floor} the total floor area that needs to be covered by lighting and η_{Light} the luminous efficacy in lumen per watt. The luminous efficacy for different armature types can be found in Table 3.5 in which the characteristics of different armature types are given.

	TL-lamp	Halogen lamp	LED lamp
$P_{Armature}$ [W]	70	50	54
Φ_V [lm]	6700	1000	6125
η_{Light} [lm/W]	96	20	113
$W_{Armature}$ [kg]	7.4	0.5	3.8

Table 3.5: Characteristics of different armature types [69, 70, 71]

Since the required power consumption to meet the illuminance requirements for lighting is known, one can calculate the number of armatures needed based on the power consumption of one armature, which is given in Table 3.5. The number of required armatures can be calculated with Equation 3.52.

$$N_{Armature} = \frac{10^3 \cdot P_{Lighting}}{P_{Armature}} \quad [-] \tag{3.52}$$

In this equation $P_{Lighting}$ is the total required power for lighting in kW and $P_{Armature}$ the power consumption of one armature in W. However research showed that the true number of installed armatures is significantly higher than the number calculated by Equation 3.52. Since the accommodation is not one open space, the required number of armatures is higher. Analysis based on numbers of RH Marine on the true installed number of armatures showed that there is approximately one armature installed for every 5 square meters of floor area. The true amount of installed armatures can be estimated with Equation 3.53.

$$N_{Armature} = round\left(2.13 \cdot 10^{-1} \cdot A_{floor}\right) \quad [-] \tag{3.53}$$

Since the extra armatures will result in additional power consumption, the corrected power consumption for lighting can be calculated with Equation 3.54. The power used for lighting in the accommodation is about 6 kW in a containerfeeder and 65 kW in a large ocean liner container vessel.

$$P_{Lighting} = \frac{N_{Armature} \cdot P_{Armature}}{10^3} \quad [kW] \tag{3.54}$$

The weight of lighting can be estimated by multiplying the number of armatures by the weight of one armature, which is given in Table 3.5, as can be seen in Equation 3.55. In this equation is $N_{Armature}$ the number of armatures and $W_{Armature}$ the weight of one armature in kg. This results in the lightweight for lighting, $W_{Lighting}$, in ton. The lightweight for lighting excludes cables, wires, switchboards etc. as those are discussed in Section 3.1.3.1 and Section 3.1.3.2.

$$W_{Lighting} = N_{Armature} \cdot \frac{W_{Armature}}{10^3} \quad [ton] \tag{3.55}$$

The weight for lighting is the accommodation is about 1 ton for a containerfeeder and 7 ton for a large ocean liner container vessel.

3.1.4 Deck equipment

The deck equipment that can be removed when the ship becomes unmanned is the life-saving equipment. This is the free-fall lifeboat on the stern of the vessel. The lifeboat is suspended in a davit and can be released in case of an emergency, saving the crew. An enclosed lifeboat suspended in a davit at the stern of a ship is shown in Figure 3.14. This type of lifeboat has its own engine with fuel oil, some emergency rations for the crew and flares to attract the attention of other ships [72]. Since the lifeboat has its own engine with fuel oil, the removal of the lifeboat will not have any effect on the power requirement and the fuel consumption of the ship itself.

Figure 3.14: Lifeboat at the stern of a ship

The size of the lifeboat is dependent on the number of crew on-board and drop height. The lifeboat and the davit are two separate systems which means that different lifeboats fit in the same davit. This can also be found in Table I.1, which is provided by Harding, a manufacturer of lifeboats [72]. It impossible to set up an estimation formula for the weight of the total system as a function of crew size and and drop height, because the size of the boat and the davit is fixed. A ship with a crew of 21 will require a lifeboat of type LBF 580 C instead of a specially designed lifeboat and davit for 21 persons for example. Therefore, when the results from the parametric study will be applied to a reference ship, will the lifeboat-davit combination be chosen that fits the crew size and drop height best instead of interpolating between two complete systems.

Type of lifeboat	Capacity [persons]	Drop height [m]	Weight lifeboat [kg]	Type of davit	Weight davit [kg]	Total system weight [kg]
LBF 490 C	16	16	3,963	JYF55	5,500	9,463
LBF 580 C	26	17	5,646	JYF55	5,500	11,146
LBF 680 C	33	22	6,440	JYF75	7,500	13,940
LBF 750 C	36	22	7,374	JYF75	7,500	14,874
LBF 850 C	40	25	8,322	JYF90	10,000	18,322

Table 3.6: Free fall systems [72]

The weight of the deck equipment is about 9.5 ton for a containerfeeder and 15 ton for a large ocean liner container vessel.

3.1.5 Secondary ship systems

The only secondary ship system that can be removed when ships become unmanned is the firefighting equipment in the accommodation. It is assumed for this study that firefighting is done with a sprinkler system. This system has a certain weight and it requires power to pump the water to the sprinklers. The weight for the firefighting equipment consists out of the weight of the piping and the weight of a pump as can be seen in Equation 3.56.

$$W_{Fifi} = W_{Piping,Fifi} + W_{Fifi,Pump} \quad [ton] \tag{3.56}$$

The number of pipes, required to determine the weight of the piping, will be determined in the same way as in Section 3.1.2.1, resulting in equal lengths of pipes for firefighting system as for one supply of the fresh water system. Next, one should determine the inner diameter of the different types of pipe as it determines the specific weight of the pipe. For this calculation it is assumed that the total cross sectional area of the subpipes equals the cross sectional area of the main pipe and that the total cross sectional area of the main pipes equals the cross sectional area of the vertical pipes. This is mathematically shown in Equation 3.57.

$$\sum A_{Pipe,Fifi,vert} = \sum A_{Pipe,Fifi,main} = \sum A_{Pipe,Fifi,sub} \tag{3.57}$$

According to the norm BS EN 12845 for automatic sprinkler systems, the diameter of the subpipe may not be smaller than 25 mm [73]. Taking this into account and based on the pipe sizes given in Table 3.2 [57], the inner diameter of the subpipes for the firefighting system should be at least 26.6 mm. When one assumes the fluid velocity in all pipes to be equal and combining this with Equation 3.57, the inner diameter of the main pipe can be calculated with Equation 3.58. In this equation $N_{Pipe,Fifi,sub}$is the number of subpipes for the firefighting systems per deck and $d_{Pipe,Fifi,sub}$ the diameter of the subpipe. Then one can find the pipe that fits best with the help of Table 3.2 [57]. In a similar way, the diameter of the vertical pipe is determined in Equation 3.59. With these diameters one can estimate the weight of the piping for the firefighting system in the same way as in Section 3.1.2.1.

$$d_{Pipe,Fifi,main} = \sqrt{N_{Pipe,Fifi,sub} \cdot d_{Pipe,Fifi,sub}{}^2} \quad [mm] \tag{3.58}$$

$$d_{Pipe,Fifi,vert} = \sqrt{N_{Deck} \cdot d_{Pipe,Fifi,main}{}^2} \quad [mm] \tag{3.59}$$

Since the lay-out of the piping system is now known, one can calculate the required power for the pump. However, this is a very basic calculation and therefore one can find the calculation of pump power in Appendix B. Once the required pump power is known, one can calculate the weight op the pump. The weight of a pump is dependent on the volumeflow and the head increase. Based on these parameters, a pump is chosen. This is very case dependent and therefore is the weight of the pump is also very case dependent. In general the pump for the firefighting system will not be used, but it still needs to be installed. In order to fulfill the requirements for the firefighting system, it is assumed that a Wärtsilä Hamworthy centrifugal pump from the dolphin range will be installed. These pumps weight between 500 and 1000 kg and have a capacity range as indicated in Figure 3.15 [74]. For this thesis it will be assumed, based on the brochure for the dolphin range pump, that the weight of the pump, $W_{Fifi,Pump}$, is 1000 kg [74]. This is the weight of the pump that could serve the accommodation and can therefore be removed. However, the firefighting pump for the engine room is still required and therefore that pump cannot be removed. The weight of the firefighting system is about 2 ton for a containerfeeder and 30 ton for a large ocean liner container vessel. Furthermore, the required power of the pump is about 22 kW for a containerfeeder and 330 kW for a large ocean liner container vessel.

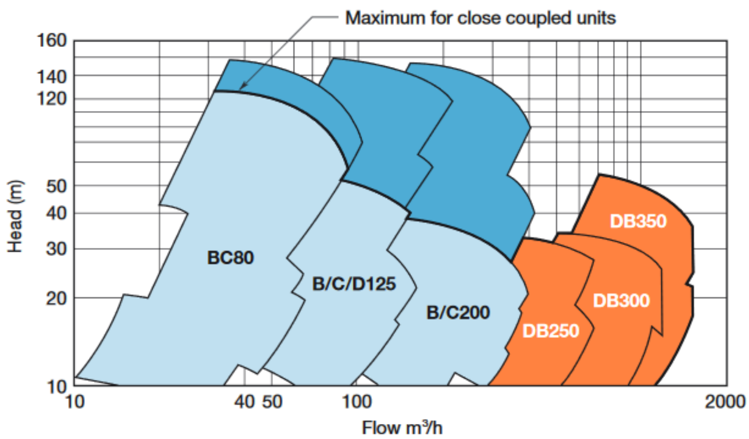


Figure 3.15: Capacity range of Wärtsilä Hamworthy centrifugal pumps Dolphin range [74]

3.1.6 Joinery and hotel equipment

The joinery and hotel equipment consists of the interior of the wheelhouse, living quarters, but also of the equipment for stores. This will both influence the lightweight of the ship and the consumed power. The weight of the joinery can be calculated with Equation 3.60. In this equation A_{floor} is the total floor area of the accommodation. The number of 0.15 ton/m^2 floor area is provided by a none public source. The weight of the joinery is about 60 ton for a containerfeeder and 650 ton for a large ocean liner container vessel.

$$W_{Joinery} = 1.5 \cdot 10^{-1} \cdot A_{floor} \quad [ton] \tag{3.60}$$

The weight and the power consumption of the equipment installed in the accommodation and wheelhouse, other than entertainment systems, is dependent on the equipment installed in the galley and wheelhouse. This is in its turn dependent on how luxurious the shipowner wants his crew to live and the size of the crew. Furthermore, only the monitors which are the interface can be removed from the bridge. The computers behind the interface are still required to execute their tasks. For the different types of equipment the weight and power per device as shown in Table 3.7 will be assumed. The distinction between a small and large fridge is shown in Figure 3.16 and Figure 3.17. The freezer has about the same size as the large fridge. The weight of the hotel equipment can be estimated with Equation 3.61.

Equipment	W_i [ton]	P_i[kW]	n_i[-]
Stove [75]	0.04	7	10
Microwave [76]	0.04	1	10
Small fridge [77]	0.04	0.08	15
Large fridge [78]	0.3	1	30
Freezer [79]	0.3	0.7	30
Computer monitor [80]	0.01	0.02	
Washing machine [81]	0.07	2.2	6
Dryer [82]	0.06	1.1	6

Table 3.7: Hotel equipment

Figure 3.16: Small fridge [77]

Figure 3.17: Large fridge [78]

$$W_{Hotel} = \sum N_i \cdot W_i \quad [kW] \tag{3.61}$$

In Equation N_i is the number of installed equipment of type i and W_i the weight of installed equipment of type i. The number of installed equipment of type i can be determined with Equation 3.62. In this equation N_{Crew} is the number of crew on a ship and n_i the number of crew per device which is given in Table 3.7. An exception is made for the number of computer monitors as there is no relationship between the number of crew and the number of computer monitors required for navigation. Therefore it is assumed that 10 monitors on the bridge are sufficient to navigate the ship. The weight of the hotel equipment is about 1 ton for a containerfeeder and 2.5 ton for a large ocean liner container vessel.

$$N_i = \frac{N_{Crew}}{n_i} \quad [-] \tag{3.62}$$

The power consumption of the hotel equipment can be estimated with Equation 3.63.

$$P_{Hotel} = \sum N_i \cdot P_i \quad [kW] \tag{3.63}$$

In Equation 3.63 N_i is the number of installed equipment of type i and P_i the power of installed equipment of type i. However, when one would apply this equation, the resulting power would be too high as not all the equipment will be used at the same time. Therefore, the power consumption schedule as indicated in Figure 3.18 is assumed. It shows what equipment is in use and when. This leads to the power consumption for the hotel equipment as shown in Figure 3.19. The power consumption for the hotel equipment is about 15 kW for a containerfeeder and 50 kW for a large ocean liner container vessel.

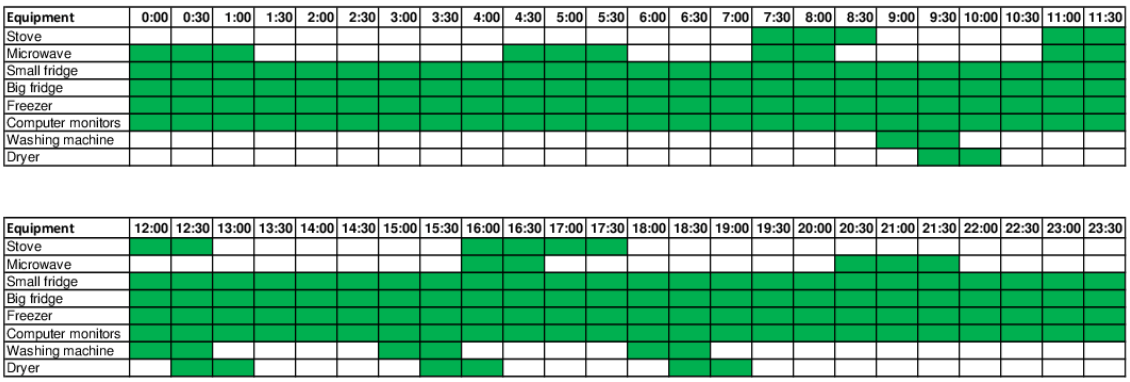


Figure 3.18: Power consumption schedule for the hotel equipment

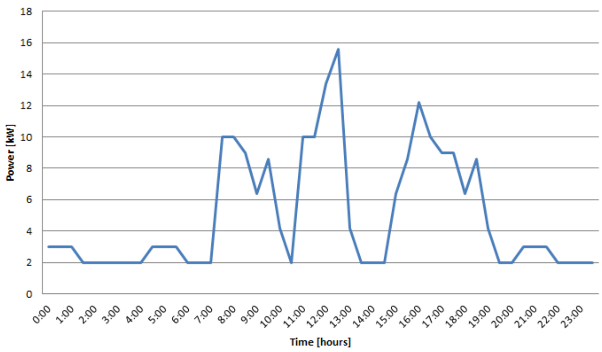


Figure 3.19: Power consumption hotel equipment

3.1.7 Nautical, navigation and communication equipment

Most equipment in this group will remain the same when ships become unmanned as ships still have to communicate with the outside world and navigate over the seas. However the the internal communication and the entertainment systems for the crew can be removed. The internal communication will be discussed in Section 3.1.7.1and the entertainment systems in Section 3.1.7.2.

3.1.7.1 Internal communication

When ships become unmanned, the internal communication will no longer be required. However, today there is in general a communication device in every space on-board. This means that every cabin has such a device, but also spaces like the galley, messroom and engine room. There is also a communication device outdoors. There are three types of internal communication devices:

- Public Address
- Intercom
- Phone

With public address the main station, which is commonly placed at the bridge, can send messages to substations. However the substations can not send messages to the main station. With intercom the main station can send messages to substations and the substations can only send messages to the main station. With phones the substations can also send messages to other substations. In general, the weight for a station is 1 kg and 2.5 kg for the terminal module that connects the different stations [83]. One terminal module has capacity for 24 stations [83]. The weight of the internal communication can be estimated with Equation 3.64. In this equation N_{Ph} is the number of stations and N_{TM} the number of terminal modules. The weight for cables and wires for internal communication is included in Equation 3.50 in Section 3.1.3.1.

$$W_{IntCom} = 1.0 \cdot 10^{-3} \cdot N_{Ph} + 2.5 \cdot 10^{-3} \cdot N_{TM} \quad [ton] \tag{3.64}$$

The weight for internal communication equipment is about 0.02 ton on a containerfeeder and 0.04 ton on a large ocean liner container vessel.

On average, a station consumes 50 W and a terminal module 65 W [83]. Combining this, the power for the internal communication can be estimated with Equation 3.65. Based on Equation 3.64 and Equation 3.65 one can state that the influence of internal communication on weight and power is very limited.

$$P_{IntCom} = 5.0 \cdot 10^{-2} \cdot N_{Ph} + 6.5 \cdot 10^{-2} \cdot N_{TM} \quad [kW] \tag{3.65}$$

The power consumption for internal communication equipment is about 1 kW on a containerfeeder and 2 kW on a large ocean liner container vessel.

3.1.7.2 Entertainment systems

As ships become unmanned there will no longer be a need for entertainment systems onboard to entertain the crew. The entertainment system consists of an antenna to receive the television signal, an amplifier which amplifies the signal received by the antenna, 24 inch LED televisions and satellite receiver which allows different televisions to be switched to different channels. The system requires one antenna, one amplifier for every 25 televisions and one satellite receiver for every television. In general there will be one television in every cabin and one in the mess room. When one assumes the weight and power consumption of the different components of the system as given in Table 3.8, the weight and the power consumption of the entertainment system can be estimated with Equation 3.66 and Equation 3.67. In these equations N_{SatA} is the number of antennas, N_{Amp} the number of amplifiers, N_{SatRec} the number of satellite receivers and N_{TV} the number of televisions.

Component	Weight [kg]	Power [W]
Antenna [84]	158.7	70
Amplifier [85]	20	120
Satellite receiver [86]	3.5	18
24" LED TV [87]	3.2	28

Table 3.8: Components of the entertainment system

$$\begin{aligned} W_{EntS} = {} & 1.587 \cdot 10^{-1} \cdot N_{SatA} + 2.0 \cdot 10^{-2} \cdot N_{Amp} + \\ & 3.5 \cdot 10^{-3} \cdot N_{SatRec} + 3.2 \cdot 10^{-3} \cdot N_{TV} \quad [ton] \end{aligned} \tag{3.66}$$

$$\begin{aligned} P_{EntS} = {} & 7.0 \cdot 10^{-2} \cdot N_{SatA} + 1.2 \cdot 10^{-1} \cdot N_{Amp} + \\ & 1.8 \cdot 10^{-2} \cdot N_{SatRec} + 2.8 \cdot 10^{-2} \cdot N_{TV} \quad [kW] \end{aligned} \tag{3.67}$$

Based on Equation 3.66 and Equation 3.67 one can state that the influence of entertainment systems on weight and power is very limited. The is also proven when one applies the equations to a containerfeeder and a large ocean liner container vessel. The weight of the entertainment system is about 0.3 ton on a containerfeeder and consumes 0.7 kW of power, while on a large ocean liner container vessel the entertainment system weighs 0.5 ton and consumes 1.5 kW of power.

3.2 Removed power supplier equipment

When ships become unmanned, the power consumption of the ship will go down as systems that use power to support human presence are no longer present. How the power consumption exactly changes for the different systems can be found in the other sections of this chapter and will effect the installed generators. In this thesis it is assumed that the generatorsets run on MDO. Before one can determine the influence on the power consumption, one has to determine the use of power during the day as not all the systems will be used continuously. When a system is switched on, can be dependent on ship position and outdoor conditions. Since this is dependent on the area where the ship sails, a distinction is made based on area. The areas are: tropic, artic and temperate. For these areas, a power consumption schedule, as given in Appendix F is assumed based on the temperature gradient of the cities Libreville, Tromsø and Halifax [88, 89] in which the power requirement at the maximum temperature difference for the HVAC system during the day is taken as 100%. Summing up the power consumption of the different systems will result in a load distribution over the period of day. The peak value in this distribution is the minimum power the generator that should be able to deliver, P_{Peak}. The area under this distribution is a measure for the fuel consumption, which is a part of the operational cost, which will be further analyzed in Chapter 4. The average massflow of fuel can be calculated with Equation 3.68. In this equation is SFC the specific fuel consumption and P_{Load} the power load at a given time during the day.

$$\dot{m}_f = \frac{SFC}{8.64 \cdot 10^7} \cdot \int_0^{24} P_{Load} dt \quad [kg/s] \tag{3.68}$$

The reduction in power consumption also has influence on the weight of the generator. Therefore an analysis on generator weight has been performed. However, there are generators that produce power at a frequency of 50 Hz and there are generators that produce power at 60 Hz. A frequency of 60 Hz is more common on ships, but since it is possible to install both types of generators, a distinction for the analysis based on frequency has been made. The result of the analysis for 50 Hz generators is shown in Figure 3.20 and the result of the analysis for 60 Hz generators is shown in Figure 3.21.

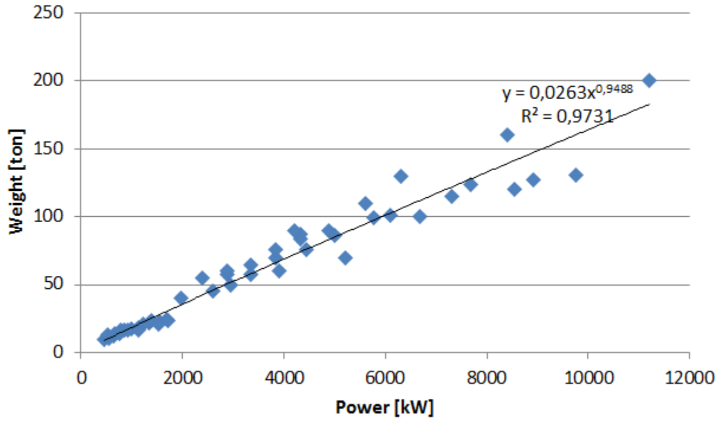


Figure 3.20: Weight analysis of the 50 Hz generator [90]

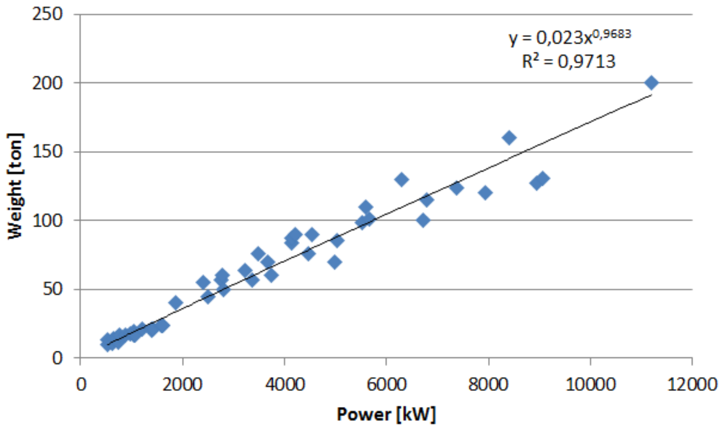


Figure 3.21: Weight analysis of the 60 Hz generator [90]

Based on the analysis, the weight of 50 Hz a generator can be estimated with Equation 3.69 [90] and the weight of a 60 Hz generator with Equation 3.70 [90]. In these equations P is the power of the generator. As mentioned before, the reduction in power consumption will result in a lower weight of the generator. The difference in weight for a 50 Hz generator can be estimated with Equation 3.71 and the difference in weight for a 60 Hz generator can be estimated with Equation 3.72. It is not possible to determine the difference in lightweight by filling in the difference between P_{gen} and P_{Peak} in Equations 3.69 and 3.70 due to the non-linear character of the equations.

$$W_{gen,50Hz} = 2.63 \cdot 10^{-2} \cdot P^{0.9488} \quad [ton] \tag{3.69}$$

$$W_{gen,60Hz} = 2.3 \cdot 10^{-2} \cdot P^{0.9683} \quad [ton] \tag{3.70}$$

$$\Delta W_{gen,50Hz} = W_{gen,50Hz}\left(P_{gen}\right) - W_{gen,50Hz}\left(P_{gen} - P_{Peak}\right) \quad [ton] \tag{3.71}$$

$$\Delta W_{gen,60Hz} = W_{gen,60Hz}\left(P_{gen}\right) - W_{gen,60Hz}\left(P_{gen} - P_{Peak}\right) \quad [ton] \tag{3.72}$$

The weight that can be saved on for the power generating systems is about 3 ton for a containerfeeder and 35 ton for a large ocean liner container vessel.

3.3 Comparison of the parametric study for different sized ships

In this section the results of the parametric study for different sizes of ships will be compared to analyze the differences between different sizes of ships. This will be done using the weight distribution and power distribution of a container feeder and a large ocean liner container vessel of which the vessel particulars are given in Table 3.9. The weight distribution of the containerfeeder is given in Figure 3.22 and the weight distribution of the large ocean liner container vessel in Figure 3.23. In these figures, one can see that the steel weight, joinery and power systems are the largest contributors to the weight that can be saved. In addition, one can see that the portion of steel weight and deck equipment decreases with size while the portion of joinery and power generating systems increases with larger ships. The decrease of the contribution of the deck equipment is caused by the relative low increase of the lifeboat weight for larger lifeboats while the relative increase of the power generating systems is mainly caused by the HVAC system. This can also be seen in Figure 3.24 to Figure 3.26 for the containerfeeder and in Figure 3.27 to Figure 3.29 for the large ocean liner container vessel in which the power distribution for the tropic, arctic and temperate zones is shown. These figures show that the HVAC system is the largest contributor for both ship sizes and that its power consumption increases much compared to other power users when the ship size increases. For the different zones the conditions, as given in Table 3.10, are assumed.

	Containerfeeder [55]	**Ocean liner container vessel [55]**
L [m]	104.80	349.00
B [m]	15.60	45.60
D [m]	7.40	27.30
T [m]	5.81	13.00
DWT [ton]	3,500	90,500
P_B [kW]	3,680	68,640
$P_{Electric}$ [kW]	2,510	13,650
l [m]	8.1	15.8
b [m]	10.4	34.4
h_{Acco} [m]	13.3	30.4
h_j [m]	11	30.4
N_{Deck} [-]	5	8
N_{Crew} [-]	10	34

Table 3.9: Vessel particulars

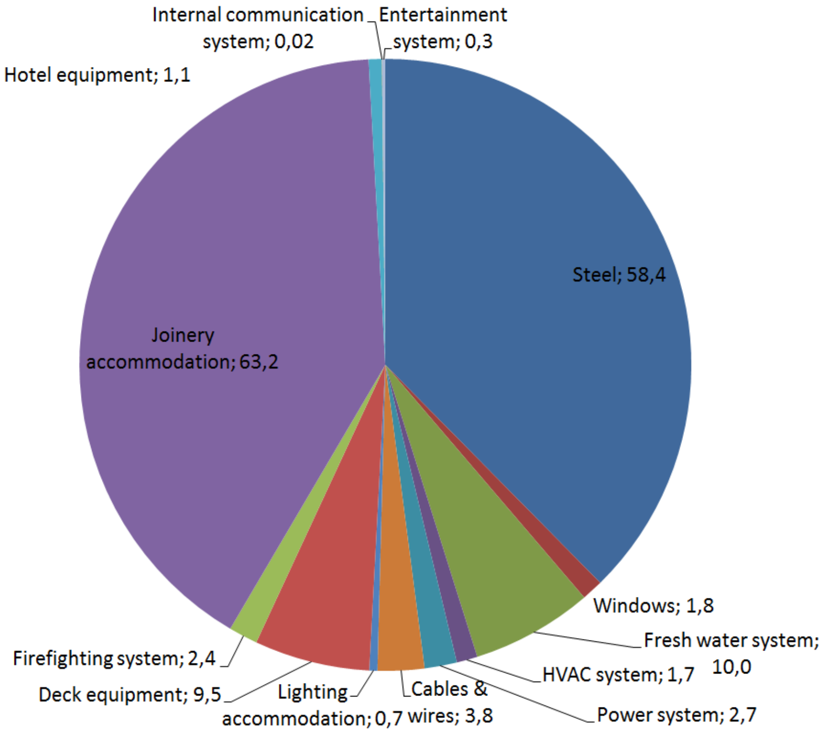


Figure 3.22: Weight distribution containerfeeder

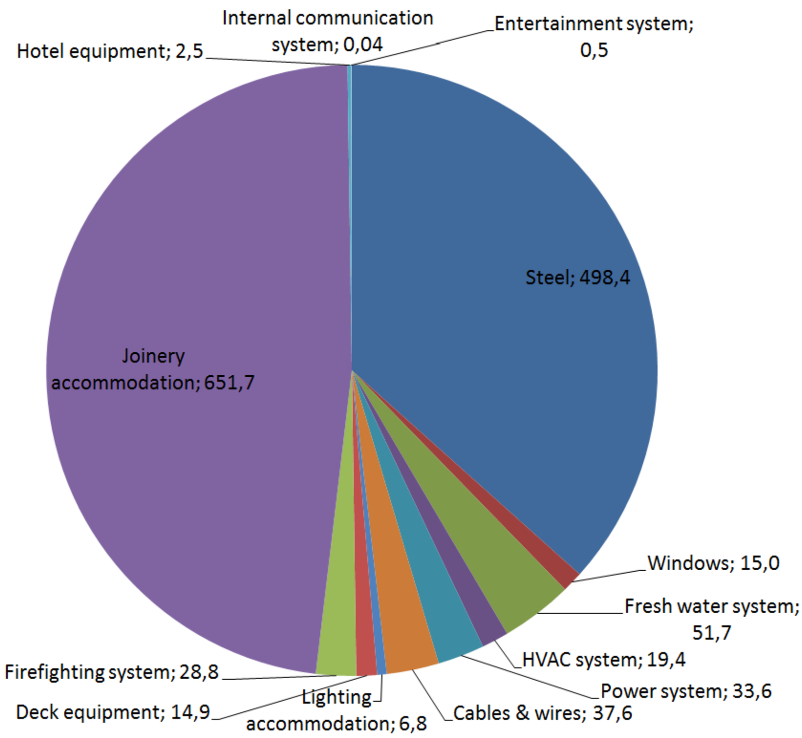


Figure 3.23: Weight distribution large ocean liner container vessel

	Tropic	Arctic	Temperate
$T_{Outdoor}$ [°C]	35	-20	15
T_{Indoor} [°C]	27	22	22
$\phi_{Outdoor}$ [%]	70		50
ϕ_{Indoor} [%]	50		50

Table 3.10: Zone conditions

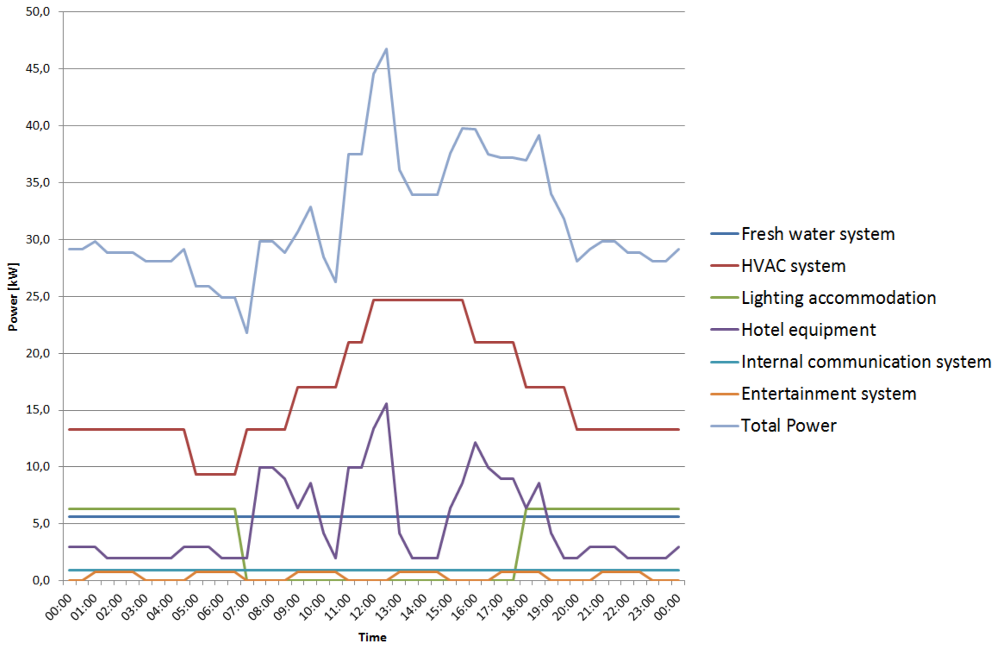


Figure 3.24: Power distribution containerfeeder in the tropic zone

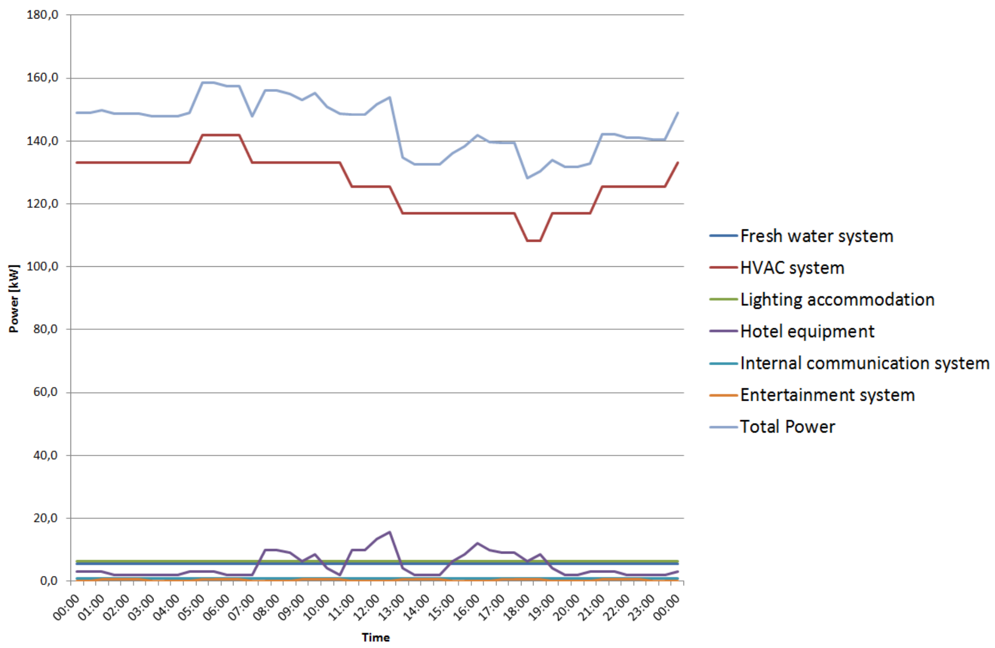


Figure 3.25: Power distribution containerfeeder in the Artic zone

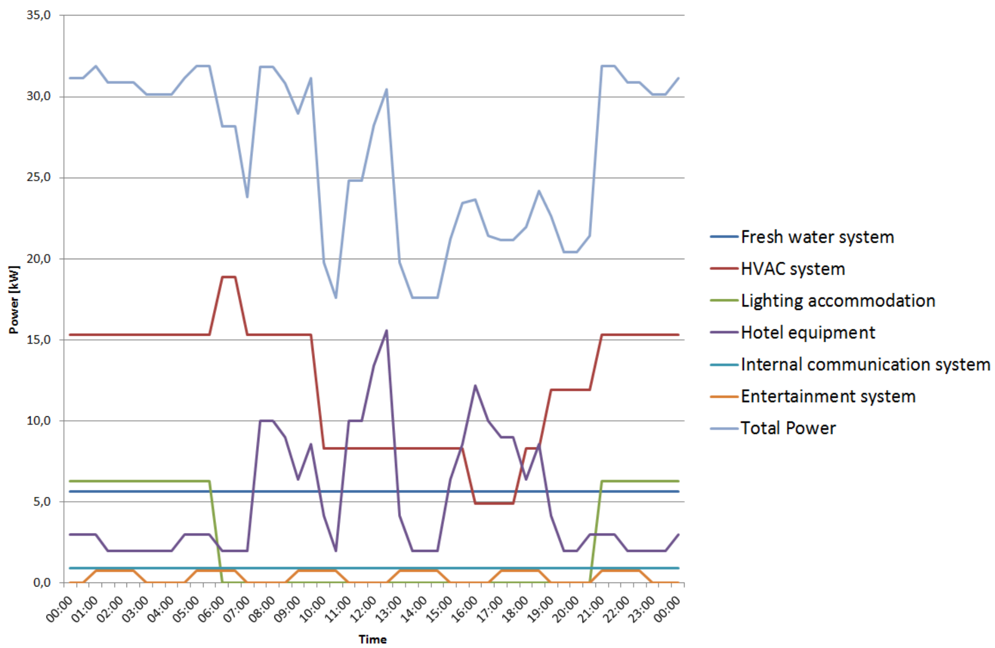


Figure 3.26: Power distribution containerfeeder in the temperate zone

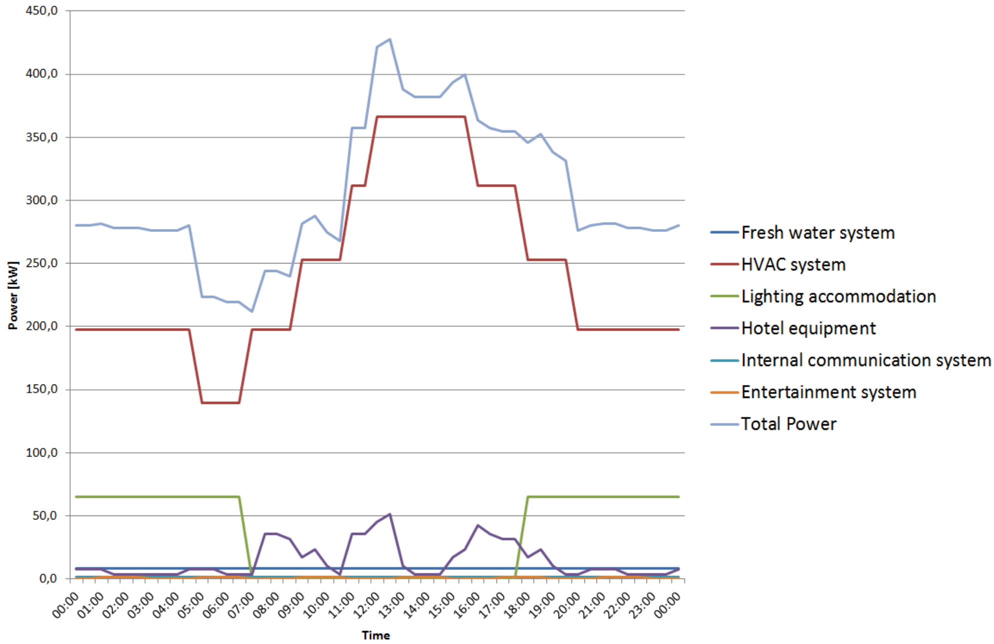


Figure 3.27: Power distribution large ocean liner container vessel in the tropic zone

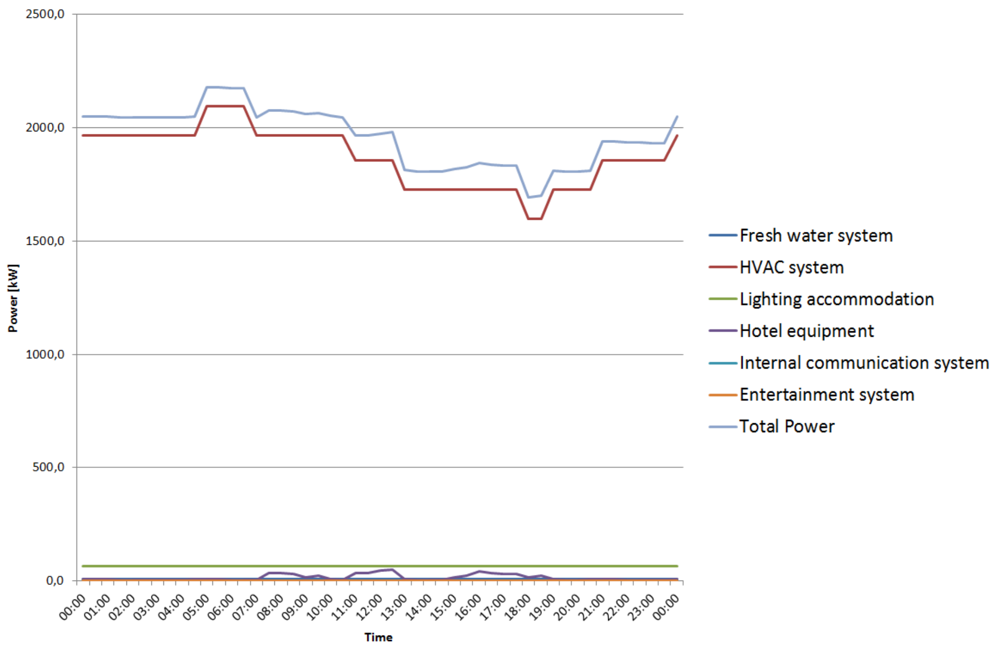


Figure 3.28: Power distribution large ocean liner container vessel in the arctic zone

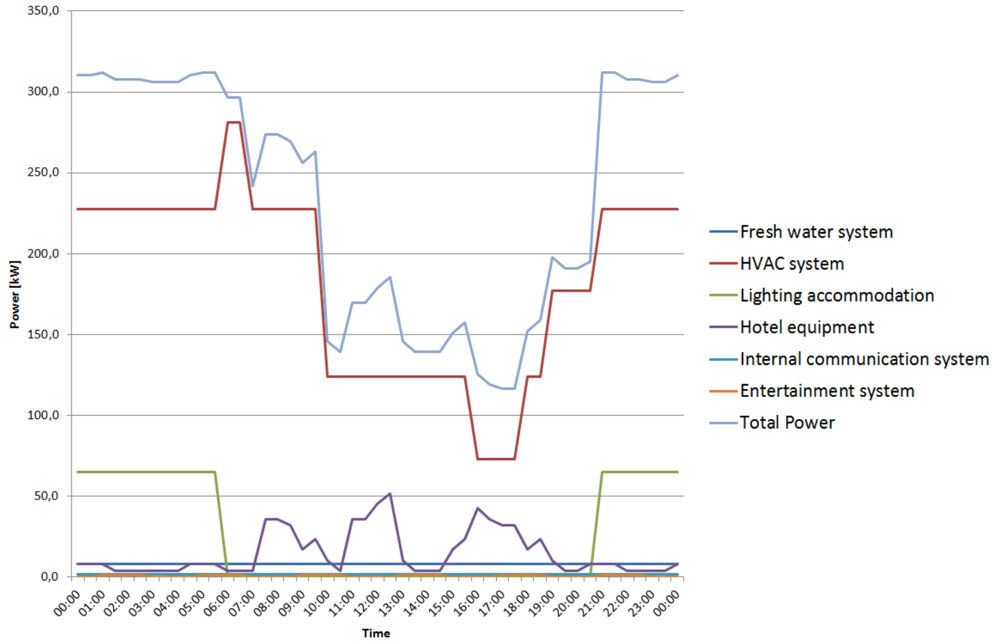


Figure 3.29: Power distribution large ocean liner container vessel in the temperate zone

Based on the parametric study, one can save 155 ton on the containerfeeder and 1361 ton on the ocean liner container vessel used in this comparison. The different zones on earth will result in different requirements for electrical power and therefore, the fuel consumption will be dependent on the zone that the ship sails in. For the containerfeeder the electrical power can be reduced by 46.8 kW in the tropic zone which will result in a fuel saving of 0.15 ton per day while in the arctic zone 158.4 kW of the electrical power can be reduced, resulting in a fuel saving of 0.69 ton per day. If the containerfeeder would sail in the temperate zone, the electrical power can be reduced by 31.9 kW, resulting in a fuel saving of 0.13 ton per day. For the ocean liner container vessel, the electrical power can be reduced by 428.0 kW in the tropic zone, which will result in a fuel saving of 1.46 ton per day while in the arctic the electrical power can be reduced by 2,181.7 kW, resulting in a fuel saving of 9.42 ton per day. If the ocean liner container vessel would sail in the temperate zone, the electrical power could be reduced by 311.9 kW, resulting in a fuel saving of 1.12 ton per day. Since ships should be able to sail in all zones, the electrical power can be reduced by 158.4 kW for the containerfeeder and 2181.9 kW for the ocean liner container vessel. A summary of the results is given in Table 3.11.

	Containerfeeder			**Ocean liner container vessel**		
Weight [ton]	155			1361		
Zone	Tropic	Artic	Temperate	Tropic	Artic	Temperate
Electrical power [kW]	46.8	158.4	31.9	428.0	2181.7	311.9
Fuel [ton/day]	0.15	0.69	0.13	1.46	9.42	1.12

Table 3.11: Summery of the results of the parametric study

To validate the results of the parametric study without the help of practical data, since this is not available, it will be looked at the source of the data that was used to create the parametric model. In Figure 3.22 and Figure 3.23, one can see that the joinery and steel of the accommodation are the largest contributors to the total weight that can be saved by removing the accommodation. The weight of the joinery is based on practical data from a shipyard and the estimation for the steel weight is based on renowned ship design knowledge by Thomas Lamb. Both sources have proven their validity. In addition is the weight of the deck equipment derived from data gained from a supplier. Furthermore are the diameters determined for the fresh water system plausible and therefore the specific weights. Only length determined for the different pipes is arguable as the lay-out is assumed. However, the largest contributors to the weight can be validated and therefore one can conclude that the magnitude of the weight results gained from the parametric study are also likely to be valid. To validate the power reduction, a similar approach as the validation of the weight will be used. In Figure 3.24 to Figure 3.29, one can see that the HVAC system is the largest contributor to the power used in the accommodation. To determine the power for the HVAC system, formulas used in lectures and practical knowledge from RH Marine has been applied. In addition, the design software used by RH Marine uses the same equations as taught in the lectures. Therefore, the equations used have proven their practicability and validity for the conditions humans can live in. The equations that make up the design model have been summarized in Appendix I.

To put the results of the parametric study in perspective, the lightweight for different sized ships has been determined with Watson based on the ratio between deadweight and displacement [49]. It results in an approximate lightweight of the containerfeeder of 1,830 ton and 32,200 ton for the ocean liner container vessel. Putting the weight reductions estimated with the parametric study in perspective, the lightweight of the containerfeeder will be reduced by 8% and the lightweight of the ocean liner container vessel will be reduced by 4%. Furthermore will the estimated power reduction result in 6% lower alternator power on the containerfeeder and 16% on the ocean liner container vessel.

3.4 Additional equipment for unmanned shipping

When ships become unmanned, a lot of spaces and equipment can be removed. However, to make unmanned shipping possible, additional equipment that is not installed today is required. What equipment should be installed in order to guarantee situational awareness will be discussed in Section 3.4.1. Besides equipment for the situational awareness of the ship, there should also be equipment installed that replaces the tasks of humans in various maneuvers and actions. This equipment will be discussed in Section 3.4.2.

3.4.1 How can situational awareness be guaranteed

In order to guarantee the situational awareness and let unmanned ships operate safely, additional equipment is required. This equipment can be divided into equipment that is required to have a good situational awareness of everything that is happening outside the ship and equipment that is required to have a good situational awareness of everything that is happening inside the ship. The equipment for the external situational awareness will be discussed in Section 3.4.1.1 and the equipment for the internal situational awareness will be discussed in Section 3.4.1.2. The equipment discussed in these sections should be redundant as it is a requirement from the analysis in Section 2.1.

3.4.1.1 External situational awareness

For the safety of the the ship and its cargo it is essential to have situational awareness of what is happening around the ship. As explained in Section 2.1.1, it is required by the COLREGS to have a proper look out at all times by both sight and sound. Nowadays, this task is done by the crew as they look through the window and listen for sound with their ears. They use systems like radar and AIS, Automatic Identification System, to assist them in their job. However, when the crew is removed from the vessel, those eyes and ears must be replaced with equipment, just as their level of skills. For example the ability to spot small objects between the waves that cannot be seen by the radar and decide of those objects can be of any harm to the vessel.

The eyes of the crew can be replaced by cameras around the ship allowing for a 360°view. However one set of cameras will not do the job as they have to be suitable for both day and night. Therefore, two sets of cameras will be needed. One set uses visible light during the day and one set uses infrared light during the night. There should also be a radar installed that is capable of detecting both small and large objects. The radars that are installed today do not have the capability to detect small objects a they show a lot of clutter. Therefore a new type of radar, the FM-CW, Frequency-Modulated Continuous-Wave radar, should be installed on unmanned ships. This type of radar is capable of detecting small objects. Next to detecting the objects it is also capable of determining the speed of the objects as it uses the Doppler-effect. Another option is to install the radar from Seadarq [91]. This radar is originally designed for monitoring the spread of oil spills, but can also process radar images to extract hydrographic, oceanographic and environmental information from the sea surface. According to design experts at RH Marine, the system can be adjusted to detect small objects at sea. Next to detecting the objects, the speed, the course, size, type, name and navigational status of other vessels should be known. The FM-CW radar determine speed. However, the Automatic Identification System, AIS, can do all these things and is still required when the FM-CW radar is installed. Therefore the AIS system is a requirement.

Sound detection is also a requirement, for example in the case of fog. Ships will have to slow down and sound their horn on a regularly basis. When two ships are close to each other, but they cannot see each other, they will try to determine where the other ship is by sound and then act accordingly. This is a difficult task for humans, as it is hard to determine the source of the sound. Human ears should be replaced by a sound reception system which can do the same but more accurately. Such a system exists and is based on the distance and delay in recording sound of a set of microphones that are placed on the ship [92]. Based on which microphone first recorded the sound, it is possible to determine the direction of the sound.

In theory the unmanned vessel has sufficient equipment on-board to be aware of the situation surrounding it. However, ships often communicate with each other via VHF radio. This communication improves the safety at sea. When ships become unmanned, operators will control them via a satellite connection. When the unmanned ship has to communicate with a manned ship the connection between the two ships can be established in two ways, as shown in Figure 3.30. One way is that the operator is connected to the unmanned ship via satellite and will communicate via the VHF radio on the ship to the manned ship. This is a very inefficient way as it has a major downside, it is only possible to communicate with local ships due to the range of VHF radio. The range of VHF radio is namely limited by the horizon. The second way of communication is directly via the satellite which has no limitation by the horizon. In this way it is possible to communicate with ships that are past the horizon. As more ships will become unmanned, the use of VHF radio is likely to go down. For the case of two manned ships that need to communicate with eachother, the VHF radio is still an option, but one that will become less and less effective when it concerns communication between ships in general. In other words, communication via satelite is likely to become the standard over the VHF radio.

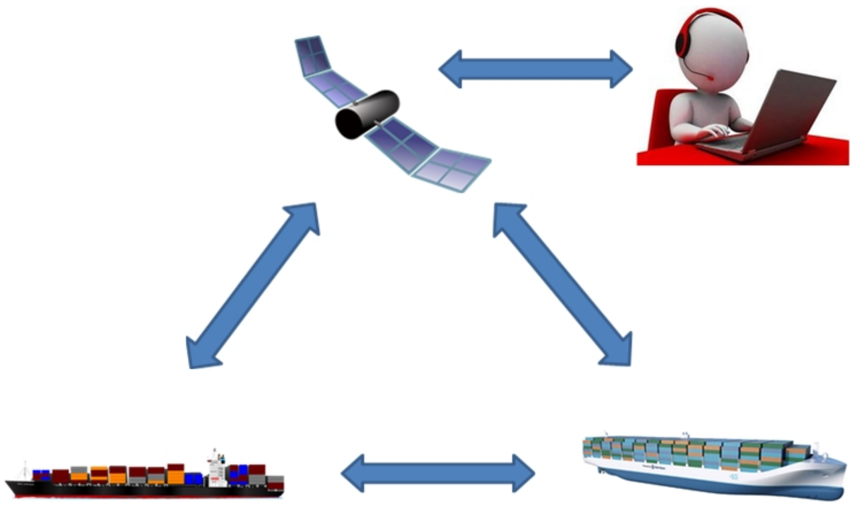


Figure 3.30: Communication between ships

3.4.1.2 Internal situational awareness

For the status of the ship it is key to have internal situational awareness of the ship. The operator or monitor of the ship wants to know and has to know what the status is of all kinds of systems on-board the ship. This gives the operator information about the capabilities of the vessel. All the information that the operator needs to know, and that can be gathered with sensors, must be combined into one single system that gives alarms when something is wrong. Such a system already exists and is called the AMCS, Alarm Monitoring Control System. In this system the operator can operate valves, pumps and connect generators to the grid. The AMCS of RH Marine, showing the screen for the propulsion train, is shown in Figure 3.31. However, when ships become unmanned, a higher level of autonomy has to be built into the system to reduce the workload for the operator. For example: when the operator wants to pump water in a ballast tank, the system itself should determine which valves to open and close and which pump to activate. Finally, the operator should be able to visually look in different rooms using cameras. The cameras should be working with both visual light and infrared, because most of the time there will not be light switched on in these rooms. The extra sensors in combination with additional computers on-board should help to create a clear overview of the situation on-board for the operator, allowing him to sail the vessel safely to its destination. However sending and receiving all the required data from the vessel requires a certain bandwidth. This bandwidth is currently very limited and more research should be carried out on how the data traffic between the vessel and the shore can be performed efficiently. This can be done by either increasing the bandwidth capacity or by compressing the data.

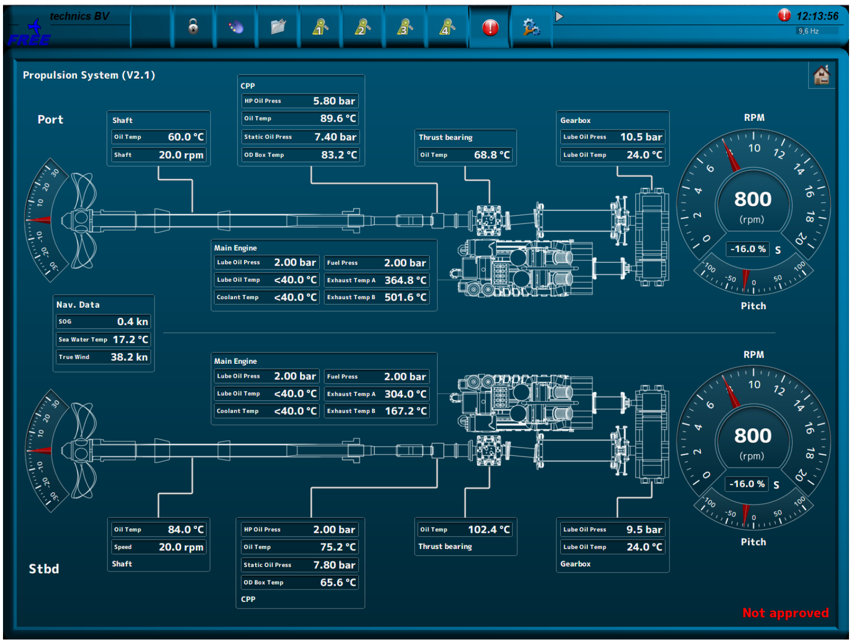


Figure 3.31: RH Marine Alarm Monitoring Control System [93]

3.4.2 Other equipment

Besides equipment that guarantees the situational awareness of the ship, there should also be equipment installed that replaces other duties of the crew. For example, when the ship enters port, the crew throws tow lines the the tugboat which guides the ship into port. When ships become unmanned the crew can no longer assist in throwing lines to the tugboat and pulling the lines in after the activity. Therefore systems should be developed that can do these tasks as those systems do not exist yet. Furthermore, one should think of different mooring systems as nowadays lines are thrown the quay to fasten the ship. However, this also requires crew to be on-board and therefore throwing lines might not be the best solution. A solution could be to install the MoorMaster of Cavotec on the quay which uses vacuum technology to moor the ship to the quay. The MoorMaster of Cavotec is shown in Figure 3.32 [94].

Figure 3.32: Cavotec MoorMaster [94]

3.5 Conclusion

It was the goal of this chapter to determine how the changed design requirements influence the design. This has been determined with the help of a parametric study. From this study it can be concluded that the steel weight and the weight for the joinery are the largest contributors to the weight of the accommodation, which can be removed when ships become unmanned. Furthermore, the weight of the power generating systems that can be removed increases relatively with ship size and is the HVAC system the largest contributor to the power consumption in the accommodation. In addition increases the total power consumption non-linear to ship size. From the analysis on what should be added it became clear that most equipment to guard the situational awareness is already in existence today.

Chapter 4

Cost model

It is the goal of this chapter to answer the question: "*What cost saving can be achieved by removing crew related equipment and the crew itself from conventional merchant ships?*" as set out in Section 1.3. To answer the question, a cost model has been developed which requires input from the design model from Chapter 3 as indicated in Figure 1.3. The cost model is divided in two parts, which are the capital cost and the operational cost. First the capital cost will be estimated. The capital cost consist out of the depreciation cost and the interest cost and. However, to estimate these cost, the building cost have to be estimated first. The building cost will be estimated in Section 4.1, The interest cost in Section 4.3 and the depreciation cost in Section 4.2. The total difference in capital cost can then be estimated in Section 4.4.

The operational cost consist out of the maintenance cost, fuel savings, manning cost and insurance cost. The maintenance cost will be estimated in Section 4.5, the fuel savings in Section 4.6 and the manning cost in Section 4.7. The total difference in operational cost can then be estimated in Section 4.9. The difference in capital cost and the difference operational cost are together the difference in total cost of ownership and will be determined in Section 4.10. Finally, a conclusion on the chapter will be given in Section 4.11. The structure of this chapter is shown in Figure 4.1.

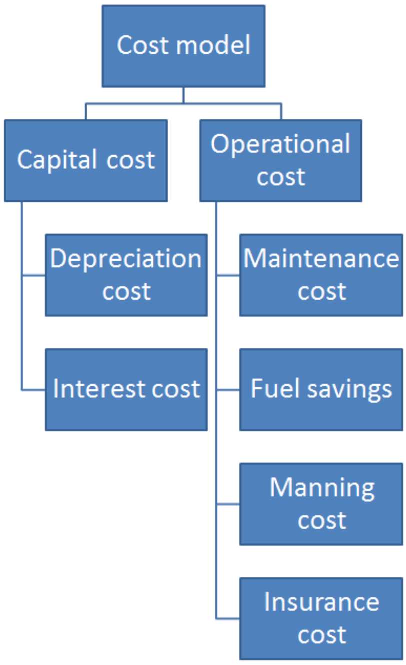


Figure 4.1: Structure of the cost model

4.1 Building cost

In this section, the building cost of the accommodation will be determined. In order to determine the building cost, the same structure as in Section 3.1, which is based on the Uniform Administration for Shipbuilding, will be used. In Section 4.1.1 the hull and outfitting cost will be discussed. The cost of the primary ship systems will be discussed in Section 4.1.2, followed by the cost for the electrical system in Section 4.1.3. Then, the cost of the deck equipment and the secondary ship systems will be looked at in Section 4.1.4 and Section 4.1.5. The cost of joinery and hotel equipment will be determined in Section 4.1.6, followed by the cost of the nautical, navigation and communication equipment in Section 4.1.7. The cost of the entertainment system will be determined in Section 4.1.7.2. Finally, the building cost will be compared for different sizes of ships in Section 4.1.8.

4.1.1 Hull and outfitting

The items that make up the hull and outfitting are the steel of the accommodation, windows, boarding platform gangway and the sun awnings. The cost of these items will be analyzed in Section 4.1.1.1 to Section 4.1.1.4.

4.1.1.1 Steel of the accommodation

The cost of the steel for the accommodation can estimated with Equation 4.1 [95]. In this equation $C_{st,material}$ is the material cost and $C_{st,installation}$ the installation cost. The steel weight for the accommodation has been determined in Section 3.1.1.1, but during production some steel will be lost due to cutting. The percentage of scrap can be determined with Equation 4.2 [95]. In this equation W_{dh} is the steel weight of the accommodation as determined in Section 3.1.1.1. The weight of the accommodation together with the scrap is the true amount of steel that has been used during the construction of the accommodation. Therefore, the gross weight of steel used can be determined with Equation 4.3 [95]. The material cost for one ton of steel are €1,320 [96]. Combining this with the amount of steel used, the material costs for the accommodation can be estimated with Equation 4.4 [95].

$$C_{st} = C_{st,material} + C_{st,installation} \quad [€] \tag{4.1}$$

$$scrap = 12 + \left(\left(\frac{W_{dh}}{1.0 \cdot 10^3} + 100 \right)^{-5.3} \cdot 54 \cdot 10^{10} \right) \quad [\%] \tag{4.2}$$

$$W_{st,gross} = W_{dh} \cdot \left(1 + \frac{scrap}{100} \right) \quad [ton] \tag{4.3}$$

$$C_{st,material} = 1.32 \cdot 10^3 \cdot W_{st,gross} \quad [€] \tag{4.4}$$

The installation costs are dependent on the amount steel used and the time it takes to process one ton of steel. The time it takes to process one ton of steel can, according to Aalbers, be determined with Equation 4.5 [95]. In this equation l is the length of the accommodation, b the beam and h_j the height of the accommodation above deck. The cost of one man-hour of work is assumed to be €50. When one combines this with the amount of steel used and the time it takes to process one ton of steel, Equation 4.6 is obtained for the installation costs of the steel for the accommodation.

$$k = 8.66 \cdot 10^{-1} \cdot \left(45.36 \cdot \left(\frac{l \cdot b \cdot h_j}{10^3} \right)^{-0.115} + 3.5 \right) \quad [\mathrm{h/ton}] \tag{4.5}$$

$$C_{st,installation} = 4.33 \cdot 10 \cdot W_{st,gross} \cdot \left(45.36 \cdot \left(\frac{l \cdot b \cdot h_j}{10^3} \right)^{-0.115} + 3.5 \right) \quad [€] \tag{4.6}$$

The total cost for steel of the accommodation is about €250,000 for a containerfeeder and €1,810,000 for a large ocean liner container vessel. The particulars of the accommodation are given in Table 3.1.

4.1.1.2 Windows

The costs for windows can be estimated with Equation 4.7 [95]. In this equation $C_{Window,material}$ is the material cost and $C_{Window,installation}$ the installation cost. The material cost can be estimated with Equation 4.8. In this equation N_{Window} is the number of windows installed and c_{Window} the cost per window, which is about €375 for a fixed window of average size of 750 x 500 mm. For the installation cost, it is assumed that it will take ten man-hours to install a window and that the cost of one man-hour is €50. Combining these numbers, the installation cost for windows is €500 per window and the total installation cost can be estimated with Equation 4.9.

$$C_{Window} = C_{Window,material} + C_{Window,installation} \quad [€] \tag{4.7}$$

$$C_{Window,material} = N_{Window} \cdot c_{Window} \quad [€] \tag{4.8}$$

$$C_{Window,installation} = 5 \cdot 10^2 \cdot N_{Window} \quad [€] \tag{4.9}$$

The total cost for windows are about €20,000 for a containerfeeder and €160,000 for a large ocean liner container vessel.

4.1.1.3 Boarding platform gangway

It is very uncertain if the boarding platform for the gangway can truly be removed from the ship when ships become unmanned as the platform might be required when people occasionally need to be on-board to do repairs or maintenance work. When the platform will removed from the ship, one assumes that human presence is never required on-board the ship. Since it is unlikely that this will be the case, the boarding platform gangway will be left out of the cost analysis.

4.1.1.4 Sun awnings

The number of sun awnings is dependent on the number of windows present on the ship. The cost for the sun awnings will be low compared to other cost. Therefore, the influence of sun awnings will not be taken into account for the cost analysis.

4.1.2 Primary ship systems

The primary ship systems that are affected by unmanned shipping are the fresh water and sanitary system and the HVAC system of the accommodation. The cost for these systems will be analyzed in Section 4.1.2.1 and Section 4.1.2.2.

4.1.2.1 Fresh water and sanitary systems

The cost for the fresh water and sanitary systems can be determined with Equation 4.10 [95]. In this equation $C_{Fresh,material}$ is the material cost and $C_{Fresh,installation}$ the installation cost. The material cost for the fresh water system can be estimated with Equation 4.11. In this equations is $C_{Piping,Fresh,supply}$ is the cost of the piping for the supply of fresh water, $C_{Piping,Fresh,return}$ the cost of the piping to the sewage tank and $C_{Fresh,pump}$ the cost of the pump.

$$C_{Fresh} = C_{Fresh,material} + C_{Fresh,installation} \quad [€] \tag{4.10}$$

$$C_{Fresh,material} = C_{Piping,Fresh,supply} + C_{Piping,Fresh,return} + C_{Fresh,pump} \quad [€] \tag{4.11}$$

The cost of the piping for the supply of fresh water can be estimated with Equation 4.12. In this equation $C_{Piping,main,supply}$ is the cost of main supply pipe per deck, $C_{Piping,sub,supply}$ the cost of supply subpipe per deck, $C_{Piping,vert,supply}$ the cost for vertical supply pipe and N_{Deck} the number of decks in the accommodation. The costs for the different types of supply pipe can be determined with Equation 4.13 to Equation 4.15. In these equations $L_{Pipe,main,supply}$, $L_{Pipe,sub,supply}$ and $L_{Pipe,vert,supply}$ are the total length of supply pipe as determined in Section 3.1.2.1 and $c_{Pipe,main,supply}$, $c_{Pipe,sub,supply}$ and $c_{Pipe,vert,supply}$ the specific costs of the different type of pipe, which are dependent on the diameter of the pipe as determined in Section 3.1.2.1. The specific cost for different diameters of pipe can be found in Table 4.1.

$$C_{Piping,Fresh,supply} = N_{Deck} \cdot (C_{Piping,main,supply} + C_{Piping,sub,supply}) + C_{Piping,vert,supply} \quad [€] \tag{4.12}$$

$$C_{Piping,main,supply} = L_{Pipe,main,supply} \cdot c_{Pipe,main,supply} \quad [€] \tag{4.13}$$

$$C_{Piping,sub,supply} = L_{Pipe,sub,supply} \cdot c_{Pipe,sub,supply} \quad [€] \tag{4.14}$$

$$C_{Piping,vert,supply} = L_{Pipe,vert,supply} \cdot c_{Pipe,vert,supply} \quad [€] \tag{4.15}$$

Nominal diameter [inch]	Internal diameter [mm]	Wall thickness [mm]	External diameter [mm]	Specific cost [€/m]
0.5	15.7	2.8	21.3	3.00
0.75	20.9	2.9	26.7	3.20
1	26.6	3.4	33.4	4.40
1.5	40.9	3.7	48.3	5.80
2	52.5	3.9	60.3	6.95
3	77.9	5.5	88.9	13.00
4	102.3	6.0	114.3	16.30
5	128.1	6.6	141.3	26.60
6	154.1	7.1	168.3	32.90
8	202.7	8.2	219.1	50.60
10	254.4	9.3	273.0	76.30
12	304.9	9.5	323.9	102.30
14	336.6	9.5	355.6	113.50
16	387.4	9.5	406.4	135.30
20	489.0	9.5	508.0	216.60

Table 4.1: Sizes and cost of piping for fresh water and sanitary systems [57]

The diameter for the return pipes is for all types of pipe equal, as explained in Section 3.1.2.1 and therefore is the specific cost for those pipes equal. This is mathematically shown in Equation 4.16. Then the cost of the return piping can be estimated with Equation 4.17. In this equation $L_{Pipe,main,return}$, $L_{Pipe,sub,return}$ and $L_{Pipe,vert,return}$ are the lengths of the different type of pipe as determined in Section 3.1.2.1, N_{Deck} the number of decks in the accommodation and $c_{Pipe,fresh,return}$ the specific cost for the return pipes.

$$c_{Pipe,sub,return} = c_{Pipe,main,return} = c_{Pipe,vert,return} = c_{Pipe,fresh,return} \quad [€/\mathrm{m}] \tag{4.16}$$

$$\begin{aligned} C_{Piping,Fresh,return} \quad = \quad & c_{Pipe,fresh,return} \cdot (N_{Deck} \cdot (L_{Pipe,main,return} + \\ & L_{Pipe,sub,return}) + L_{Pipe,vert,return}) \quad [€] \end{aligned} \tag{4.17}$$

The cost for the pump, $C_{Fresh,pump}$ is approximately €8,000, according to Wärtsilä, for the pump chosen in Section 3.1.2.1. The installation cost for the fresh water and sanitary systems, based on a man-hour rate of €50, can be estimated with Equation 4.18 [95]. In this equation l is the length of the accommodation, b the breadth of the accommodation and h_{Acco} the height of the accommodation.

$$C_{Fresh,installation} = 1.38 \cdot 10^2 \cdot l \cdot (b + h_{Acco}) \quad [€] \tag{4.18}$$

The total cost for the fresh water and sanitary systems is about €50,000 for a container-feeder and €190,000 for a large ocean liner container vessel.

4.1.2.2 HVAC Accommodation

For the determination of the cost of the HVAC system in the accommodation, a slightly different approach is used than in the other sections of this chapter. For the HVAC system in the accommodation, a HVAC system for a reference ship is designed at RH Marine and the cost have been determined. The volume of the accommodation of the reference vessel is about 1,200 m^3 and the HVAC system for this accommodation costs about €210,000. When one wants to calculate the cost of the HVAC system for a accommodation with a different volume, one can use Equation 4.19.

$$C_{HVAC} = 2.1 \cdot 10^5 \cdot \left(\frac{l \cdot b \cdot h_{Acco}}{1.2 \cdot 10^3} \right)^{0.65} \quad [€] \tag{4.19}$$

The equation uses the volume ratio between the accommodation of the reference ship and the ship one wants to calculate to the power of 0.65. This power is used to compensate for the aspect that larger systems are relatively cheaper. The approach described is also used at RH Marine to estimate the cost for HVAC systems at ships before a detailed design is made. The cost for the HVAC system are about €200,000 for a containerfeeder and €1,150,000 for a large ocean liner container vessel.

4.1.3 Electrical system

The parts of the electrical system that are affected by unmanned shipping are the power generating system, the cables and wires in the accommodation, switch boards and the lighting in the accommodation. The cost of these items will be analyzed in Section 4.1.3.1 to Section 4.1.3.4.

4.1.3.1 Power generating systems

The cost that can be saved by installing a smaller generator can be divided in cost for the generator itself and cost for the installation of the generator. The material cost and the installation cost are dependent on the power of the generator, P, and can be calculated with Equation 4.20 [95] and Equation 4.21 [95]. To determine the difference in cost, it is not possible to fill in the difference in power in these equations, due to the non-linear character of these equations. Instead, one should substitute P_{Gen} and P_{Peak} in Equation 4.20 and Equation 4.21. P_{Gen} is the power of the installed generator and P_{Peak} the required power determined in Section 3.2. The difference in material cost and installation cost can then be determined with the help of Equation 4.22 and Equation 4.23. Finally, the difference in cost for power generating system can be determined with Equation 4.24.

$$C_{gen,material} = 9.25 \cdot 10^3 \cdot P^{0.62} \quad [€] \tag{4.20}$$

$$C_{gen,installation} = 1.0 \cdot 10^3 \cdot P^{0.55} \quad [€] \tag{4.21}$$

$$\Delta C_{gen,material} = C_{gen,material} \left(P_{gen}\right) - C_{gen,material} \left(P_{gen} - P_{Peak}\right) \quad [€] \tag{4.22}$$

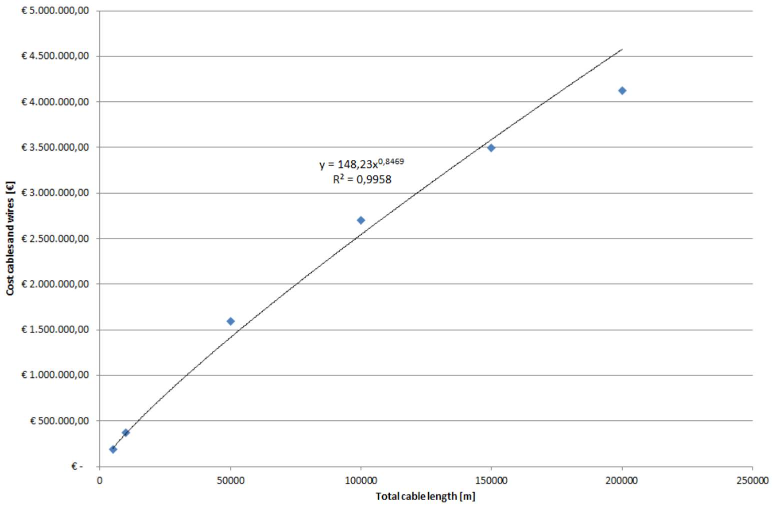


Figure 4.2: Analysis cable and wire cost

$$\Delta C_{gen,installation} = C_{gen,installation}\left(P_{gen}\right) - C_{gen,installation}\left(P_{gen} - P_{Peak}\right) \quad [€] \tag{4.23}$$

$$\Delta C_{gen} = \Delta C_{gen,material} + \Delta C_{gen,installation} \quad [€] \tag{4.24}$$

The total cost saving for the power generating system is about €50,000 for containerfeeder and €360,000 for a large ocean liner container vessel.

4.1.3.2 Cables and wires accommodation

The required amount of cables and wires that distributes the power from the engine room to the users in the ship is determined in Section 3.1.3.1 with Equation 3.49. However, next to weight, these cables and wires have a cost for material and installation. The total cost for cables and wires is based on the total length used and the specific cost per meter of installed cable, which decreases with length, according to experts at RH Marine [66]. At RH Marine, a calculation sheet is used to determine cost for cables and wires. The calculation sheet takes both material and installation cost into account. The cost for cables and wires has been analyzed with the help of this calculation sheet and the results of this analysis are given in Figure 4.2. Since the total length of installed cables and wires is known, the cost for cables and wires can be estimated with Equation 4.25.

$$C_{cables} = 148.23 \cdot S_{cables}^{0.8469} \quad [€] \tag{4.25}$$

The total cost for cables and wires is about €420,000 for containerfeeder and €3,060,000 for a large ocean liner container vessel.

4.1.3.3 Switch boards

As explained in Section 3.1.3.2, the amount and size of switch boards will not change much due to unmanned shipping, according to experts at RH Marine, as most power users will still be present when ships become unmanned. Next, the users that are no longer present, are relatively small users. However, what could happen, according to these experts, is that fewer local distribution boards are needed. The cost of these local distribution boards is, according to the experts, in the order of €40,000. Since there is in general one local distribution board for the accommodation, it is assumed for this thesis that the cost reduction for switch boards is €40,000.

4.1.3.4 Lighting accommodation

The cost for lighting in the accommodation is dependent on the type of lamp chosen and the amount of lamps required to light the accommodation. The number of armatures can be calculated with Equation 3.53 in Section 3.1.3.3. The cost for a TL-lamp are €140 per armature, for a LED lamp €200 and for a halogen lamp €70. This includes both the material cost and the cost for installation. The cost for cables are not included here, as those are accounted for in Section 4.1.3.2. The cost for lighting in the accommodation can be estimated with Equation 4.26.

$$C_{Lighting} = N_{Armature} \cdot C_{Armature} \quad [€] \tag{4.26}$$

In this equation is $N_{Armature}$ is the number of installed armatures and $C_{Armature}$ the cost of one armature. The total cost for lighting in the accommodation is about €20,000 for a containerfeeder and €190,000 for large ocean liner container vessel.

4.1.4 Deck equipment

The only deck equipment that can be removed is the lifesaving equipment, consisting of the lifeboat and the davit. The size of the lifeboat is dependent on the number of crew and the drop height. Different lifeboats fit in the same davit as can be seen in Table 4.2. The table shows the cost of the complete system for both material and installation cost combined.

Type of lifeboat	Capacity [persons]	Drop height [m]	Type of davit	Total system cost [€]
LBF 490 C	16	16	JYF55	82,000
LBF 580 C	26	17	JYF55	84,000
LBF 680 C	33	22	JYF75	94,000
LBF 750 C	36	22	JYF75	102,000
LBF 850 C	40	25	JYF90	123,000

Table 4.2: Cost of free-fall systems [72]

The cost for deck equipment is €82,000 for a containerfeeder and €102,000 for a large ocean liner containervessel.

4.1.5 Secondary ship systems

The only secondary ship system that can be removed is the firefighting system in the accommodation. The cost for the firefighting system can be estimated with Equation 4.27 [95]. In this equation $C_{Fifi,material}$ is the material cost and $C_{Fifi,installation}$ the installation cost. The installation cost for the firefighting system can be estimated with Equation 4.18 [95], since both types of piping require the same work in the same space. The material cost for the firefighting system can be estimated with Equation 4.28. In this equation $C_{Piping,Fifi}$ is the cost for the piping of the firefighting system and $C_{Fifi,Pump}$ the cost for the pump of the firefighting system. The cost for piping of the firefighting system can be determined with Equation 4.29.

$$C_{Fifi} = C_{Fifi,material} + C_{Fifi,installation} \tag{4.27}$$

$$C_{Fifi,material} = C_{Piping,Fifi} + C_{Fifi,Pump} \quad [€] \tag{4.28}$$

$$C_{Piping,Fifi} = N_{Deck} \cdot (C_{Piping,Fifi,sub} + C_{Piping,Fifi,main}) + C_{Piping,Fifi,vert} \quad [€] \tag{4.29}$$

In this equation $C_{Piping,Fifi,sub}$, $C_{Piping,Fifi,main}$ and $C_{Piping,Fifi,vert}$ are the costs for the different types of pipe which can be determined with Equation 4.30 to Equation 4.32 and N_{Deck} is the number of decks in the accommodation. The lengths in Equation 4.30 to Equation 4.32 are the lengths which have been determined in Section 3.1.5. Furthermore, $c_{Pipe,Fifi,sub}$, $c_{Pipe,Fifi,main}$ and $c_{Pipe,Fifi,vert}$ are the specific costs for the different types of pipe. These specific costs can be determined with the help of Table 4.1 and are dependent on the diameter of the pipe as determined in Section 3.1.5.

$$C_{Piping,Fifi,sub} = L_{Pipe,Fifi,sub} \cdot c_{Pipe,Fifi,sub} \quad [€] \tag{4.30}$$

$$C_{Piping,Fifi,main} = L_{Pipe,Fifi,main} \cdot c_{Pipe,Fifi,main} \quad [€] \tag{4.31}$$

$$C_{Piping,Fifi,vert} = L_{Pipe,Fifi,vert} \cdot c_{Pipe,Fifi,vert} \quad [€] \tag{4.32}$$

Finally, the cost for the pump has to be determined. According to Wärtsilä, the pump chosen in Section 3.1.5 costs approximately €12,000. Summing up the different cost will result in a total cost for the firefighting system of about €40,000 for a containerfeeder and €190,000 for a large ocean liner container vessel.

4.1.6 Joinery and hotel equipment

The joinery and hotel equipment of the accommodation consists of the interior of the wheelhouse, living quarters, but also of the equipment for stores as explained in Section 3.1.6. However, the joinery and hotel equipment cost can be calculated with Equation 4.33 [95]. In this Equation $C_{Joinery,material}$ is the cost for the different equipment and $C_{Joinery,installation}$ the cost for installing the equipment.

$$C_{Joinery} = C_{Joinery,material} + C_{Joinery,installation} \quad [€] \tag{4.33}$$

According to Aalbers, it costs about €750 per square meter in material cost to arrange the accommodation [95]. Therefore the material cost for the joinery can be estimated with Equation 4.34. Furthermore, the cost for installation can, according to Aalbers, be estimated with Equation 4.35 [95]. For this equation it is assumed that one man-hour costs €50. Next suggests the power of 0.55 that larger floor areas result in relatively lower cost.

$$C_{Joinery,material} = 7.5 \cdot 10^2 \cdot A_{floor} \quad [€] \tag{4.34}$$

$$C_{Joinery,installation} = 1.25 \cdot 10^4 \cdot A_{floor}^{0.55} \quad [€] \tag{4.35}$$

The total cost for joinery hotel equipment is about €660,000 for containerfeeder and €4,510,000 for a large ocean liner container vessel.

4.1.7 Nautical, navigation and communication equipment

The systems that are affected by unmanned shipping and that are part of this group are the internal communication and the entertainment systems. The cost for these systems will be determined in Section 4.1.7.1 and Section 4.1.7.2.

4.1.7.1 Internal communication

The cost for the internal communication system can be divided in cost for the stations and the cost for the terminal module. The cost for one terminal module with a capacity of 24 stations is €1,750 and the cost for a station is €100 [83]. This excludes the cost of cables and wires, which have been accounted for in Section 4.1.3.2. Therefore the cost for the internal communication system can be estimated with Equation4.36 [83].

$$C_{IntCom} = 1.0 \cdot 10^2 \cdot N_{Ph} + 1.75 \cdot 10^3 \cdot N_{TM} \quad [€] \tag{4.36}$$

In this equation N_{Ph} is the number of stations and N_{TM} the number of terminal modules. Based on Equation 4.36, one can state that the influence of the internal communication system on cost is very limited. The total cost for internal communication are about €2,000 for containerfeeder and €3,000 for a large ocean liner container vessel.

Component	Cost [€]
Antenna [84]	17,500.-
Amplifier [85]	500.-
Satellite receiver [86]	100.-
24" LED TV [87]	200,-

Table 4.3: Cost of components of the entertainment system

4.1.7.2 Entertainment systems

The entertainment system consists of an antenna to receive the television signal, an amplifier which amplifies the signal received by the antenna, a 24 inch LED television and a satellite receiver which allows different televisions to be switched to different channels. The system requires one antenna, one amplifier for every 25 televisions and one satellite receiver for every television. The cost for the different components of the system are given in Table 4.3. The cost for the entertainment system can be estimated with Equation 4.37. In this equation N_{SatA} is the number of antennas, N_{Amp} the number of amplifiers, N_{SatRec} the number of satellite receivers and N_{TV} the number of televisions.

$$\begin{aligned} C_{EntS} &= 1.75 \cdot 10^4 \cdot N_{SatA} + 5.0 \cdot 10^2 \cdot N_{Amp} + \\ & \quad 1.0 \cdot 10^2 \cdot N_{SatRec} + 2.0 \cdot 10^2 \cdot N_{TV} \quad [€] \end{aligned} \tag{4.37}$$

The total cost for the entertainment system are about €20,000 for a containerfeeder and €40,000 for a large ocean liner container vessel.

4.1.8 Comparison of the building cost for different sized ships

In this section the results of the building cost for different size of ships will be compared, to analyze if there are significant differences. The analysis is based on the difference in building cost distribution of a container feeder and a large ocean liner container vessel. The vessel particulars of the ships are given in Table 3.9. The difference in building cost distribution of the containerfeeder is given in Figure 4.3 and the difference in building cost distribution of the large ocean liner container vessel in Figure 4.4. One can see that the major contributors to the building cost are about the same portion for both sizes of ships as those are dependent on the dimensions of the accommodation. The contribution of deck equipment to the total building cost reduces as the investment required for a larger crew is relatively lower. Furthermore, one can see that the cost for fresh water and sanitary systems and the firefighting system reduces relatively with size. Overall, one can conclude that the distribution of the items that make up the building cost is similar for both the containerfeeder and the large ocean liner container vessel. The total building cost are about €1,854,000 for a containerfeeder and €11,805,000 for a large ocean liner container vessel.

To validate the results of the building cost estimation without the help of practical data, since this was not available, it will be looked at the source of the data that was used to create the estimation of the building cost. In Figure 4.3 and Figure 4.4 it can seen that joinery and hotel equipment, cables and wires accommodation, steel accommodation and HVAC accommodation are the largest contributors to the building cost of the accommodation. The cost for the joinery and hotel equipment and the steel accommodation have been determined with the help of the approach defined by Aalbers [95]. However, the figures used in this approach have become dated. Therefore, the figures have been updated to current values. The approach defined by Aalbers has proven its validity and by updating the values in the figures, the results for the joinery and hotel equipment and steel accommodation are also valid. The cost for the cables and wires in the accommodation has been determined with the help of practical data from RH Marine and therefore the result for cables and wires is valid. The cost for the HVAC system is estimated by calculating the cost the HVAC system on a reference ship and correct for the volume of the accommodation. This approach is also used by RH Marine to estimate the cost for the HVAC system before a detailed design is made. Since the same approach is used at RH Marine, the result for the HVAC system is valid. Furthermore, the cost for the deck equipment and windows have been derived from supplier data and are therefore valid. For the power generating systems, the approach as defined by Aalbers is again applied and therefore the result is valid. The result for the fresh water and sanitary systems and the firefighting system, the result is less certain, because for these systems a piping lay-out has been assumed which results in estimated piping lengths. However, the piping diameter is plausible and therefore the specific cost for the piping is plausible. Besides, the largest contributors to the building cost can be validated and therefore one can conclude that the magnitude of the building cost results are also likely to be valid.

To put the result of the building cost estimation in perspective, the building cost of the complete ship have been determined with the help of the approach defined by Aalbers [95]. It results in an approximate building cost for the containerfeeder of about €12,000,000 and €169,000,000 for the ocean liner container vessel. Putting the cost reductions by removing the accommodation in perspective, the building cost can be reduced by 15% for a containerfeeder and by 7% for a large ocean liner container vessel.

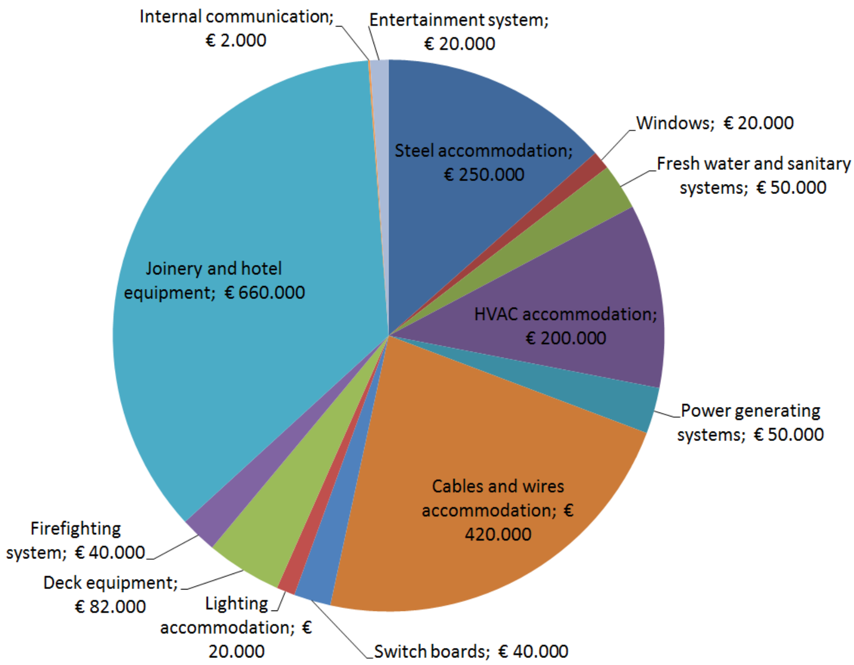


Figure 4.3: Difference in building cost distribution containerfeeder

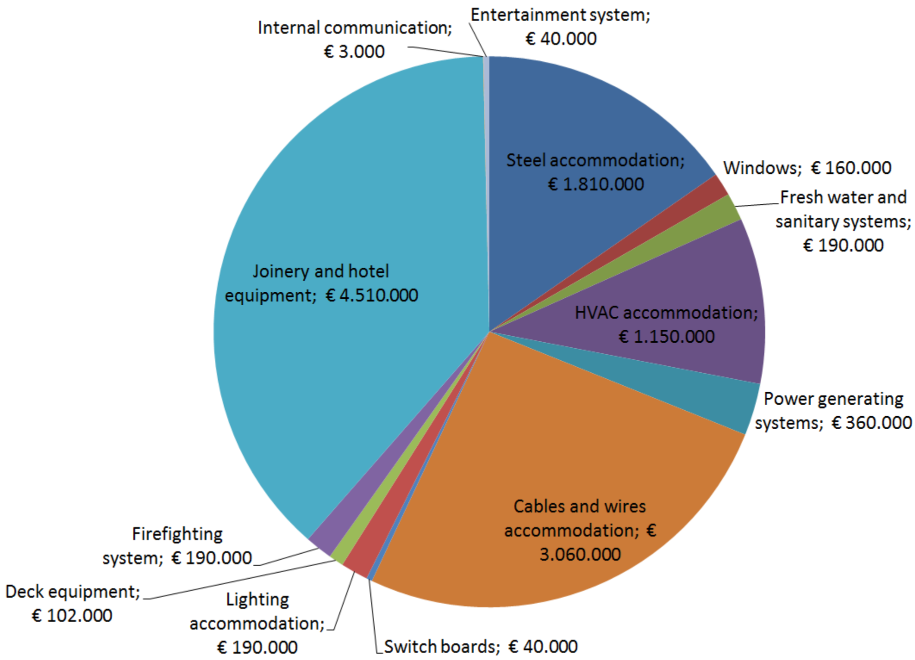


Figure 4.4: Difference in building cost distribution large ocean liner container vessel

4.2 Depreciation cost

The yearly depreciation cost, which account for the devaluation of the ship, and which are the savings the ship owner should make to be able to buy a similar ship after the depreciation period is over, can be estimated with Equation 4.38. In this equation $C_{Building}$ is the building cost of the accommodation as that part of the ship can be removed when ships become unmanned. These cost have been determined in Section 4.1. Furthermore, R_{Acco} is the residual value of the accommodation after the depreciation period T_{Dep}. The depreciation period equals the lifetime of the ship. The residual value in demolition is €240 per lightweight ton[1] [98]. The residual value can be calculated with Equation 4.39. In this equation is δW the lightweight reduction caused by the removal of the accommodation.

$$C_{Dep} = \frac{C_{Building} - R_{Acco}}{T_{Dep}} \quad [€] \tag{4.38}$$

$$R_{Acco} = 2.4 \cdot 10^2 \cdot \delta W \quad [€] \tag{4.39}$$

The depreciation costs are about €72,800 per year for a containerfeeder and €459,600 per year for a large ocean liner container vessel. With a lifetime of 25 years, the depreciation costs are about €1,820,000 for a containerfeeder and €11,490,000 for a large ocean liner container vessel.

4.3 Interest cost

The interest cost are the costs the ship owner has to pay for the loan on the ship, which can be calculated with Equation 4.40, which uses the linear method for calculating the interest cost. In Equation 4.40 is $C_{Building}$ is the building cost of the accommodation, L_{Rate} the percentage of the building cost that have been financed with a loan, I_{Rate} the interest rate, T_{Int} the period over which the loan has to be paid back in years which equals the lifetime of the ship [99]. The factor 0.5 and the additional year for the interest period compensate that one pays more interest at the beginning of the interest period than at the end.

$$C_{Int} = 0.5 \cdot L_{Rate} \cdot C_{Building} \cdot I_{Rate} \cdot (T_{Int} + 1) \quad [€] \tag{4.40}$$

For this thesis it is assumed that 60% of the building costs have been financed with a loan at an interest rate of 7% over a period of 25 years [99]. The total interest cost is about €1,010,000 for a containerfeeder and €6,450,000 for a large ocean liner container vessel. With a period of 25 years, the average annual interest cost will be about €40,400 for a containerfeeder and €320,400 for a large ocean liner container vessel.

[1] For the conversion of the demolition prices, it is taken that €1 is $0.96 [97].

4.4 Difference in capital cost for different sized ships

In Section 4.3 the interest cost and in Section 4.2 the depreciation cost have been estimated. Together, these costs are the difference in capital cost. Combining the results from these sections, the total difference in capital cost is €2,830,000 for a containerfeeder and €17,940,000 for a large ocean liner container vessel. To validate the results for the difference in capital cost without the help of practical data, since this is not available, it will be looked at the source of the data that was used to estimate the difference in capital cost. The approach used to determine the interest cost is also used in ship finance and therefore valid [99]. Furthermore is the approach used to determine the depreciation cost in literature [100]. Since both the approaches are valid, the results for the difference in capital cost are likely to be valid too.

To put the results for the difference in capital cost in perspective, the capital cost for the complete ship have been determined for the building cost of the complete ship. It results in an approximate capital cost for the containerfeeder of about €18,113,000 and €253,546,000 for the ocean liner container vessel. Putting the capital cost reductions by removing the accommodation in perspective, the capital cost can be reduced by 15% for a containerfeeder and by 7% for a large ocean liner container vessel.

4.5 Maintenance cost

Maintaining a vessel is next to being necessary also required by company policy, the classification society and the charterers of the vessel who choose to inspect it [101]. *"There are two types of maintenance that can be assessed. One is routine maintenance which includes maintaining the main engine and auxiliary equipment, painting the superstructure and carry out steel renewal in those holds and cargo tanks that safely be accessed when the ship is out sea"* [101][p164]. The other type of maintenance can happen when something breaks down. In this case may mechanical failure result in additional cost outside covered by routine maintenance. Work of this type is often performed at a ship repair yard and therefore likely to be expensive [101]. Performing maintenance at sea is a day job for the engineer which should be moved to shore when ships become unmanned. The maintenance should then be performed while the ship is in port or during dry docking, leading to extra off-hire days [25]. On the other hand may improved maintenance regimes lead to less off-hire days [25]. Methods that could help with this are preventive and condition based maintenance. With condition based maintenance, the equipment tells the engineer when maintenance is required. Since maintenance cost is among the most poorly researched and documented of ship operation, it is, for the purpose of this research, assumed that the consequences of better maintenance regimes and extra maintenance performed in port, cancel out against each other and that therefore the number of off-hire days and maintenance cost for the unmanned ship will be similar to the manned ship [25, 101, 100].

4.6 Fuel savings

The fuel cost saving by the generators is dependent on the time traveled. The time traveled for one single way trip can be determined with Equation 4.41 [100]. In this equation S is the distance between two ports in nautical miles and V_S the ship's velocity in knots. However, the ship also has to cover some distance in ports to get from the quay to sea or the other way around. This distance is given by S_{Port} and the velocity in the harbor is often lower than the velocity at sea. Therefore, the speed in the harbor is given by $V_{S,Port}$. Furthermore, the vessel needs to be loaded and unloaded and must maintenance be performed. The time spend on this is given by T_{Port}.

$$T_{Trip} = \frac{S}{V_S} + \frac{S_{Port}}{V_{S,Port}} + T_{Port} \quad [\mathrm{h}] \tag{4.41}$$

The amount of fuel on one trip can be calculated with Equation 4.42. In this equation T_{Trip} is the time in hours it takes to make one trip, $\dot{m}_f$ the average massflow of fuel in kg/s, as can be determined with Equation 3.68, and 3.6 a factor to convert from kg/s to ton/h.

$$m_{f,Trip,acco} = 3.6 \cdot T_{Trip} \cdot \dot{m}_f \quad [ton] \tag{4.42}$$

The fuel savings per year depend on the number of trips, which can be determined with Equation 4.43. In this equation T_{off} is the number of days off-hire per year and T_{Trip} the time it takes for one trip. The off-hire days are lost due to unforeseen maintenance and repairs and are assumed to be equal for both manned and unmanned ships. Once the number of trips per year is known, one can determine the fuel mass in ton used in one year with Equation 4.44.

$$N_{Trip} = \frac{24 \cdot (365 - T_{off})}{T_{Trip}} \quad [-] \tag{4.43}$$

$$m_{f,Year,acco} = m_{f,Trip,acco} \cdot N_{Trip} \quad [ton] \tag{4.44}$$

Since the fuel mass used per trip and per year is known, one can determine the fuel saved per trip and per year by sailing unmanned with Equation 4.45 and Equation 4.46[2]. In these equations $c_{Fuel,acco}$ is the fuel price of MDO used in the accommodation, and which may vary with time and port. One should keep in mind that the fuel savings calculated with Equation 4.45 and Equation 4.46 are only the savings caused by having a lower electrical power demand for unmanned ships, because systems and equipment installed on manned ships for the presence of humans have been removed.

$$C_{Fuel,Trip,acco} = m_{f,Trip,acco} \cdot c_{Fuel,acco} \quad [€] \tag{4.45}$$

[2]Once the fuel mass is known, one can determine the amount of emitted CO_2 as 3.2 ton of CO_2 is emmited per ton of fuel consumed [62].

$$C_{Fuel,Year,acco} = m_{f,Year,acco} \cdot c_{Fuel,acco} \quad [€] \tag{4.46}$$

When the dimensions of the ship are not limited by infrastructure, the dimensions of the unmanned ship will be smaller than the dimensions of the manned ship, resulting in a lower fuel consumption of the unmanned ship. To determine the fuel savings, as a result of these smaller dimensions, one should first determine the power required to sail at a certain speed with the manned ship. This can be done with the method of Holtrop and Mennen [102]. Then the admiralty constant, which is given in Equation 4.47, can be determined [62]. This constant can be used to estimate the power that has to be installed on ships with similar dimensions, which is the case for the difference between manned and unmanned ships.

$$C_{adm} = \frac{\Delta^{\frac{2}{3}} \cdot V_S^3}{P_B} \quad [\frac{ton^{\frac{2}{3}} \cdot kts^3}{kW}] \tag{4.47}$$

In this equation Δ is the displacement of the ship in ton, V_S the speed of the ship in knots and P_B the required power in kW. By applying Equation 4.47 to the manned and unmanned ship, the difference in required power for sailing at the same speed can be estimated with Equation4.48.

$$\delta P_B = P_{B,Manned} - P_{B,Unmanned} \quad [ton] \tag{4.48}$$

The fuel mass saved per trip, by sailing unmanned, with a smaller ship can be estimated with Equation 4.49 and the fuel saved per year can be determined with Equation 4.50.

$$m_{f,Trip,size} = \delta P_B \cdot SFC \cdot T_{Trip} \cdot 10^{-6} \quad [ton] \tag{4.49}$$

$$m_{f,Year,size} = m_{f,Trip,size} \cdot N_{Trip} \quad [ton] \tag{4.50}$$

In these equation δP_B is the difference in required power, SFC the specific fuel consumption in g/kWh, T_{Trip} the time it takes to do one single trip in hours, $m_{f,Trip,size}$ the fuel mass used in ton due to a smaller unmanned ship and N_{Trip} the number of trips per year. The fuel cost saving for having a smaller ship per trip and per year can be estimated with Equation 4.51 and Equation 4.52. In these equations is $c_{Fuel,size}$ the fuel price for the main engine which is assumed to be HFO, and which may vary with time and port.

$$C_{Fuel,Trip,size} = m_{f,Trip,size} \cdot c_{Fuel,size} \quad [€] \tag{4.51}$$

$$C_{Fuel,Year,size} = m_{f,Year,size} \cdot c_{Fuel,size} \quad [€] \tag{4.52}$$

The total fuel savings per trip and per year can be estimated with Equation 4.53 and Equation 4.54.

$$C_{Fuel,Trip} = C_{Fuel,Trip,acco} + C_{Fuel,Trip,size} \quad [€] \tag{4.53}$$

$$C_{Fuel,Year} = C_{Fuel,Year,acco} + C_{Fuel,Year,size} \quad [€] \tag{4.54}$$

If one assumes the fuel prices to be €375 per metric ton for MDO and €210 per metric ton for HFO [103][3], and a 3,000 nautical mile route. On this route, the containerfeeder sails 15 kts and the large ocean liner container vessel 17 kts. Furthermore taking 5 off-hire days per year and the ship not being limited by infrastructure for its dimensions. Then, the annual fuel cost saving is, dependent on the climate zone, between €59,200 and €136,400 for the containerfeeder and between €190,000 and €1,310,000 for the large ocean liner. With a lifetime of 25 years of the ship, the fuel cost saving can, dependent on the climate zone, be between €1,480,000 and €3,410,000 for the containerfeeder and between €4,750,000 and €32,750,000 for the large ocean liner container vessel. The fuel savings for the different climate zones can be seen in Figure 4.5. To determine the true fuel cost saving, one has to look at every individual case separately. Therefore the fuel cost saving will be determined for a specific ship in the case study in Chapter 5.

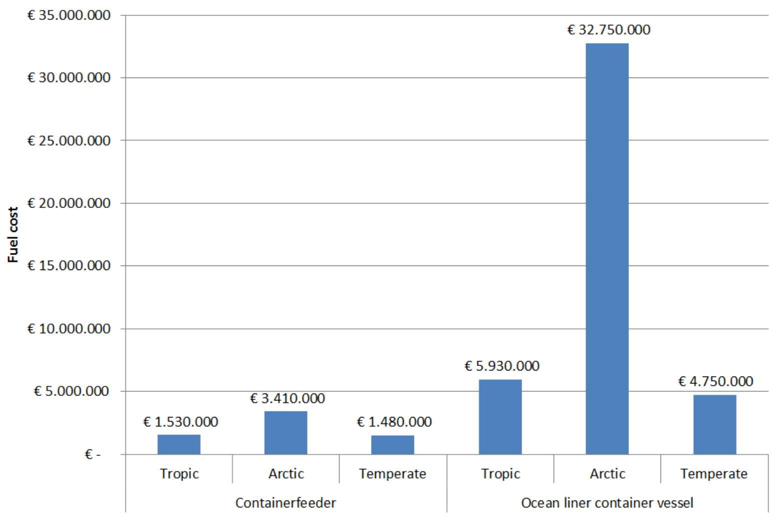


Figure 4.5: Fuel saving for different sized ships for a lifetime of 25 years in different climate zones

4.7 Manning cost

The cost for manning is the largest part of the operational cost [95]. However the cost for manning strongly depends on the nationality of the crew and the number of crew [95]. The annual manning cost can be calculated with Equation 4.55. In this equation N_{Crew} is the number of crew on the ship, c_{Crew} the average cost per crew per year in euros. This includes wages, traveling cost and victuals. Furthermore β is the upper roll factor to take into account for costs of crew on holidays [95].

[3] For the conversion of the fuel prices, it is taken that €1 is $0.96 [97].

$$C_{Manning} = N_{Crew} \cdot c_{Crew} \cdot \beta \quad [€] \tag{4.55}$$

The manning cost are €750,000 per year for a containerfeeder and €2,550,000 per year for a large ocean liner container vessel, when one assumes the average cost per crew per year to be €50,000 for a mixed crew with an upper roll factor of 1.5. With a 25 year lifetime of the ship, the saving on manning cost is about €18,750,000 for a containerfeeder and €63,750,000 for a large ocean liner container vessel.

4.8 Insurance cost

The cost for insurance can be estimated with Equation 4.56 and is divided into two parts, Protection & Indemnity and Hull & Machinery.

$$C_{Insurance} = C_{P\&I} + C_{H\&M} \quad [€] \tag{4.56}$$

The Protection & Indemnity insurance provides cover against third party liabilities as collision damage, oil pollution or injury of death of crew members [101]. It is also possible to take additional voluntary insurance to cover against war risks, strikes and loss of earnings [101]. The Hull & Machinery protects the owner of the vessel against physical damage of the ship and loss. Two important factors contribute in determining the level of H&M insurance: the owner's claim record and the age and condition of the ship. The insurance cost may change when more ships become unmanned, as the cost for P&I might go down when less claims are made. This is caused by unmanned shipping being more safe than manned shipping. On the other hand, the cost for H&M may go up as the equipment installed on unmanned ships is more sophisticated and therefore more expensive. However, it is also possible that cost for H&M will go down, as the way ships are maintained will change from repair after breaks down to preventive or condition based maintenance. Therefore, it is hard to say how the insurance cost will change, but one can expect the insurance cost in the early days of unmanned shipping to be higher than for manned shipping, due to unfamiliarity with this new type of shipping. Only time can tell how the insurance costs will change for unmanned shipping and making predictions about this is outside the scope of this research. Therefore, it will be assumed for this thesis that the insurance costs are similar for both the manned and unmanned ship.

4.9 Difference in operational cost for different sized ships

In Section 4.5 the maintenance cost and in Section 4.8 the insurance cost have been qualitatively analyzed and it has been concluded that the these cost will not significantly change when ships become unmanned. However, the fuel savings that have been analyzed in Section 4.6 and the manning cost which have been analyzed in Section 4.7 are influenced by unmanned shipping. These cost together are the difference in operational cost. Combining the results from these sections, the total difference in operational cost, for a lifetime of 25 years and for ships not being limited by infrastructure, is between €20,230,000 and €22,160,000 for a containerfeeder and between €68,500,000 and €96,500,000 for a large ocean liner container vessel.

To validate the results for the difference in operational cost without the help of practical data, since this is not available, it will be looked at the source of the data that was used to estimate the difference in operational cost. To determine the fuel savings, the approach defined by Hekkenberg have been used to determine the fuel savings for the accommodation [100]. The fuel savings due to the smaller dimensions of the ship have been determined with the help the approach defined by Kleinwoud and Stapersma [62]. For the fuel price, the current price in Rotterdam is used. The approaches used by Hekkenberg and Kleinwoud and Stapersma have both proven their validity and therefore, the results for the savings are also valid. However, one should keep in mind that the fuel price changes with time and therefore changes the result for the fuel savings with time.

To determine the manning cost, the approach defined by Aalbers is used [95]. In this approach an average cost per crew per year of €50,000 is used. To validate the manning cost, this figure should be validated. Therefore, the composition of the crew on-board Flinter owned ships was asked at Flinter. From this data it could be concluded that ships sail with mixed crews. Then the benchmarking tool Opcost 2016 from Moore Stephens was used to determine the average cost per crew per year [104]. From this benchmarking tool it was given that the average annual cost per crew are €55,000 in 2015. Since the validated figure is higher than the used figure, one can conclude that the results in this thesis for manning cost are slightly conservative. Although this is the case, the magnitude of the results is similar. Therefore, the results are still valid.

To put the results in perspective, the fuel cost for the manned ship have been determined. The fuel cost for a lifetime of 25 years are €29,400,000 for a containerfeeder and €458,060,000 for a large ocean liner container liner when one assumes the current price level. Sailing unmanned will therefore reduce the fuel cost by 5% to 12% for a containerfeeder and by 1% to 7% for a large ocean liner container vessel. However, one should keep in mind that the absolute figures given for the fuel cost are time depended and therefore currently low due to the low fuel price. The fuel price is related to the crude oil price which is currently low, as can be seen in Figure 4.6[105]. To put the manning cost in perspective, the manning cost are on average 51% of the operational cost on manned ships [104]. This is also shown in Figure 4.7. Putting the total operational cost in perspective, the operational cost can be reduced by 42% to 46% for a containerfeeder and by 13% to 18% for a large ocean liner container vessel.

Figure 4.6: Crude oil price [105]

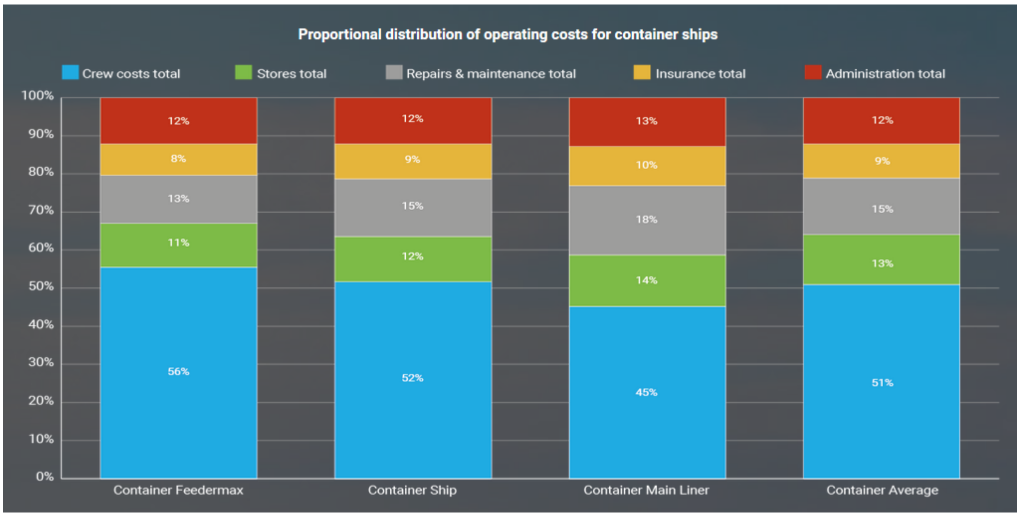
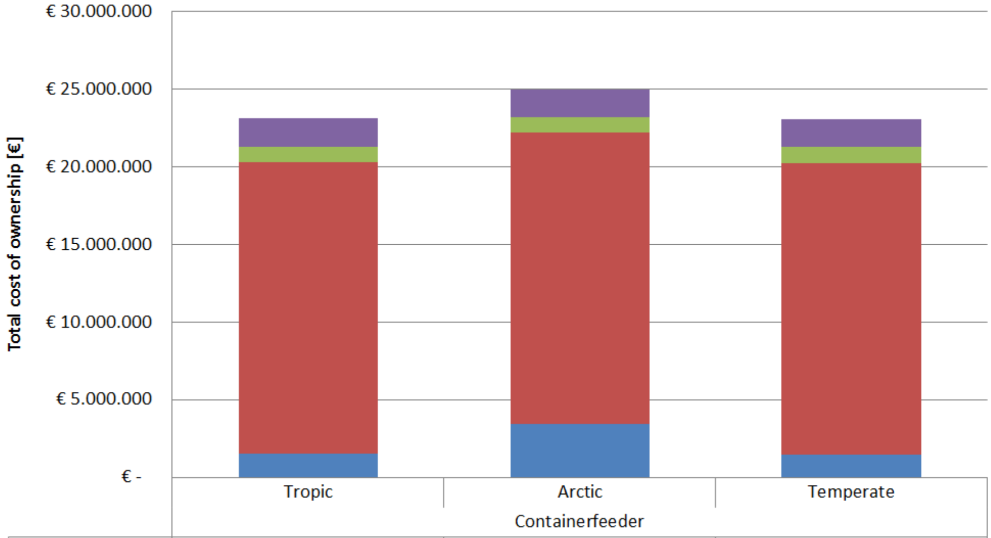


Figure 4.7: Operational cost distribution [104]

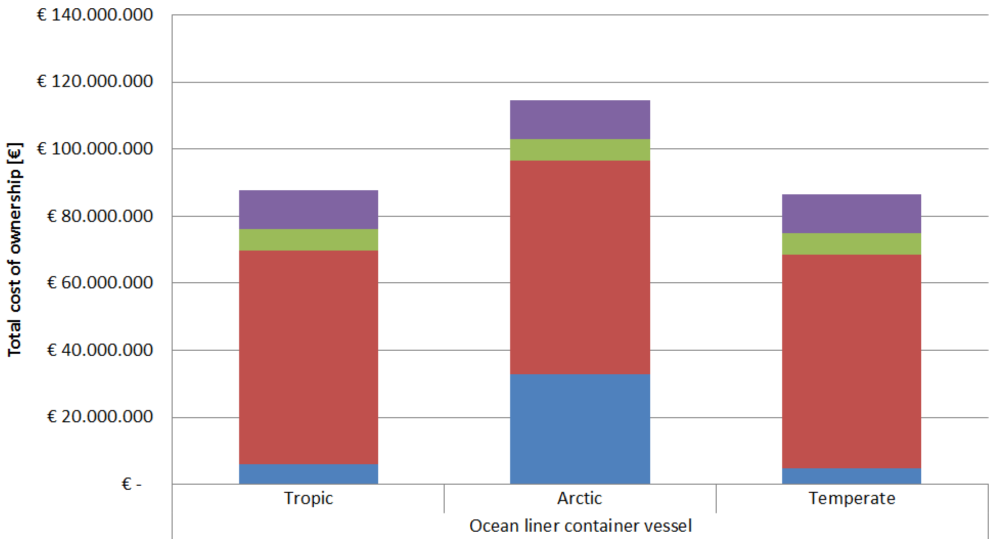
4.10 Difference in total cost of ownership for different sized ships

In this section the result of the difference in total cost of ownership for different sizes of ship will be compared to analyze if there are significant differences. The vessel particulars of the ships are given in Table 3.9. For this comparison, a lifetime of 25 years is assumed for the ship. The difference in capital cost is €2,830,000 for a containerfeeder and €17,940,000 for a large ocean liner container vessel. Furthermore, the difference in operational cost is is between €20,230,000 and €22,160,000 for a containerfeeder and between €68,500,000 and €96,500,000 for a large ocean liner container vessel. Combining the results for the capital and operational cost, results in a total saving between €23,060,000 and €24,990,000 over the lifetime for a containerfeeder and between €86,440,000 and €114,440,000 for a large ocean liner container vessel. A cost distribution for a containerfeeder in different climate zones is shown in Figure 4.8 and for a large ocean liner container vessel in Figure 4.9.



Containerfeeder	Tropic	Arctic	Temperate
Depreciation cost	€ 1.820.000	€ 1.820.000	€ 1.820.000
Interest cost	€ 1.010.000	€ 1.010.000	€ 1.010.000
Manning cost	€ 18.750.000,000	€ 18.750.000,000	€ 18.750.000,000
Fuel cost	€ 1.530.000	€ 3.410.000	€ 1.480.000

Figure 4.8: 25 year lifetime difference in cost distribution containerfeeder



Ocean liner container vessel	Tropic	Arctic	Temperate
Depreciation cost	€ 11.490.000	€ 11.490.000	€ 11.490.000
Interest cost	€ 6.450.000	€ 6.450.000	€ 6.450.000
Manning cost	€ 63.750.000,000	€ 63.750.000,000	€ 63.750.000,000
Fuel cost	€ 5.930.000	€ 32.750.000	€ 4.750.000

Figure 4.9: 25 year lifetime difference in cost distribution large ocean liner container vessel

One can see that the manning cost is the major part of the total cost of ownership. One can also see that the portion of the manning cost decreases with ship size. This is caused by the relatively lower number of crew compared to the size of the accommodation for larger ships. The building cost is mainly related to the size of the accommodation as explained in Section 4.1.8. This is also the case for depreciation cost and interest cost, as those costs are directly related to the building cost. Furthermore, the fuel cost saving is, next to fuel prices and route, also strongly dependent on the the size of the accommodation as the main contributor to the fuel consumption is the HVAC system which is strongly dependent on the size of the accommodation.

Since manning cost is the major part of the total cost of ownership, one can conclude that sailing unmanned will result in a major cost reduction which can be achieved by designing ships specially for unmanned shipping. Designing and operating these ships will require additional measures which have been discussed in Section 3.4, which require additional investments. The concept is only economically feasible when the reduction in costs exceeds the additional investments. This means that the additional investments should, for a period of 25 years, be less than €23,060,000 for a containerfeeder and be less than €86,440,000 for an ocean liner container vessel. The difference in total cost of ownership saved shows that one can save relatively more on small ships, than on large ones due to the relative difference in number of crew. The equations that make up the cost model have been summarized in Appendix J.

4.11 Conclusion

It is the goal of this chapter to answer the question "What are the cost of unmanned shipping compared to conventional ships?" as set out in Section 1.3. Based on a cost analysis for a containerfeeder and a large ocean liner container vessel, one can conclude that the distribution of the difference in building cost is similar for different sizes of ships. Furthermore, one can conclude that the largest contributors to the building cost are the joinery and hotel equipment, cables and wires in the accommodation and the HVAC system. Furthermore, one can conclude, based on a analysis of the total cost of ownership, that manning cost is the largest contributor to the total cost of ownership for a lifetime of 25 years. However the contribution of manning cost to the total cost of ownership reduces with size as relatively less crew is present on large ships. This also shows in the difference in total cost of ownership saved for the different sized ships. Over a lifetime of 25 years €23,060,000 for a containerfeeder and €86,440,000 on a large ocean liner container vessel can be saved. Conclusion, one can say that small ships are more interesting to design and operate as unmanned ships than large ships.

Chapter 5

Case study

The design model and the cost model which have been developed in Chapter 3 and Chapter 4 will be applied to a specific case in this chapter. However, before the design model and cost model can be applied, a reference vessel and a reference route are needed. These will be chosen in Section 5.1. Then, the design model can be applied to the reference ship and the reference route in Section 5.2. Changing the ship from a manned ship to an unmanned ship will also have consequences on parts of the ship that have nothing to do with human presence as discussed in Section 2.2.1. These parts are capacity, ship dimensions, trim and stability, seakeeping and the general arrangement of the systems. How the change from manned to unmanned will influence the reference ship will be discussed in Section 5.3. Then the cost analysis will be applied to the reference ship and route in Section 5.4. The chapter will end with a conclusion on the results in Section 5.5. The structure of this chapter is shown in Figure 5.1.

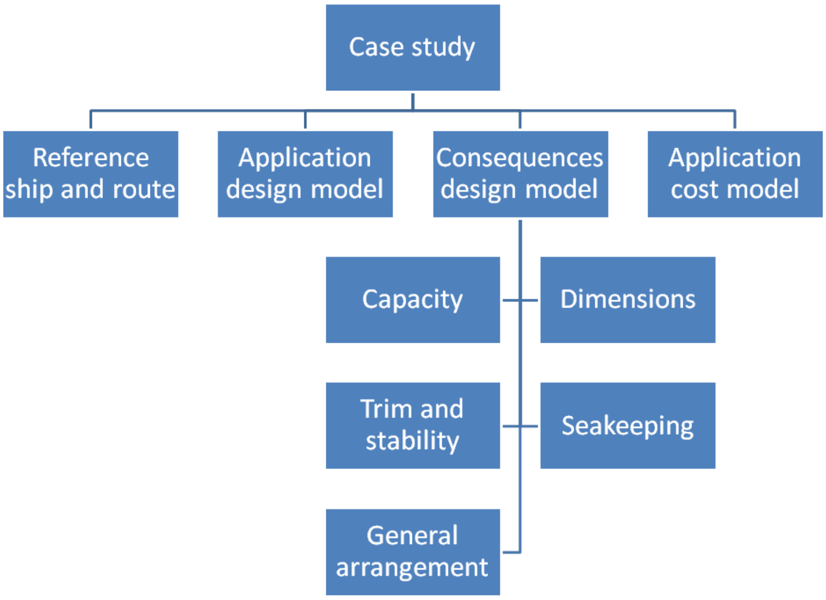


Figure 5.1: Structure of the case study

5.1 Reference ship and reference route

For the case study in which the parametric study will be applied, a reference ship and a reference route are needed. The ship will be used to quantify the change in the design requirements when the ship is specifically designed for unmanned shipping. The ship that will be used is a medium sized general cargo vessel, because medium sized ships are more likely to become unmanned than small and large ships. Small ships operate mainly close to shore and in busy waters which results in a higher risk of collision, while large ships mainly sail the oceans, but also have to enter the busy waterways when going to port. Large ships have a larger consequences in terms of damage to the environment when something goes wrong in the busy waterways. The medium sized ship however takes the best of both as it mainly sails the oceans and has lower consequences than the large ship when something goes wrong. A general cargo vessel is chosen because this vessel can ship both containers and bulk cargo. The reference ship, which is shown in Figure 5.2, is a general cargo vessel of M-Borg type, which is designed by Conoship. The particulars of the vessel can be found in Appendix K, but are summerized in Table 5.1. The general arrangement plan of the ship can be found in Appendix L.

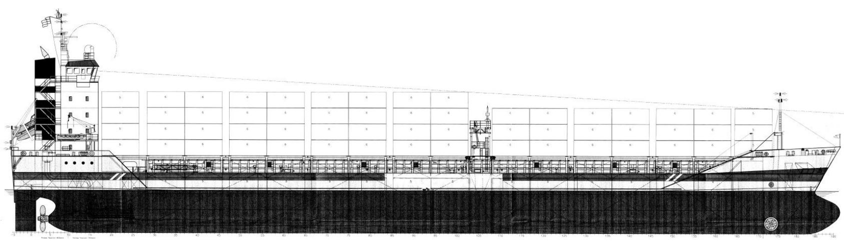


Figure 5.2: General cargo vessel of type M-borg

	Reference ship
L [m]	134.5
B [m]	16.5
D [m]	9.8
T [m]	7
DWT [ton]	8950
P_B [kW]	5280
$P_{Electric}$ [kW]	4100
l [m]	6.1
b [m]	10.5
h_{Acco} [m]	18.5
h_j [m]	15.85
N_{Deck} [-]	6
N_{Crew} [-]	11

Table 5.1: Vessel particulars reference ship

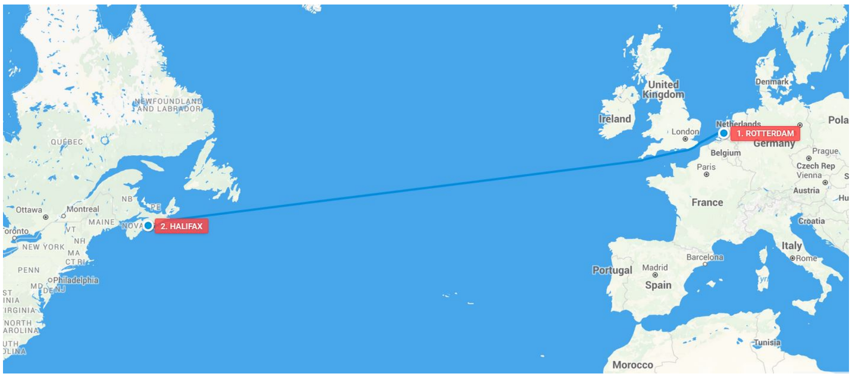


Figure 5.3: Shipping route between Rotterdam and Halifax [106]

The reference route, which is shown in Figure 5.3, is required to determine what weather and what climate the ship sails in. The ship will sail between the ports of Rotterdam in the Netherlands and Halifax in Canada. This route has a length of 3,150 nautical miles it is chosen because it lies in the temperate zone and the majority of ocean going ships sails in the temperate zone, as can be seen in Figure 5.4. The conditions the ship will encounter, which are required to determine the power of the HVAC system, can be found in Table 5.2.

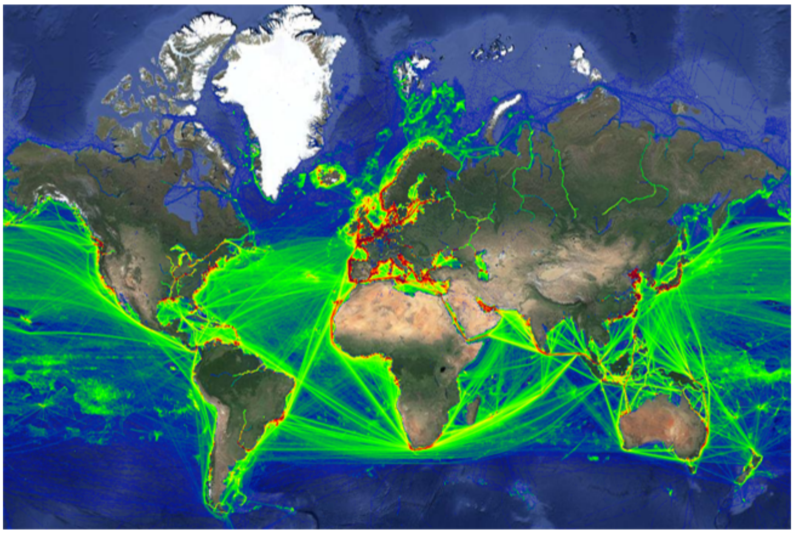


Figure 5.4: Density map marine traffic [107]

	Summer	Winter
Outdoor air temperature [°C]	18	0
Indoor air temperature [°C]	22	22
Outdoor humidity [%]	50	
Indoor humidity [%]	50	

Table 5.2: Weather conditions [108, 109]

5.2 Application of the design model

When one applies the parametric study for weight and power from Section 3.1 to the reference vessel and the reference route, the results show that the lightweight of the ship can be reduced by 159 ton if the ship would be unmanned and the installed generator power can be reduced by 72.6 kW. This power reduction is lower than the power reduction estimated by MUNIN [25]. MUNIN however, remains unclear about the particulars of their reference ship and the route sailed, making it impossible to compare the results achieved with this study. The results of the parametric study for weight and power are also shown in Table 5.3. It can be seen in the table that a distinction is made between the summer and the winter condition for the HVAC system as both seasons have different weather. The weather conditions are given in Table 5.2. Furthermore, once can see that the peak power is less than to the sum of the power consumption of the different systems. There are two reasons for this difference in power consumption. One, not all the equipment is in use at the same time. Secondly, the power for the HVAC system varies over the day as the temperature varies. Which system is in use and the power distribution of the HVAC system can be seen in Appendix F. The power given in Table 5.3 is the maximum power during the day.

Part	Lightweight [ton]	Power [kW]
100: Hull & Outfitting		-
120: Steel Accommodation	66.6	-
135: Windows	2.0	-
144: Boarding Platform Gangway	-	-
157: Sun awnings	-	-
300: Primary Ship Systems		
340: Fresh water and Sanitary Systems	12.3	6.4
370: HVAC Accommodation	1.9	Summer: 38.6 Winter: 58.2
400: Electrical System		
410: Power generating Systems	1.2	-
420: Cables and Wires Accommodation	3.5	-
430: Switch boards	-	-
450: Lighting Accommodation	0.6	5.7
500: Deck equipment		
570: Lifesaving Equipment	9.5	-
600: Secondary Ship Systems		
670: Internal Firefighting System Accommodation	2.9	22.9
700: Joinery & Arrangement Accommodation		
710: Interior Accommodation	58.8	22.6
800: Nautical, Navigation & Communication Equipment		
881: Internal Communication	0.02	1.0
883: Entertainment Systems	0.3	0.8
Total weight / $\mathbf{P_{Peak}}$	159	Summer: 56.7 Winter: 72.6

Table 5.3: Weight and power reduction of the reference ship

5.3 The consequences of the design model

In Section 5.2 the design model has been applied. The results from this study will influence the design of the unmanned ship as mentioned in Section 2.2. It has been concluded that the changes in capacity, dimensions, trim and stability, seakeeping, general arrangement and tonnage require further attention. Therefore, the capacity of the unmanned vessel will be discussed in Section 5.3.1 and the dimensions of the unmanned ship will be determined in Section 5.3.2. Then the trim and stability and the seakeeping will be discussed in Section 5.3.3 and Section 5.3.4, followed by the general arrangement plan in Section 5.3.5. Finally the tonnage of the unmanned ship is determined in Section 5.3.6.

5.3.1 Capacity

The capacity of the vessel is dependent on the amount of cargo that needs to be transported between two ports and the infrastructure the ship encounters on its journey. When the capacity is limited by the infrastructure, the dimensions of the ship will not change and the weight saved by hotel services will be used to transport extra cargo. However, in the case of the reference route, the ship is not limited by infrastructure and the capacity of the ship will decrease by the weight of the hotel services. For the reference vessel this would mean that the loading capacity would remain the same, while the displacement of the ship would decrease with 159 ton. With this new capacity come new dimensions of the ship. These dimensions will be determined in Section 5.3.2.

5.3.2 Dimensions

The dimensions will change as a result of the removal of hotel services and the route the reference vessel sails. However, before one can determine the dimension for the unmanned ship, one has to determine the displacement of the reference vessel in ton. This can be done with Equation 5.1. In this equation L is the length over all, B the beam, T the draft and C_B the block coefficient. By removing the weight of the hotel services, as determined in the parametric study, the displacement of the unmanned ship can be determined with Equation 5.2.

$$\Delta = \rho \cdot L \cdot B \cdot T \cdot C_B \tag{5.1}$$

$$\Delta_{Unmanned} = \Delta - \delta W \tag{5.2}$$

For the determination of the dimensions of the unmanned ship, it is assumed that the ratios between length, beam, depth and draft are fixed. When one applies this assumption, the dimensions of the unmanned ship can be determined with Equation 5.3.

$$Dim_{Unmanned} = Dim_{Manned} \cdot \sqrt[3]{\frac{\Delta_{Unmanned}}{\Delta}} \tag{5.3}$$

When one applies the calculation to the reference ship, the dimensions as given in Table 5.4 are obtained. Comparing the dimensions of the unmanned ship to the reference ship, one can see that the difference in dimensions is very limited.

	Reference vessel	Unmanned reference vessel	Percentage difference
Length [m]	134.50	133.93	-0.42%
Beam [m]	16.50	16.43	-0.42%
Depth [m]	9.80	9.76	-0.42%
Draft [m]	7.00	6.97	-0.42%

Table 5.4: Dimensions unmanned ship

5.3.3 Trim and stability

First the trim of the ship will be determined as the result of the removal of the accommodation. This is done for the ship at its original size by determining the trimming moment. This trimming moment can be determined with Equation 5.4.

$$M_{tr} = 10^3 \cdot g \cdot \delta W \cdot (x_{Acco} - x_a) \cdot \cos\alpha \quad [Nm] \tag{5.4}$$

In this equation δW is the lightweight reduction in ton, x_a the distance to the center floatation, the x_{Acco} the distance to the center of gravity of the accommodation in horizontal direction and α the pitch angle of the vessel. x_a and x_{Acco} should be measured from ordinate 10, which is at midship. The factor 1,000 is to convert from ton to kg. In a similar way, the stabilizing moment can be determined with Equation 5.5.

$$M_{st} = \rho \cdot g \cdot \nabla' \cdot GM_L \cdot \sin\alpha \quad [Nm] \tag{5.5}$$

In this equation is ∇' the displacement of the ship in m^3, without accommodation, GM_L the longitudinal metacentric height and α again the pitch angle of the vessel. The ship is in equilibrium when the trimming moment equals the stabilizing moment. By rewriting the equation, the pitch angle can be determined with Equation 5.7. Then the total trim of the vessel can be determined with Equation5.8.

$$M_{tr} = M_{st} \tag{5.6}$$

$$\tan\alpha = \frac{10^3 \cdot \delta W \cdot (x_{Acco} - x_a)}{\rho \cdot \nabla' GM_L} \tag{5.7}$$

$$t = L \cdot \tan\alpha \quad [m] \tag{5.8}$$

When one applies this calculation to the reference ship, one finds that the total trim will be 0,42 m. This trim can be compensated by the weight of the redundant equipment that must be installed and making the aft body of the hull more slender. However, applying these solutions is outside the scope of this research.

For the transverse stability, the transverse metacentric height GM_t is a measure. GM_t can be calculated with Equation 5.9.

$$GM_t = KB + BM - KG \quad [m] \tag{5.9}$$

with

$$BM = \frac{I_T}{\nabla} \quad [m] \tag{5.10}$$

In this equation I_t is the transverse moment of inertia of the design waterline in m^4. The values for calculating the orignal metacentric height are given in Appendix K. However, when the accommodation is removed, the terms that make up the metacentric height will change. For this calculation it is assumed that the decrease in draft, δT, will be equal over the ships length and that the transverse inertia will not change. Therefore, the corrected terms that make up the metacentric height can be calculated with Equation 5.11 to Equation 5.13.

$$KB' = KB - 0.5 \cdot \delta T \quad [m] \tag{5.11}$$

$$BM' = \frac{I_T}{\nabla'} \quad [m] \tag{5.12}$$

$$KG' = \frac{\rho\nabla \cdot KG - \delta W \cdot (D + D_{Poop} - 0.5 \cdot h_{Acco} + h_j)}{\nabla'} \quad [m] \tag{5.13}$$

When one applies the calculations, the metacentric height GM_t will change from 0.45 m to 0.62 m. Therefore will the unmanned ship be more stable that the manned ship. This is mainly caused by the relatively high center of gravity of the accommodation.

5.3.4 Seakeeping

Since the stability will increase and the trim can be compensated for by designing a more slender hull form, in combination with the additional weight of redundant equipment, one can state that the seakeeping behavior of the unmanned ship will be similar to the manned ship. Therefore no additional measures are required to improve the seakeeping of the ship.

5.3.5 The changed general arrangement plan

As a result of the spaces and equipment that are no longer needed, the general arrangement plan of the ship will also change. Therefore, the general arrangement plan of the reference vessel has been modified by removing the spaces and equipment that are no longer present when the ship becomes unmanned. The general arrangement plan of the unmanned reference ship can be found in Appendix M.

5.3.6 Tonnage

When the vessel is designed, the gross tonnage, GT, can be calculated. The gross tonnage forms the basis for manning regulations, safety rules and registration fees and port fees. The gross tonnage can be calculated with Equation 5.14 [110]. In this equation V_c is the total volume of all enclosed spaces of the ship in m^3.

$$GT = K_1 V_c \quad [GT] \tag{5.14}$$

with

$$K_1 = 0.2 + 0.02 \log_{10} V_c \quad [GT/m^3] \tag{5.15}$$

When one applies the tonnage calculation to the reference ship, which is 6540 GT according to the particulars given in Appendix K, the volume of the enclosed spaces of the ship can be determined. It turnes out that the reference vessel has 22,775.6 m^3 of enclosed spaces. Now, one can remove the 1,332 m^3 of enclosed spaces that are no longer present when the ship becomes unmanned. With this new volume of 21,445 m^3 of enclosed spaces one can calculate the tonnage of the ship when it is unmanned with Equation 5.14. The tonnage of the unmanned ship is 6147 GT, a reduction of 6%.

5.4 Application of the cost model

In this section the cost model will be applied to the reference ship on the reference route when the ship becomes unmanned. In Section 5.4.1 will be determined what can be saved on the building cost by removing the accommodation and correlated systems and then the total cost of ownership reduction will be estimated for a lifetime of 25 years in Section 5.4.2.

5.4.1 Building cost

In this section the difference in building cost, which are in total €1,784,000 for the reference ship, will be analyzed. The analysis will be based on the difference in building cost distribution, which is given in Figure 5.5. In this distribution, one can see that the main contributors to the difference in building cost are the joinery and hotel equipment, cables and wires and the steel of the accommodation. The joinery and hotel equipment, cables and wires and the steel of the accommodation are mainly dependent on the dimensions of the accommodation, while the saving in power generating systems is mainly dependent on the power consumption of the HVAC system, which is dependent on the dimensions of the accommodation and the route of the vessel.

The difference in building cost and the distribution of the difference in building cost for the reference ship are very similar to the distribution of the building cost and the difference in building cost of a containerfeeder. This is caused by the dimensions of the accommodation, which are very similar for a containerfeeder and the reference ship. Therefore, one can conclude that the results for the reference ship are in line with the estimations made for different sized ships in Section 4.1.8.

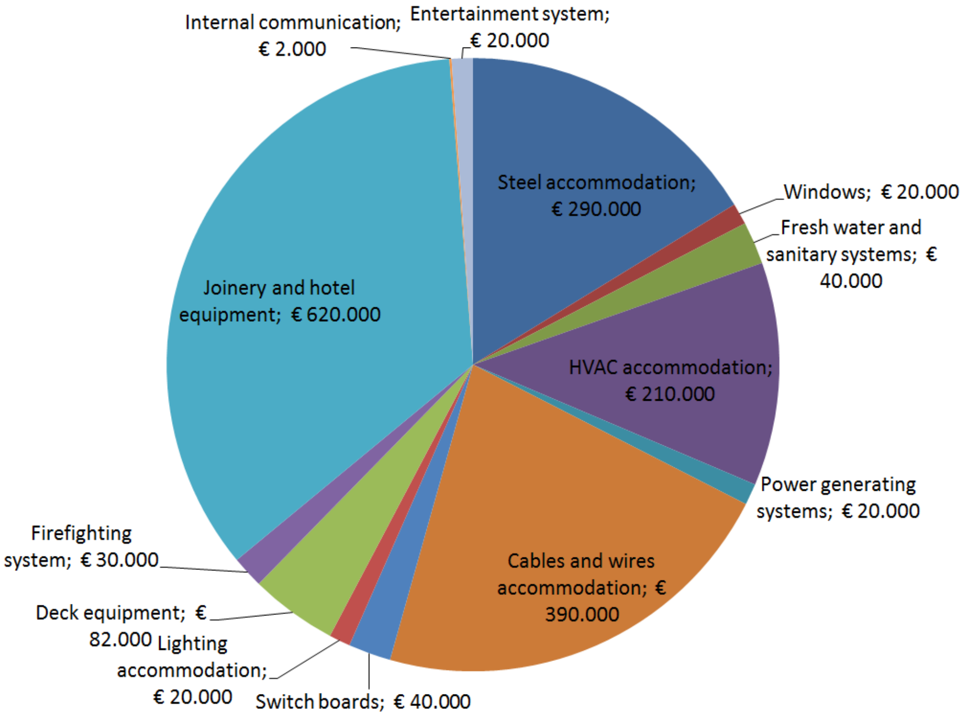


Figure 5.5: Difference in building cost distribution reference ship

5.4.2 Total cost of ownership

In this section the difference in total cost of ownership, which are in total €24,750,000 for the reference ship for a 25 year lifetime, will be analyzed in Figure 5.6. Hereof is €2,720,000 capital costs and €22,030,000 operational costs. In Figure 5.6 one can see that manning cost is the largest contributor to the total cost of ownership, with €20,750,000. This is followed by depreciation cost and fuel savings. The depreciation cost and interest cost are directly related to the building cost while the fuel cost saving is next to related to the size of the accommodation, also related to the route of the vessel and whether this limits the dimensions of the vessel. If the vessel is limited by infrastructure, the dimensions of the vessel will not change when the ship becomes unmanned and the fuel cost saving will be lower. Then the saving in lightweight, by removing the accommodation, will be used to transport extra cargo. When the vessel is not limited by infrastructure, as is the case for the reference vessel on the reference route, the dimensions of the vessel can be reduced to the dimensions calculated in Section 5.3.2. The changed dimensions will result in a lower power requirement for the ship, resulting in an additional fuel cost saving.

The difference in total cost of ownership and the distribution of the difference in total cost of ownership for the reference ship is very similar to the distribution of the total cost of ownership and the difference in total cost of ownership of a containerfeeder. This is caused by the number of crew and the dimensions of the accommodation which are very similar for a containerfeeder and the reference ship. Furthermore, the reference ship can save 15,000 ton of emitted CO_2, which is similar to the containerfeeder. Therefore, one can conclude that the results for the reference ship are in line with the estimations made for different sized ships in Section 4.10.

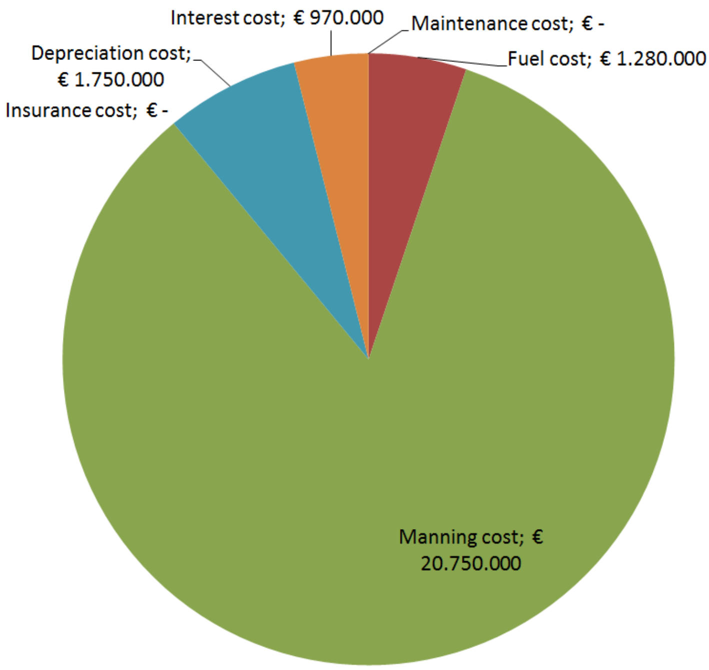


Figure 5.6: Difference in total cost of ownership distribution of the reference ship

5.5 Conclusion

It can be concluded, from applying the parametric study to the reference vessel, that the change in lightweight due to the removal of the accommodation and associated systems would be minimal. Therefore, the change in dimensions for unmanned ships compared to manned ships will be minimal too, as the ship is not limited by infrastructure. Otherwise, the dimensions will not change. Furthermore, removing the accommodation of the ship will result in a significant trim due to the large moment the accommodation normally creates around the longitudinal center of floatation and which is no longer present when the ship is unmanned. However, the trim can be reduced by changing the hull form and by placing more redundant equipment in the engine room.

From the cost analysis it can be concluded that the change in building cost is significant, but that the largest saving is in reducing manning cost. Furthermore, the cost saved for the reference ship is in line with the estimations made for different size of ships.

Chapter 6

Sensitivity study

In this chapter it will be checked if the conclusions from Chapter 5 are still valid if several parameters change. The parameters that will be varied, will be dived into parameters that influence the capital cost and parameters that influence the operational cost. The capital cost parameters will be researched in Section 6.1 and the operational cost parameters in Section 6.2. The capital cost parameters that will be researched are: building cost, steel price, depreciation period and interest period. The operational cost parameters that will be researched are: manning cost, fuel price and route. The figures in these sections have been derived by varying the different parameters in the cost model and by putting them in an overview. The combined influence of the different parameters on the total cost of ownership will be discussed in Section 6.2.3.4. Finally, a conclusion on the chapter will be given in Section 6.3. The structure of this chapter is shown in Figure 6.1.

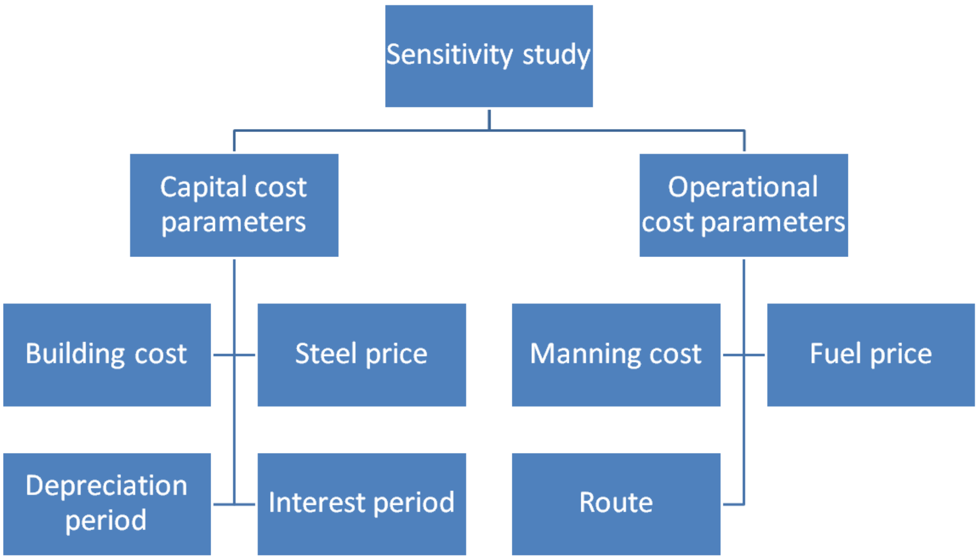


Figure 6.1: Structure sensitivity study

6.1 Capital cost parameters

In this section the capital cost parameters will be varied. In Section 6.1.1 the building cost will be varied and in Section 6.1.2 the steel price will be varied. Hereafter the depreciation period will be varied in Section 6.1.3. Finally, the interest period will be varied in Section 6.1.4.

6.1.1 Building cost

In this section the influence of building cost on the total cost of ownership will be discussed. Although the building cost is not a direct part of the total cost of ownership, it still has influence on the total cost of ownership as the depreciation cost and interest cost are directly related to the building cost. A more higher building cost would result in higher depreciation cost. In a similar way, the interest cost will also increase for a fixed loan period when the building cost increases, as the interest cost are a percentage of the building cost. The results of reducing and increasing the building cost by 30% are given in Figure 6.2. Here one can see that reducing or increasing the building cost by 30% will result in a difference in total cost of ownership of 3.4%. The difference in total cost of ownership is €23,920,000 when the building cost is decreased by 30% and €25,580,000 when the building cost is increased by 30%. In conclusion, one can say that the the building costs have medium influence on the total difference in cost.

However, one should keep in mind that the building cost can not be determined accurately. Therefore one should determine a range for the building cost of the accommodation. In Figure 5.5 the difference in building cost distribution of the reference ship is shown. To determine the range of the difference in building cost, the values given in Figure 5.5 will be validated for the contributors that can be validated by asking experts the accuracy range. The steel of the accommodation has about 90% accuracy and the HVAC in the accommodation about 87%. The cables and wires in the accommodation have about 85% accuracy and the lighting in the accommodation about 90%. The accuracy of the deck equipment is about 90% and the accuracy of the internal communication is about 70% and the accuracy of the entertainment system about 88%. Combining these results, the overall accuracy of the building cost is about 88%. Therefore, the building cost are likely to be between €1,567,000 and €1,999,000 and the difference in total cost of ownership between €24,420,000 and €25,080,000.

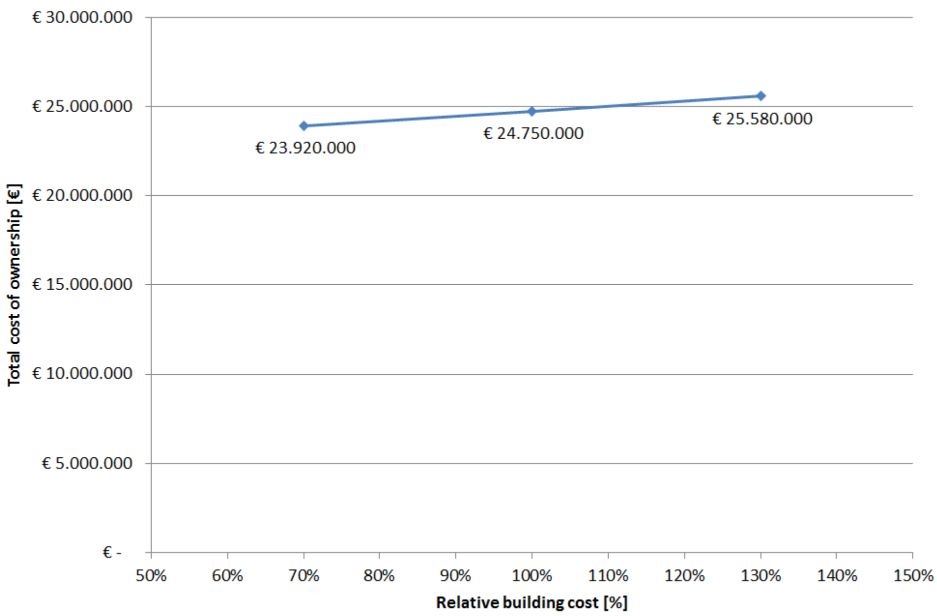


Figure 6.2: The influence of building cost on the difference in total cost of ownership

6.1.2 Steel price

For this thesis a steel price based on the current market price is assumed. However, the steel price fluctuates with time. Therefore, the influence of the steel price on the difference in total cost of ownership will be analyzed. In order to determine this influence, the steel price has been decreased and increased by 30%. Reducing the steel price by 30% results in a decrease of 1.7% for the building cost, which in its turn results in a 0.24% change in total cost of ownership to €24,690,000. Increasing the steel price by 30% results in an increase of 1.7% for building cost, which in its turn results in a 0.24% change in the total cost of ownership to €24,810,000. The difference in total cost of ownership as a function of the steel price is shown in Figure 6.3. Since the change in total cost of ownership is limited for large variations of the steel price, one can conclude that the influence of the steel price is limited.

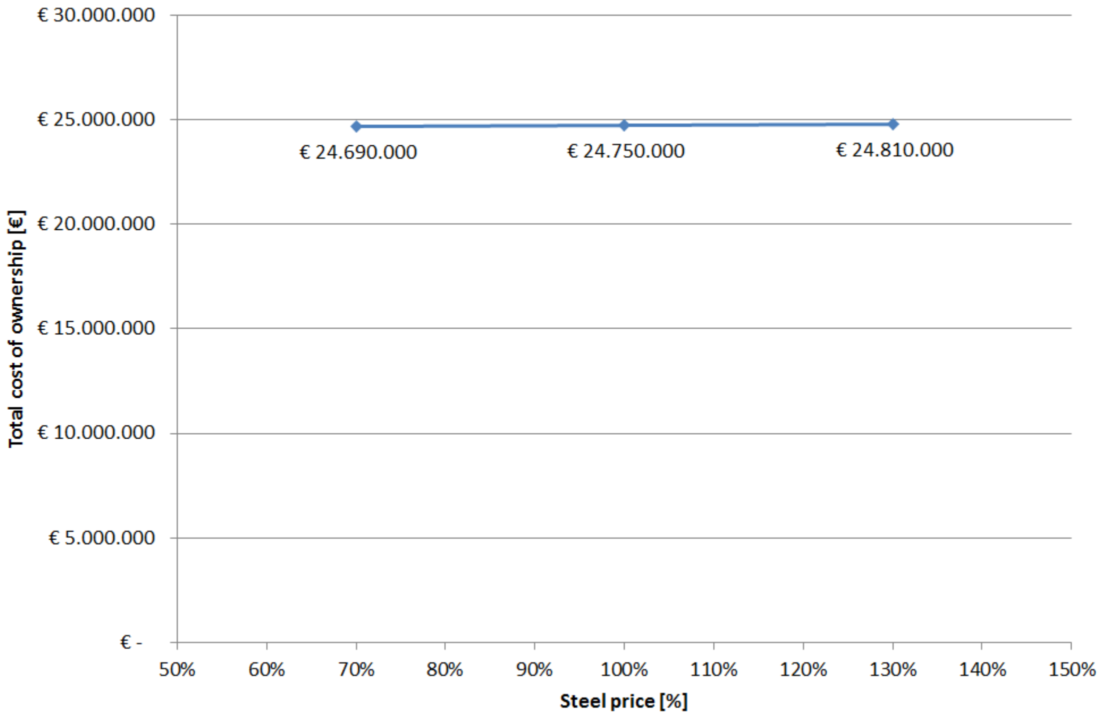


Figure 6.3: The influence of the steel price on the difference in total cost of ownership

6.1.3 Depreciation period

For this thesis it is assumed that the depreciation period is equal to the lifetime of the ship, which is assumed to be 25 years. However it is also possible to depreciate over a shorter or longer period, but the length of the depreciation period has no influence on the total depreciation cost as the total depreciation cost is dependent on the building cost and scrap value. On the other hand, the annual depreciation cost is dependent on the depreciation period as it is the total depreciation cost divided by the depreciation period. This will result in an annual depreciation cost for different depreciation periods as shown in Figure 6.4.

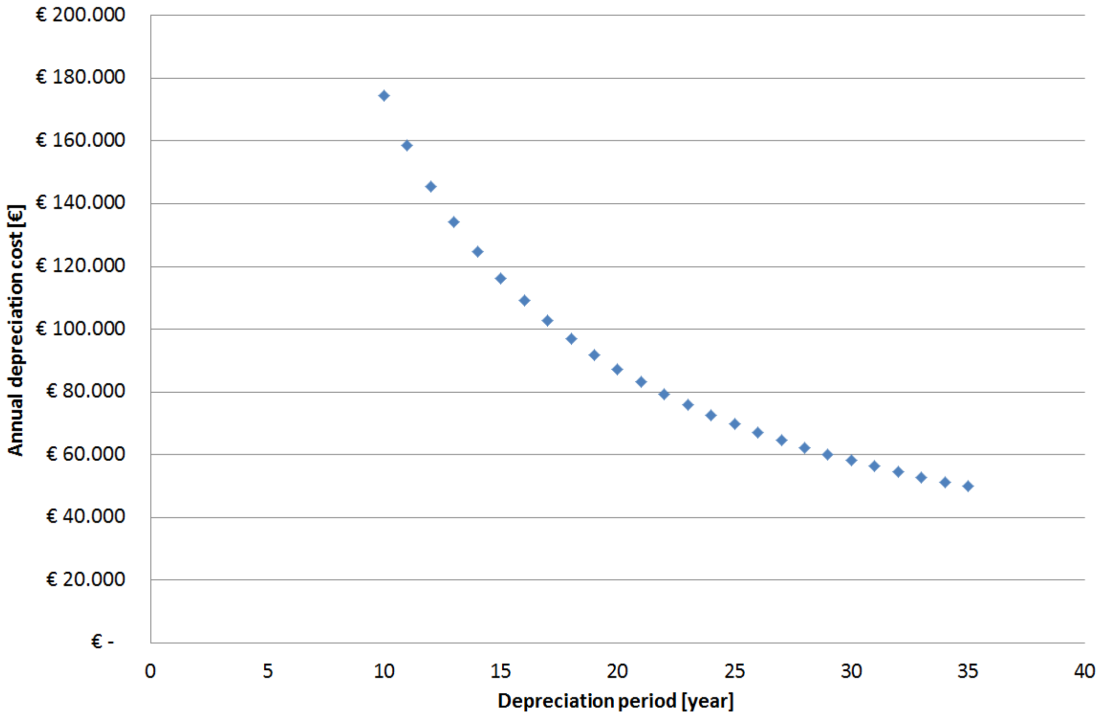


Figure 6.4: Influence of the depreciation period on the annual depreciation cost

6.1.4 Interest period

For this thesis it is assumed that the interest period is equal to the lifetime of the ship, which is assumed to be 25 year. However it also possible to pay back the loan over a shorter period than 25 years. When the loan is paid back in a shorter time period than 25 years, the period for which fuel cost saving and manning cost are determined is set to 25 years. Interest periods longer than 25 years will not be analyzed, as it is uncommon in ship finance to take a loan longer than the lifetime of the ship. When the interest period is set at 15 years, the difference in total cost of ownership decreases by 1.6% to €24,362,000. The results for interest cost and total cost of ownership for different interest periods are given in Table 6.1. Furthermore, the interest cost as a function of the interest period is shown in Figure 6.5. Here one can see that the interest cost are linearly dependent on the interest period. Since the change in the difference in total cost of ownership is limited for shorter interest periods, one can conclude that the influenced of the interest period is limited.

Interest period [year]	Interest cost [€]	Total cost of ownership [€]	$\delta C_{tot}/C_{tot,25}$ [%]
5	194,000	23,974,000	-3.1
10	388,000	24,168,000	-2.4
15	582,000	24,362,000	-1.6
20	776,000	24,556,000	-0.8
25	970,000	24,750,000	0

Table 6.1: Results of the variation in interest period on the difference in total cost of ownership

Figure 6.5: Influence of interest period on the interest cost

6.2 Operational cost parameters

In this section the operational cost parameters will be varied. First will the manning cost be varied in Section 6.2.1. Then the fuel price in Section 6.2.2 and finally, the route in Section 6.2.3.

6.2.1 Manning cost

In this section the manning cost will be varied and the influence on the total cost of ownership will be discussed. Since the manning cost is a large contributor to the total cost of ownership, its influence is also significant. In addition, the manning cost may vary per shipping company as the composition of the crew may vary. Some companies may sail with a Dutch crew, while another sails a much cheaper Filipino, or Russian crew. Yet another company may sail with a mixed crew. The crew composition has a significant influence on the average cost per crew member per year and therefore on the total cost of ownership. To check whether the total cost of ownership changes in such a way, that conclusions made in Chapter 5, are still valid, the manning cost have been varied. First, the manning cost has been decreased by 30% and then the manning cost has been increased by 30%. The results of the change in manning cost on the difference in total cost of ownership are shown in Figure 6.6. Here one can see that the difference in total cost of ownership for unmanned shipping is €18,525,000 when the manning costs are decreased by 30% and that the difference in total cost of ownership is €30,975,000 when the manning costs are increased by 30%. Changing the manning cost by 30% results in a change in total cost of ownership of 25%. Therefore, one can conclude that the manning cost has a large influence on the total cost of ownership. Since manning cost has a large influence on the total cost of ownership, which is the maximum possible investment for additional equipment that makes unmanned shipping possible, one can conclude that the an in depth analysis of the manning is required to determine the true budget for unmanned shipping. In Section 4.9, it can be found that the actual manning cost are 10% higher than calculated for a mixed crew. Therefore, the difference in total cost of ownership is more close to €26,825,000.

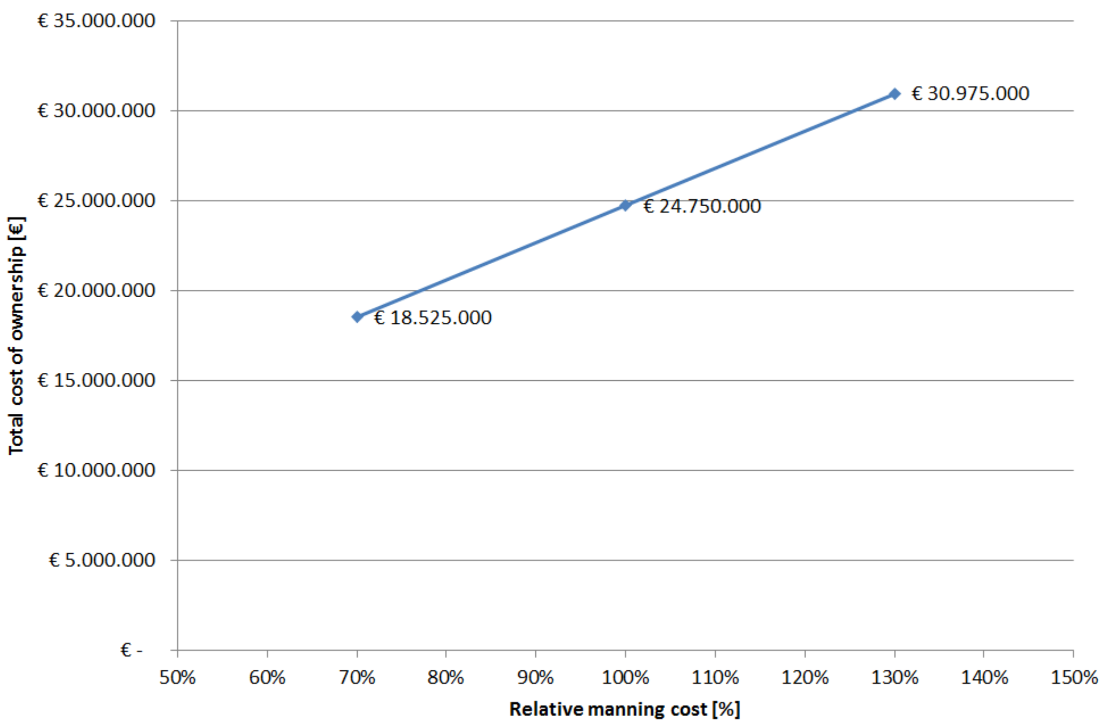


Figure 6.6: The influence of manning cost on the difference in total cost of ownership

6.2.2 Fuel price

For this thesis a fuel price is assumed based on the current market price. However, the fuel price fluctuates with time and port. Therefore the influence of the fuel price on the total difference in cost will be analyzed. In order to determine the influence, both the fuel price for HFO and MDO have been varied by 50%. When the ship is not limited by infrastructure and the fuel price is decreased by 50%, the difference in total cost of ownership decreases by 1.6% to €24,360,000. For the case the fuel price is increased by 50% , the total difference in cost increases by 1.6% to €25,140,000. The difference in total cost of ownership as a function of the fuel price is shown in Figure 6.7. Since the change in total cost of ownership is medium for large variations in fuel price, one can conclude that the fuel price has medium influence on the difference in total cost of ownership. Since the current fuel price is rather low, and a more average fuel price is 50% higher as can be seen in Figure 4.6, the total difference in cost is more closely to €25,140,000.

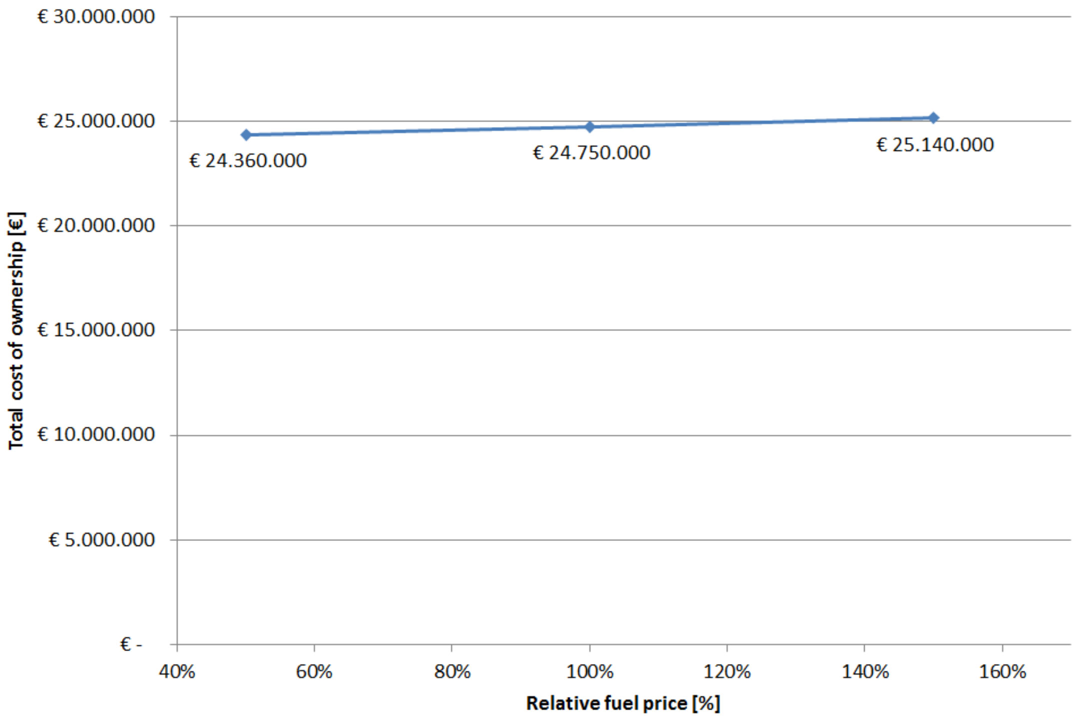


Figure 6.7: The influence of the fuel price on the difference in total cost of ownership

6.2.3 Route

For this thesis it is assumed that the reference vessel sails on a route between Rotterdam and Halifax. This route is in the temperate zone, but it is also possible that the ship sails a different route, for example in the tropic or arctic zone. Furthermore, the assumed route does not limit the dimensions of the ship, but it is also possible that the ship needs to pass a canal or locks. In that case a part of the fuel cost saving is lost. Another option is to sail routes of different lengths. All these things are possible and influence the total difference in cost. Therefore, one can say that a route is trajectory between two ports which can be defined by climate, infrastructure, distance and sailing speed. First the influence of climate will be discussed in Section 6.2.3.1. Then the influence of infrastructure will be discussed in Section 6.2.3.2 and the influence of the length of the route will be discussed in Section 6.2.3.3. Finally the influence of sailing speed will be discussed in Section 6.2.3.4.

6.2.3.1 Climate zone

The climate on the route influences the power consumption of the HVAC system, which is a large contributor to the total power consumption of the accommodation. The total power consumption of the accommodation directly influences the fuel consumption and therefore the fuel savings. Since the fuel savings are affected by the climate the ship sails in, the difference in total cost of ownership is also influenced by the climate. When the ship sails in the tropic zone instead of the temperate zone the difference in total cost of ownership decreases by 0.4% to €24,640,000 and when the ship sails in the arctic zone the difference in total cost of ownership increases by 3.2% to €25,550,000. Due to the coefficient of performance, used in the power consumption calculation for the HVAC system, it requires relatively less power to cool down a space than to heat it, resulting in a lower power requirement in the tropic zone than in the arctic zone. The difference in required power results in a different fuel consumption and therefore cooling down a space costs less fuel. When less fuel is consumed, the fuel savings are also lower, resulting in a lower total cost of ownership that can be saved. Based on the difference in total cost of ownership for the different climate zones, one can conclude that the influence of the climate on the total cost of ownership is significant.

6.2.3.2 Infrastructure

When the ship has to pass through a lock or canal, the dimensions of that lock or canal limit the dimensions of the ship. When ships become unmanned, the removal of the accommodation will result in smaller ship dimensions when the ship is not limited by infrastructure. Otherwise, the dimensions will remain equal and the weight saved by removing the accommodation will be used to increase the cargo capacity of the vessel. Making the dimensions smaller results in a lower power requirement for a given speed, which in its turn results in a higher fuel cost saving. This difference in fuel savings increases with increasing fuel prices as can be seen in Figure 6.8. Furthermore, one can see that the fuel savings for a ship, which is limited by infrastructure is 47% lower and that this ratio remains equal for all fuel prices. However, being limited by infrastructure only influences the difference in total cost of ownership by 2.4% to €24,150,000 for the fuel prices at 100%. This is a medium change of the total difference in cost and therefore one can conclude that the influence of infrastructure is medium.

Figure 6.8: The influence of infrastructure on fuel cost saving

6.2.3.3 Distance

One would expect the distance of the route to be of importance to the fuel cost saving, but this is not the case. In Chapter 4 the fuel savings have been separated in a part caused by the accommodation and a part caused by having smaller ship dimensions when the ship is not limited by infrastructure, which requires less propulsive power. For the fuel savings of the accommodation it does not matter what the distance of the route is, as the power consumption is set to be the same every day and the accommodation is in use every day, except for the off-hire days. For the part which is dependent on size, only the fuel cost saving per trip are dependent on the distance of the route and not the fuel cost saving per year as a shorter route will result in lower fuel cost saving per trip, but more trips per year. Since the distance of the route does not influence the fuel cost saving per year, one can conclude that the influence on the difference in total cost of ownership is none.

6.2.3.4 Sailing speed

The sailing speed of the vessel influences the difference in fuel consumption. The change in displacement, due to the removal of the accommodation, causes the ship to require relatively less power to maintain the same speed. This difference in power results in larger changes in fuel savings for higher speeds, which in its turn influences the difference in total cost of ownership, in the case the ship is not limited by infrastructure. This can also be seen in Figure 6.9. However, the difference in total cost of ownership changes only 1.5% when the vessel speed is increased from 15 kts to 17 kts. Since this is a minor difference, one can conclude that the influence of sailing speed is also limited when both the manned and unmanned ship sail the same speed.

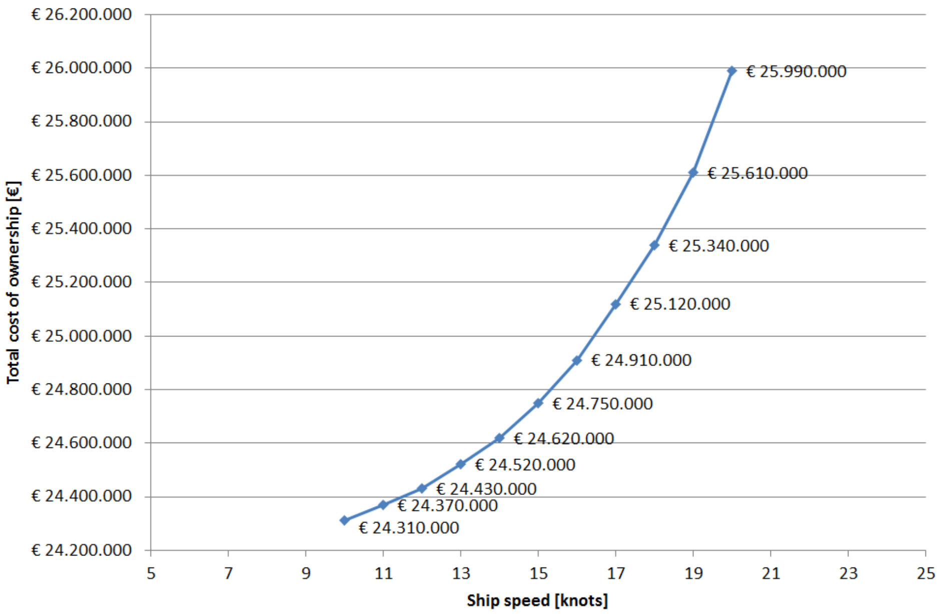


Figure 6.9: The influence of the sailing speed on the total cost of ownership

Change in total cost of ownership

The ranges for the building cost, fuel cost and manning cost influence the range for the total cost of ownership. In Section 6.1.1 it has been determined that the accuracy of the building cost is approximately 88%. Since the building cost influences the depreciation cost and the interest cost, the accuracy of these cost is also 88%. Furthermore, it has been determined in Section 6.2.2 that the fuel price can be twice as high, but that an average fuel price is approximately 50% higher. In addition, a more accurate average manning cost has been determined in Section 6.2.1. Combining the results, the change in total cost of ownership is between €24,420,000 and €28,430,000 for the reference ship.

6.3 Conclusion

In conclusion, the influence of the manning cost is high, but varying the manning cost does not change the conclusions drawn earlier in this thesis. However, further research on manning cost is required to determine the difference in total cost of ownership more accurately. Furthermore, one can conclude that the influence of building cost, fuel price, climate zone and infrastructure is medium as changes in these parameters significantly change the total difference in cost, but not in such a way that conclusions from earlier chapters become invalid. The steel price, interest period and sailing speed have a low impact on the difference in total cost of ownership. These parameters influence the difference in total cost of ownership, but relatively to other parameters, they do not change the difference in total cost of ownership much. An error in the estimates for these parameters would therefore not change the outcome of the result much. Finally, the depreciation period and distance of the route have no influence on the difference in total cost of ownership. For the depreciation cost, this is the case because only the total value over 25 years is required for the difference in total cost of ownership. The distance has no influence as only the total time traveled is required to determine the total fuel savings and therefore the difference in total cost of ownership. Overall one can conclude that the conclusions made in Chapter 5 are still valid and the the change in total cost of ownership is between €24,420,000 and €28,430,000 for the reference ship.

Chapter 7

Conclusions

In this chapter, conclusions will be drawn based on the results from previous chapters. The research questions as given in Chapter 1 will be answered in Section 7.1 and some recommendations for further research will be given in Section 7.2.

7.1 Conclusions

The research question introduced in Chapter 1 is:

What are the influences of unmanned shipping on the design considerations and what cost saving can be achieved by removing crew related equipment and the crew itself from merchant ships?

To answer this question, legislation and the design spiral of ships have been analyzed to determine the influence of unmanned shipping on the design of a ship. Based on analysis of legislation, it can be concluded that the influence of international law is limited, because of the various legislation analyzed, only the SOLAS Convention and the COLREGS make demands that need to be solved by technology. International law has mainly influence when the tasks and duties of crew need to be replaced by equipment. This equipment should guard the full situational awareness of the ship and be redundant in the case of critical equipment. Furthermore, the influence of the changed design requirements has been analyzed using the design spiral. From this analysis, it can be concluded that parts of the design significantly change as a result of unmanned shipping. The impact on ship design is generally high in these parts of the design and it mostly requires low to medium high effort to change that part of the design. From the analysis using the design spiral it can be concluded that deadweight, lightweight, powering, machinery selection, general arrangement and costing require further analysis.

To quantify the change in deadweight, lightweight and powering for different sized ships, a parametric study has been carried out. From this study it can be concluded that steel weight and joinery weight are the largest contributors to accommodation weight, which can be removed for unmanned ships. One can reduce the lightweight by about 155 ton for a containerfeeder and by about 1361 ton for a large ocean liner container vessel. Furthermore, it can be concluded from the parametric study that the total power consumption increases non-linearly with ship size. Large ships relatively consume more power than small ships for accommodation equipment. The total power consumption in the accommodation, dependent on the ships position, varies for a containerfeeder between about 31.9 kW and 158.4 kW, and for a large ocean liner container vessel between about 311.9 kW and 2181.7 kW. Furthermore, it can be concluded from analysis on what equipment should be added to the unmanned ship, that most equipment to guard the situational awareness is already in existence today.

To answer the questions on cost introduced in Chapter 1, a cost analysis has been carried out. Based on this analysis, one can conclude that the distribution of the difference in building cost is similar for different sized ships. The largest contributors to the building cost are the joinery, hotel equipment, power generating systems and the cables and wires in the accommodation. Furthermore, one can conclude, based on an analysis of the difference in total cost of ownership, that manning cost is the largest contributor to the difference in total cost of ownership over a lifetime of 25 years. However, the contribution of manning cost to the difference in total cost of ownership reduces with ship size, as relatively less crew is present on large ships. Over a lifetime of 25 years, on a route in the temperate zone which is not limited by infrastructure, one can save €23,060,000 in total cost of ownership for a containerfeeder and €86,440,000 for a large ocean liner container vessel. Since the relative savings are higher on small ships, one can conclude that small ships are more interesting to design and operate as unmanned ships than large ships.

To determine the true influence of unmanned shipping on the design, the parametric study and cost analysis have been applied to a specific case in the case study. From this study it can be concluded that the change in lightweight is minimal, as it can only be reduced by 159 ton, on a ship displacement of 11689 ton. Since the change in lightweight is minimal, the dimensions of the unmanned ship will be similar to the manned ship, as the ship is not limited by infrastructure. Removing the accommodation of the ship will result in a significant trim due to the large moment the accommodation normally creates around the longitudinal center of floatation, but which is no longer present when the ship is unmanned. However, the trim can be solved by changing the hull form and by replacing more redundant equipment in the engine room. Furthermore, the power can be reduced by 56.7 kW. From applying the cost analysis to the case study, it can be concluded that the difference in total cost of ownership, which is €24,750,000 for the reference vessel, is in line with the estimations made for different sizes of ships.

Finally, a sensitivity study has been carried out to determine the accuracy of the results based on the assumptions made in the thesis. From this study it can be concluded that differences in manning cost strongly influence the total difference in cost. Therefore, further research on manning cost is required. Parameters that have medium impact are building cost, fuel price, climate zone and infrastructure. These parameters change the difference in total cost of ownership, but not in such a way that earlier conclusions become invalid and therefore do not require further analysis. Parameters like steel price, interest period and sailing speed have low impact on the difference in total cost of ownership and therefore do not require further analysis. Finally the influence of depreciation period and distance of the route have been determined to have no influence on the difference in total cost of ownership. This is caused by the total value being significant and not the annual value or value per trip. As a result of the sensitivity study, the difference in total cost of ownership is between €24,420,000 and €28,430,000 for the reference ship.

7.2 Recommendations for further research

Over the course of the research, new topics related to unmanned ships have come up that deserve further research. Furthermore, several things were noticed that could improve the results of this research, if the research would be repeated or a similar research would be carried out in the future.

The legal study in this research mainly focused on design requirements to which the unmanned ship must or ought to comply. It was concluded that legislation which could be of any hindrance to the design of the unmanned ship, would not be of any hindrance due to the possibility of exemptions in the legislation. However further research is required to determine whether these exemptions are legally arguable.

In this research, the design spiral has been used to determine the change in design requirements. Here it has been stated that a part of the design will not be further analyzed in this thesis if the impact on the design is low and the required effort to change that part of the design is high. This is the case for the hull form as the influence of trim and machinery should be further researched.

The parametric study performed in this thesis focuses on the accommodation, but other sections in the ship, like the engine room, might also significantly change due to unmanned shipping. Engineers are present here when the ship is in port, but also when the ship is at sea to perform maintenance and repairs. Furthermore, there should be more redundant equipment installed in the engine room. How this influences the weight, cost and arrangement of the engine room requires further research.

The reduction in lightweight estimated in this thesis is the result of the removal of the accommodation and associated systems. However, when the structural weight of the remainder of the ship can be reduced, due to the acceptance of higher risks for the loss of the unmanned ship, higher fuel savings can be obtained, resulting in additional budget for systems that make unmanned shipping possible. Therefore an extended risk analysis and an analysis of the structural design, should be carried out.

Sailing unmanned will require a lot of data to be transmitted between the ship and the shore station. However, this is still very expensive today and the amount of data that can be transmitted bamdwidth is limited. Therefore, further research on data transmission is necessary.

Finally, a more detailed analysis on the composition and cost of manning should be performed, as the method applied in this thesis is rather crude. Performing a more detailed analysis would result in a more accurate difference in total cost of ownership, which is the budget for additional equipment required for unmanned shipping.

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Appendix A

Uniform Administration for Shipbuilding: System codes

This appendix contains the system codes according to the uniform administration for shipbuilding. The list is given on the next page:

System Codes 16-10-2002

[000] GENERAL ITEMS
001 UNFORESEEN
[010] ACQUISITION (COSTS)
013 MAN HOURS OTHER DEPARTMENTS (Dept. 999)
014 TRAVELLING AND ACCOMMODATION EXPENSES
015 MAN HOURS PURCHASE DEPARTMENT (Dept. 300)
[020] SPARE PARTS
021 SPARE PARTS ACCORDING CLASS
022 OTHER SPARE PARTS
[030] CLASSIFICATION (COSTS)
031 CLASSIFICATION
032 SHIPPING INSPECTORATE/ NATIONAL AUTHORITIES
033 RADIO INSPECTION/ CERTIFICATION
034 SHIP MEASUREMENT (TONNAGE)/ CERTIFICATION
035 OTHER INSPECTION COSTS AND CERTIFICATES
[040] TRIALS AND SUPERVISION
041 MODEL TESTING/ HYDRODYNAMICS
042 FACTORY TESTS/ QUAY TESTS
043 TRIALS INCLUDING TUG ASSISTANCE
044 QUALITY CONTROL (External)
045 PRODUCTION CO-ORDINATION (Dept. 502, 507, 531)
046 ~~DFS SUPERVISION (DEPT. 610)~~
047 INSPECTION CASCO/UB (Dept. 504)
048 SUPERVISION COSTS CLIENT
049 FUEL OIL AND OIL
[050] SHIPMENT (COSTS)
051 TRANSPORT PACKAGES
052 PREPARATION FOR SEA TRANSPORT
053 TRANSPORT COSTS (SHIPMENT OF READY PRODUCT/ DELIVERY UNDER OWN POWER)
054 INSURANCE FOR TRANSPORT
055 SHIPMENT CRADLES
056 STOREHOUSE (Dept. 342)
057 MAN HOURS EXPEDITION/SHIPMENTS (Dept. 330)
058 TRANSPORTS DAMEN DELIVERIES (TO HULL YARD, DTC YARD, ETC.)
059 DHL / TAXI
[060] MISCELLANEOUS
061 COSTS FOR ADVICE/CONSULTANCY ETC.
062 CLEANING COSTS
063 LIFT- AND CRANE ASSISTANCE
064 TUG ASSISTANCE
065 DOCKING COSTS
066 DELIVERY AND HANDING-OVER COSTS
067 OVERHEAD PRODUCTION GORINCHEM (Dept. 501)
068 SHIP MODEL- AND PHOTO COSTS
069 DFS (Dept. 610, 615)
[070] DESIGN ASPECTS
071 CENTRAL ENGINEERING (Dept. 540, 541, 544, 545)
072 PLANNING AND CONTROL (Dept. 503)
073 REPRODUCTION (Dept. 542)
074 ICT (Dept. 220)
075 RESEARCH (Dept. 505)
076 HYDROSTATICS/ STABILITY
077 HYDRODYNAMICS
078 STRENGTH AND VIBRATIONS
079 WEIGHT CALCULATIONS
[080] FINANCING AND BANKING EXPENSES
081 INTEREST ON PRE-FINANCING
082 INTEREST ON POST-FINANCING
083 COMPENSATION INTERESTS AND OTHER COSTS RELATED TO INTEREST
084 EXPENSES "DUTCH" CREDIT COMPANY (NCM)
085 BANKING EXPENSES (SALES)
086 RATE OF EXCHANGE DIFFERENCES
087 BANKING EXPENSES HULL
[090] RE-CHARGEABLE EXPENSES AND ADDITIONAL CHARGES
091 ACCOMMODATION ALLOWANCE
092 BUILDING INSURANCE
094 GUARANTEE EXPENSES
095 MOULDS AND LOFTING COSTS
096 NEWBUILDING-SHED COSTS
098 SMALL PARTS (incl. fastening material + extra deliveries)

[100] SHIPBUILDING (hull and outfitting)
101 HULL COMPLETION
102 WELDING MATERIAL
103 AGENT'S COMMISION
104 HULL TRANSPORT, INCLUDING TUG ASSISTANCE
110 HULL
111 RESERVED FOR SECTION DRAWINGS
/
119
120 SUPERSTRUCTURE
121 RESERVED FOR SECTION DRAWINGS
/
129
[130] HATCHES, DOORS, WINDOWS ETC.
131 HATCHES
132 MANHOLES (incl. manhole covers)
133 WATERTIGHT DOORS (in shell, bulkheads and superstructure)
134 BOW DOORS, STERN DOORS, RAMPS
135 WINDOWS/PORTHOLES/BLINDAGES
137 BLINDAGE COVERS
139 DOCKING PLUGS, DRAIN PLUGS
[140] STAIRS, LADDERS, HANDRAILS, PLATFORMS ETC.
141 STAIRS, LADDERS AND CLIMBING STEPS
142 RAILINGS, HANDRAILS, GRIPS
143 PLATFORMS, GRATINGS
144 BOARDING PLATFORM GANGWAY
145 REMAINING ITEMS
[150] ADDITIONS TO SHIP'S CONSTRUCTION
151 FENDERS (steel, rubber, synthetic material and/or tyres)
152 PUSHBOW
153 BOLLARDS AND BITTS
154 LIFTING LUGS
155 BALLAST
156 LASHING MATERIAL
157 SUN AWNING AND SUPERSTRUCTURE ROPE GUARDS
158 MASTS
159 MARKINGS HULL AND SUPERSTRUCTURE
[160] CORROSION PROTECTION AND DECK COVERING (OUTSIDE)
161 PAINT SYSTEM INCLUDING ANTIFOULING (REGULAR)
162 DECK COVERING (OUTSIDE)
163 CATHODIC PROTECTION
164 ANTI FOULING SYSTEM (ACTIVE)
170 REMAINING ITEMS
[200] MACHINERY (propulsion)
201 ASSEMBLY MAN HOURS GORINCHEM (Dept. 535)
202 MACHINING SHOP MAN HOURS (Dept. 580)
203 ~~MANAGEMENT GORINCHEM (Dept. 501)~~
204 ~~REMAINING DEPARTMENTS (Dept. 999)~~
[210] PROPULSION SYSTEM
211 PROPULSION ENGINE INSTALLATION
212 REDUCTION GEAR INSTALLATION
213 SHAFT, PROPELLER AND NOZZLE INSTALLATION
214 CONTROL SYSTEM PROPULSION INSTALLATION
[220] STEERING SYSTEM
221 RUDDER INSTALLATION AND
222 STEERING GEAR INSTALLATION AND CONTROL
223 TRANSVERSE THRUSTER (bow/stern)
224 REMAINING ITEMS
[300] PRIMARY SHIP SYSTEMS
301 PIPE FITTING (subcontractor)
302 MATERIAL FOR PIPE FITTING
310 BILGE-, BALLAST-, DECKWASH-, AND INTERNAL FIFI SYSTEM
320 FUEL OIL SYSTEM
330 COOLING WATER SYSTEM
340 FRESH/ AND SEA WATER SYSTEM
350 FILLING/, SOUNDING/ AND DE-AERATION SYSTEM
360 LUBRICATION OIL SYSTEM
[370] VENTILATION, AIRCONDITIONING AND HEATING SYSTEM
371 NATURAL AND MECHANICAL VENTILATION SYSTEM (supply and exhaust)
372 AIRCONDITIONING SYSTEM
373 HEATING SYSTEM
374 REMAINING ITEMS
380 EXHAUST SYSTEM
390 REMAINING PRIMARY SHIP SYSTEMS

[400] ELECTRICAL SYSTEM
401 ELECTRICAL INSTALLATION (SUBCONTRACTORS)
410 POWER GENERATING SYSTEM
420 CABLES AND WIRING
430 SWITCH BOARDS
440 ALARM SYSTEM
450 LIGHTING
460 INTEGRATED INFORMATION SYSTEMS
490 REMAINING ITEMS
[500] DECK EQUIPMENT
510 ANCHOR EQUIPMENT
520 MOORING SYSTEM
530 FISHING GEAR
540 HOISTING EQUIPMENT
550 ANCHOR HANDLING, TOWING AND PUSHING EQUIPMENT
560 DIVING SYSTEM
570 LIFE SAVING/ FIRE PROTECTION EQUIPMENT
590 REMAINING ITEMS
[600] SECONDARY SHIP SYSTEMS
610 HYDRAULIC SYSTEM
620 COMPRESSED AIR SYSTEM
630 CARGO HANDLING SYSTEM
640 (OIL) POLLUTION CONTROL
650 EXTERNAL FIRE FIGHTING AND SALVAGE SYSTEM
660 PRE-WETTING SYSTEM
670 FIXED INSTALLATIONS FOR INTERNAL FIRE EXTINGUISHING
680 COOLING AND FREEZING SYSTEM
690 SEA KEEPING IMPROVEMENT DEVICES
[700] JOINERY AND ARRANGEMENT OF ACCOMMODATION
701 MAN HOURS TIFA (Dept. 590)
702 JOINERY (SUBCONTRACTORS)
710 JOINERY (GENERAL)
720 INSULATION
730 ARRANGEMENT ENGINE ROOM
740 ARRANGEMENT WHEELHOUSE
750 ARRANGEMENT LIVING QUARTERS
760 ARRANGEMENT STORE AND BOATSWAIN EQUIPMENT
770 ARRANGEMENT ADDITIONAL SPACES ~~AND SANITARY SPACES~~
780 TOOLS
790 ACCOMMODATION PASSENGERS
[800] NAUTICAL, NAVIGATION AND COMMUNICATION EQUIPMENT
801 INSTALLATION WORK NAUTICAL EQUIPMENT
810 NAVIGATION LIGHTING
820 OPTICAL SIGNALLING EQUIPMENT/ SEARCH LIGHT SYSTEM
830 ACOUSTICAL SIGNALLING SYSTEM
840 RADAR SYSTEM
[850] DIRECTION FINDING AND COURSEKEEPING SYSTEM
851 COMPASS (MAGNETIC, ELECTRICAL, GYRO)
852 AUTOPILOT
853 TURN INDICATOR
854 REMAINING ITEMS
860 POSITION FINDING AND POSITIONING SYSTEM
[870] SONAR, SPEEDLOG AND DEPTH SOUNDING SYSTEM
871 SONAR EQUIPMENT
872 ECHOSOUNDER
873 SPEEDLOG (LOG)
874 HAND LEAD
875 SOUNDING SHAFT
876 REMAINING ITEMS
[880] INTERNAL AND EXTERNAL COMMUNICATION (INCL. TV/AUDIO/VIDEO)
881 INTERNAL COMMUNICATION
882 EXTERNAL COMMUNICATION
883 ENTERTAINMENT SYSTEMS
890 METEOROLOGICAL AND OTHER MEASURING AND MONITORING SYSTEMS
[900] SPECIAL EQUIPMENT
910 HYDROLOGICAL AND OCEANOGRAPHIC EQUIPMENT
920 DREDGING EQUIPMENT
930 MILITARY EQUIPMENT
940 HELICOPTER EQUIPMENT

* System codes between parentheses [...] are non bookable (i.e. no costs can be directly attributed).

Figure A.1: Uniform Administration for Shipbuilding: System codes [111]

Appendix B

Pump calculations

In this appendix will the calculations for the pump power be performed for the fresh water and sanitary system, HVAC system and firefighting system.

B.1 Fresh water and sanitary system

Next to the power required to produce the fresh water will it also cost power to pump the water from the potable water tank to the user. In order to calculate the power for the pump, we start with the equation for steady flow energy which is given in Equation B.1 [112]. In this equation stands subscript 1 for the position in the potable water tank just before the water enters the pipe and subscript 2 for the position just before the water leaves the pipe at the user side. In the equation is p the pressure and V the velocity of the water at the given point, h_p is the head increase over the pump, h_f is the head increase due to friction and h_m is the head increase due to minor losses. Since the potable water tank is a reservoir, the velocity in front of the entrance of the pipe is approximately zero and the velocity just before the water leaves the pipe is equal to the velocity of the water in the pipe, V_{Pipe}. By rewriting Equation B.1, Equation B.2 for the head increase over the pump is obtained [112].

$$\frac{p_1}{\rho \cdot g} + \frac{V_1^2}{2 \cdot g} + z_1 = \left(\frac{p_2}{\rho \cdot g} + \frac{V_2^2}{2 \cdot g} + z_2 \right) + h_f + \sum h_m - h_p \tag{B.1}$$

$$h_p = \frac{p_2 - p_1}{\rho \cdot g} + \frac{V_{Pipe}^2}{2 \cdot g} + z_2 - z_1 + h_f + \sum h_m \quad [m] \tag{B.2}$$

The head increase due to minor losses caused by a sharp entrance or exit, valves, elbows etc, can be calculated with Equation B.3 [112]. In this equation is K_{losses} the resistance coefficient which can be determined for different fittings with the help of Appendix B [112]. The head increase due friction in the pipes can be calculated with Equation B.4 [112]. In this equation is$h_{f,sub}$ the head increase due to friction in the subpipes, $h_{f,main}$ the head increase due to friction in the main pipes and $h_{f,vert}$ the head increase due to friction in the vertical pipes. The head increase for the different types of pipe can be calculated with Equation B.5 to Equation B.7. For this calculation it is assumed that the user is on the highest deck at the farthest possible position from the fresh water tank.

$$h_m = \frac{V_{Pipe}^2 \cdot \sum K_{losses}}{2 \cdot g} \quad [m] \tag{B.3}$$

$$h_f = h_{f,sub} + h_{f,main} + h_{f,vert} \quad [m] \tag{B.4}$$

$$h_{f,sub} = \frac{8 \cdot V_{Pipe}^2 \cdot f_{sub}}{d_{Pipe,sub,supply}} \quad [m] \tag{B.5}$$

$$h_{f,main} = \frac{b \cdot V_{Pipe}^2 \cdot f_{main}}{d_{Pipe,main,supply}} \quad [m] \tag{B.6}$$

$$h_{f,vert} = \frac{(N_{Deck} - 1) \cdot h_{Acco} \cdot V_{Pipe}^2 \cdot f_{vert}}{N_{Deck} \cdot d_{Pipe,vert,supply}} \quad [m] \tag{B.7}$$

The friction coefficient f in Equation B.5to Equation B.7 can be calculated with Equation B.8 [112]. In this equation is Re_d the Reynolds number for pipe flows which can be calculated with Equation B.9 [112], ϵ the roughness of the piping material and d_{Pipe} the diameter of the pipe. The roughness for different materials of ducts can be found in Table B.1 [112].

$$\frac{1}{f^{1/2}} = -1.8 \log\left(\frac{6.9}{Re_d} + \left(\frac{\epsilon/d_{Pipe}}{3.7}\right)^{1.11}\right) \quad [m^{1/2}/s] \tag{B.8}$$

$$Re_d = \frac{\rho \cdot V_{Pipe} \cdot d_{Pipe}}{\mu} \quad [-] \tag{B.9}$$

In Equation B.9 is ρ the density of water, V_{Pipe} the velocity in the pipe and μ the viscosity which is strongly dependent on temperature. The viscosity is also dependent on pressure but generally speaking has pressure only a minor effect on the viscosity. For example, increasing the pressure from 1 bar to 50 bar will increase viscosity of air only by 10% [112]. The viscosity and density for water at 1 bar as a function of temperature is given in Table B.2 [112]. Now it is possible to calculate the head increase over the pump therefore one can calculate the required power for the pump with Equation B.10 [112]. In this equation isρ the density of the water, g the gravitational acceleration, Q_{Pump} the volumeflow in m^3/s, h_p the head increase over the pump and η_{Pump} the efficiency of the pump which lies between 60% and 80% [112]. The factor 2/1000 is to convert the power to kW and account for both the hot and the cold flow.

$$P_{fresh,pump} = \frac{2 \cdot \rho \cdot g \cdot Q_{Pump} \cdot h_p}{1000 \cdot \eta_{Pump}} \quad [kW] \tag{B.10}$$

Combining the required power for the pump with the required power for the watermaker, the total required power for the fresh water system can written as in Equation B.11.

$$P_{fresh} = P_{Watermaker} + P_{fresh,pump} \quad [kW] \tag{B.11}$$

Material	Condition	ϵ [mm]
Steel	Sheet metal, new	0.05
	Stainless, new	0.002
	Commercial, new	0.046
	Riveted	3.0
	Rusted	2.0
Iron	Cast, new	0.26
	Wrought, new	0.046
	Galvanized, new	0.15
	Asphalted cast	0.12
Brass	Drawn, new	0.002
Plastic	Drawn tubing	0.0015
Rubber	Smoothed	0.01

Table B.1: Recommended roughness values for commercial ducts [112]

Water temperature [°C]	Density [kg/m^3]	Viscosity [Ns/m^2]
0	1000	1.788E-3
10	1000	1.307E-3
20	998	1.003E-3
30	996	0.799E-3
40	992	0.657E-3
50	988	0.548E-3
60	983	0.467E-3
70	978	0.405E-3
80	972	0.355E-3
90	965	0.316E-3
100	958	0.283E-3

Table B.2: Viscosity and density of fresh water [112]

B.2 HVAC accommodation

The power for the fan can be calculated with Equation B.12 [112]. In this equation is ρ the density of the air, g the gravitational acceleration, h_{Fan} the head increase over the fan and η_{Fan} the efficiency of the fan. h_{Fan} can be found by writing down the energy equation for steady flow, which is given in Equation B.13 [112]. In this equation is p the pressure, V the velocity, z the height, h_f the head increase due to friction and h_m the head increase due to minor losses. The subscript 1 means the position just before the air is sucked into the pipe in front of the fan. and subscript 2 means the position in the room where the air flows to. These positions are assumed to be reservoirs where the the velocity is close to zero with no pressure difference between the two positions. Therefore Equation B.13 can be rewritten for the head increase over the fan to Equation B.14 [112].

$$P_{HVAC,fan} = \frac{\rho \cdot g \cdot Q_{Fan} \cdot h_{Fan}}{1000 \cdot \eta_{Fan}} \quad [kW] \tag{B.12}$$

$$\frac{p_1}{\rho \cdot g} + \frac{V_1^2}{2 \cdot g} + z_1 = \left(\frac{p_2}{\rho \cdot g} + \frac{V_2^2}{2 \cdot g} + z_2 \right) + h_{f,HVAC} + \sum h_m - h_{Fan} \tag{B.13}$$

$$h_{Fan} = z_2 - z_1 + h_f + \sum h_m \quad [m] \tag{B.14}$$

The head increase due to minor losses can be calculated with EquationB.3 [112]. The air velocity in the pipe, V_{Pipe}, in this equation can be calculated with Equation B.15. Since Equation 3.41 holds true, the velocity in all the pipes is equal.

$$V_{Pipe} = \frac{\dot{V}_{Deck}}{3600 \cdot N_{Pipe,main} \cdot A_{Pipe,main}} \quad [m/s] \tag{B.15}$$

The head increase due friction in the pipes can be calculated with Equation B.16. In this equation is $h_{f,HVAC,sub}$ the head increase due to friction in the subpipes, $h_{f,HVAC,main}$ the head increase due to friction in the main pipes and $h_{f,HVAC,vert}$ the head increase due to friction in the vertical pipes. The head increase for the different types of pipe can be calculated with Equation B.17 [112] to Equation B.19 [112]. For this calculation it is assumed that the room that needs to be cooled or heated is on the highest deck at the farthest possible position from the HVAC system.

$$h_{f,HVAC} = h_{f,HVAC,sub} + h_{f,HVAC,main} + h_{f,HVAC,vert} \quad [m] \tag{B.16}$$

$$h_{f,HVAC,sub} = \frac{3 \cdot V_{Pipe}^2 \cdot f_{sub}}{d_{Pipe,sub,supply}} \quad [m] \tag{B.17}$$

$$h_{f,HVAC,main} = \frac{b \cdot V_{Pipe}^2 \cdot f_{main}}{d_{Pipe,main,supply}} \quad [m] \tag{B.18}$$

$$h_{f,HVAC,vert} = \frac{h_{Acco} \cdot V_{Pipe}^2 \cdot f_{vert}}{d_{Pipe,vert,supply}} \quad [m] \tag{B.19}$$

The friction coefficient f in Equation B.17to Equation B.19 can be calculated with Equation B.8 [112]. In this equation is Re_d the Reynolds number for pipe flows which can be calculated with Equation B.9 [112], ϵ the roughness of the piping material and d_{Pipe}, the diameter of the pipe. The roughness for different materials of ducts can be found in Table B.1 [112]. The Reynolds number is dependent on the viscosity μ which is strongly dependent on temperature. The viscosity of air at atmospheric pressure as a function of temperature is given in Table B.3 [112]. The head increase due to friction can now be calculated and therefore the head increase over the fan. Since the head increase over the fan is known, one can determine the required power for the fan. Then one can determine the total power for the HVAC system with Equation B.20.

$$P_{HVAC} = P_{HVAC,heat} + P_{HVAC,fan} \quad [kW] \tag{B.20}$$

Air temperature [°C]	Density [kg/m³]	Viscosity [Ns/m²]
-40	1.52	1.51E-5
0	1.29	1.71E-5
20	1.20	1.80E-5
50	1.09	1.95E-5

Table B.3: Viscosity and density of air

B.3 Firefighting system accommodation

The power required to transport the water from the sea to the sprinklers must be calculated. In order to calculate this power, we start start again with the equation for steady flow energy which is given in Equation B.21 [112]. In this equation stands subscript 1 for the position in sea just before the water enters the pipe and subscript 2 for the position just before the water leaves the pipe at the sprinkler end. In the equation is p the pressure and V the velocity of the water and z the height at the given point, h_p is the head increase over the pump, h_f is the head increase due to friction and h_m is the head increase due to minor losses. Since the sea is a very large reservoir of water, the velocity in front of the entrance of the pipe is approximately zero and the velocity before just the water leaves the pipe is equal to the velocity of the water in the pipe, V_{Pipe}. The maximum velocity in the pipe is set to 2.5 m/s. By rewriting Equation B.21, Equation B.22 for the head increase over the pump is obtained [112].

$$\frac{p_1}{\rho \cdot g} + \frac{V_1^2}{2 \cdot g} + z_1 = \left(\frac{p_2}{\rho \cdot g} + \frac{V_2^2}{2 \cdot g} + z_2 \right) + h_f + \sum h_m - h_p \tag{B.21}$$

$$h_p = \frac{p_2 - p_1}{\rho \cdot g} + \frac{V_{Pipe}^2}{2 \cdot g} + z_2 - z_1 + h_f + \sum h_m \quad [m] \tag{B.22}$$

The pressure at the entrance of the pipe is 1.0 bar and the pressure at the sprinkler must be 2.0 bar [73]. The head increase due to minor losses caused by a sharp entrance or exit, valves, elbows etc, can be calculated with Equation B.3 [112]. The head increase due friction in the pipes can be calculated with Equation B.23 [112]. In this equation is$h_{f,Fifi,sub}$ the head increase due to friction in the subpipes, $h_{f,Fifi,main}$ the head increase due to friction in the main pipes and $h_{f,Fifi,vert}$ the head increase due to friction in the vertical pipes. The head increase for the different types of pipe can be calculated with Equation B.24 to Equation B.26. For this calculation it is assumed that the sprinkler that needs to be supplied is on the highest deck at the farthest possible position from pump.

$$h_f = h_{f,Fifi,sub} + h_{f,Fifi,main} + h_{f,Fifi,vert} \quad [m] \tag{B.23}$$

$$h_{f,Fifi,sub} = \frac{3 \cdot V_{Pipe}^2 \cdot f_{sub}}{d_{Pipe,Fifi,sub}} \quad [m] \tag{B.24}$$

$$h_{f,Fifi,main} = \frac{b \cdot V_{Pipe}^2 \cdot f_{main}}{d_{Pipe,Fifi,main}} \quad [m] \tag{B.25}$$

$$h_{f,Fifi,vert} = \frac{h_{Acco} \cdot V_{Pipe}^2 \cdot f_{vert}}{d_{Pipe,Fifi,vert}} \quad [m] \tag{B.26}$$

The friction coefficient f in Equation B.24to Equation B.26 can be calculated with Equation B.8 [112]. Now it is possible to calculate the head increase over the pump therefore one can calculate the required power for the pump with Equation B.27 [112]. In this equation isρ the density of the water, g the gravitational acceleration, $Q_{Pump,Fifi}$ the volumeflow in m^3/s, h_p the head increase over the pump and η_{Pump} the efficiency of the pump which lies between 60% and 80% [112]. The factor 1/1000 is to convert the power to kW. However the norm BS EN 12845 for automatic sprinkler systems requires sprinkler systems to be able to transport 5 mm of water per area per minute [73]. In order to fulfill this requirement for the total floor area, the minimum capacity of volumeflow through the pump must be as defined in Equation B.28.

$$P_{Fifi,pump} = \frac{\rho \cdot g \cdot Q_{Pump,Fifi} \cdot h_p}{1000 \cdot \eta_{Pump}} \quad [kW] \tag{B.27}$$

$$Q_{Pump,Fifi} = \frac{5.0 \cdot 10^{-3} \cdot N_{Deck} \cdot l \cdot b}{60} \quad [m^3/\mathrm{s}] \tag{B.28}$$

Appendix C

Resistance coefficients for pipes

The resistance coefficient for valves, elbows and tees are given in Table C.1. The resistance coefficient for partially opened valves can be found in Figure C.1, the resistance coefficient for reentrant inlets in Figure C.2, the resistance coefficient for rounded and beveled inlets in Figure C.3 and the resistance coefficient for sudden expansion and sudden contraction in Figure C.4.

Type of connection	**Screwed**				**Flanged**				
Nominal diameter [in]	0.5	1	2	4	1	2	4	8	20
Valves (fully open)									
Globe	14	8.2	6.9	5.7	13	8.5	6.0	5.8	5.5
Gate	0.30	0.24	0.16	0.11	0.80	0.35	0.16	0.07	0.03
Swing check	5.1	2.9	2.1	2.0	2.0	2.0	2.0	2.0	2.0
Angle	9.0	4.7	2.0	1.0	4.5	2.4	2.0	2.0	2.0
Elbows									
45° regular	0.39	0.32	0.30	0.29					
45° long radius					0.21	0.20	0.19	0.16	0.14
90° regular	2.0	1.5	0.95	0.64	0.50	0.39	0.30	0.26	0.21
90° long radius	1.0	0.72	0.41	0.23	0.40	0.30	0.19	0.15	0.10
180° regular	2.0	1.5	0.95	0.64	0.41	0.35	0.30	0.25	0.20
180° long radius					0.40	0.30	0.21	0.15	0.10
Tees									
Line flow	0.90	0.90	0.90	0.90	0.24	0.19	0.14	0.10	0.07
Branch flow	2.4	1.8	1.4	1.1	1.0	0.80	0.64	0.58	0.41

Table C.1: Coefficients for open valves, elbows and tees [112]

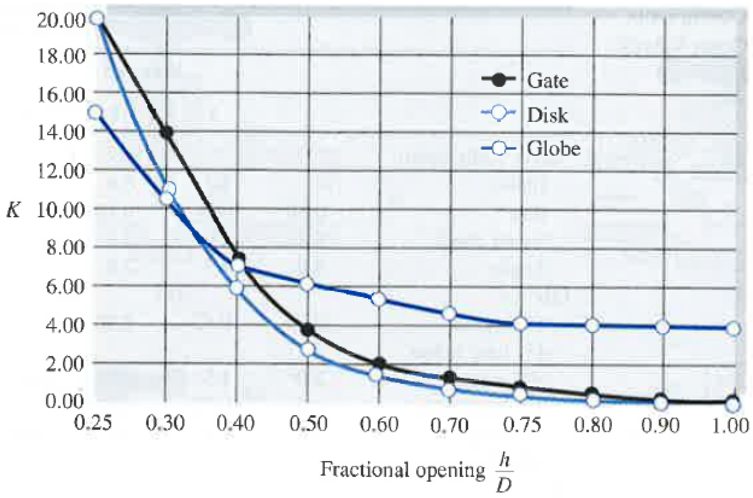


Figure C.1: Resistance coefficient for partially open valves [112]

Figure C.2: Resistance coefficient for reentrant inlets [112]

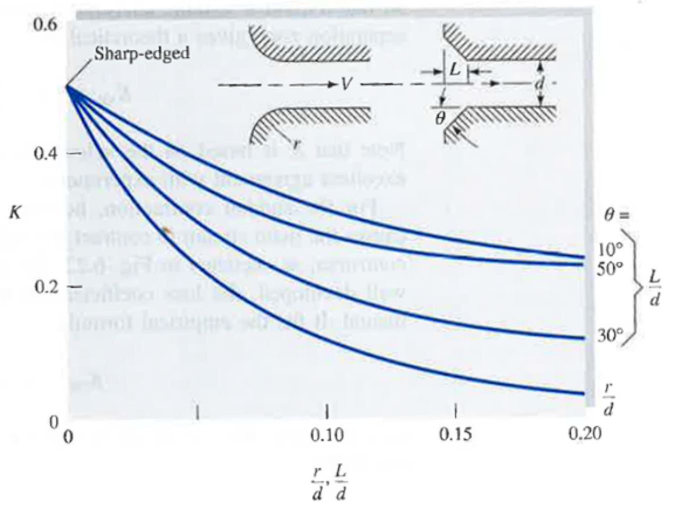


Figure C.3: Resistance coefficient for rounded and beveled inlets [112]

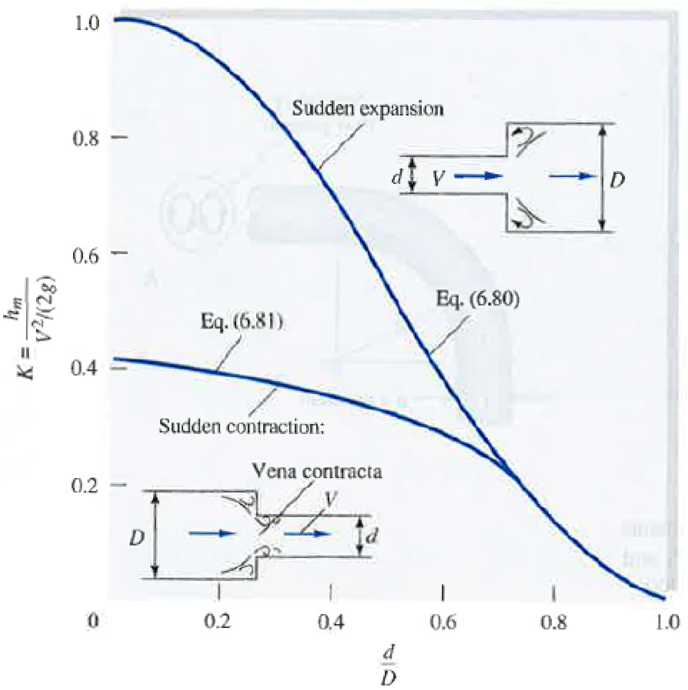


Figure C.4: Resistance coefficient for sudden expansion and sudden contraction [112]

$$K_{SE} = \left(1 - \frac{d^2}{D^2}\right)^2 \quad \text{(C.1)}$$

$$K_{SC} = 0.42 \cdot \left(1 - \frac{d^2}{D^2}\right) \quad \text{(C.2)}$$

Appendix D

Mollier diagram

This appendix contains the Mollier diagram which is shown on the next page:

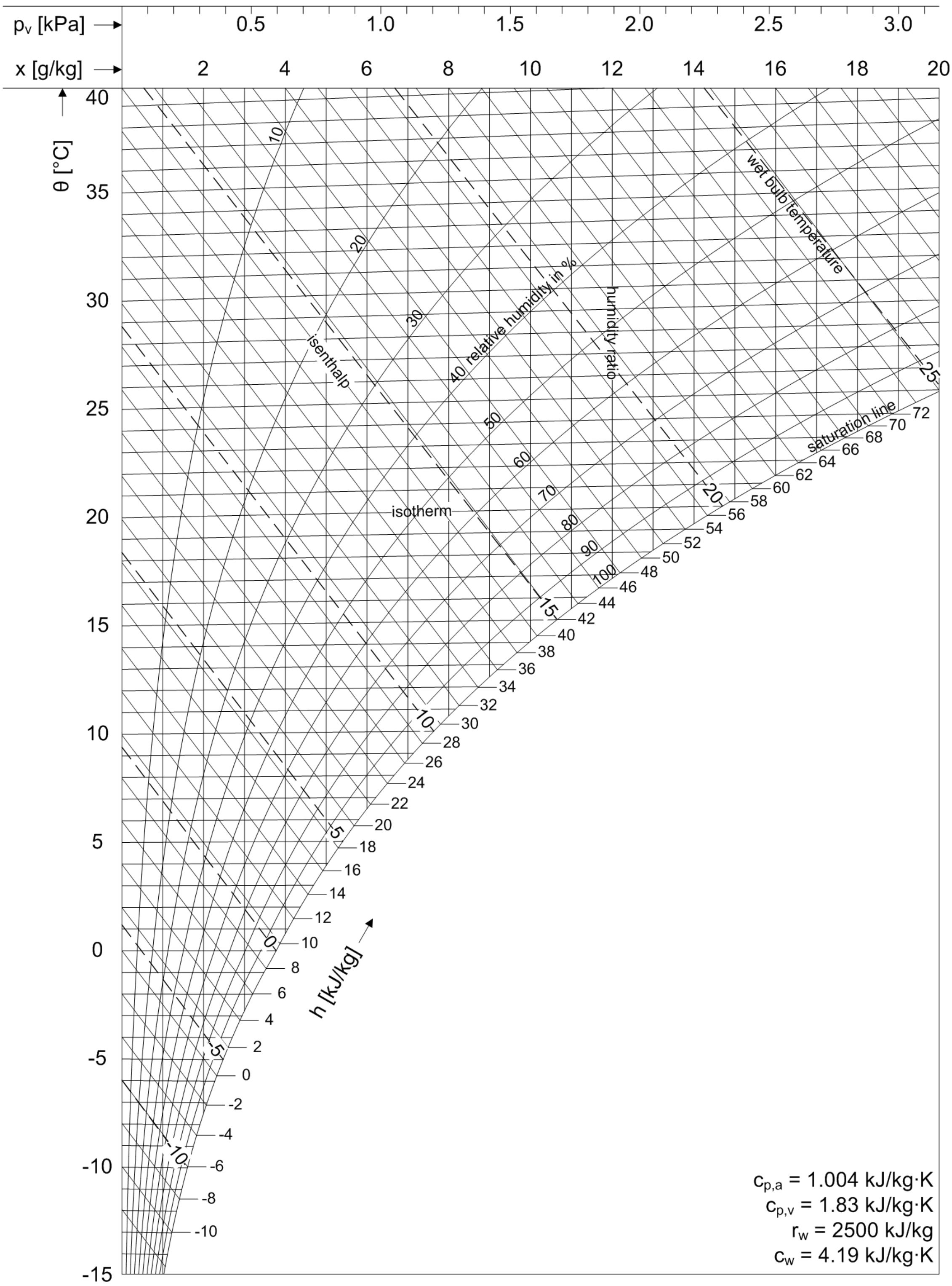


Figure D.1: Mollier diagram [60]

Appendix E

Saturated vapor pressure

The saturated vapour pressure as a function of temperature can be found in Table E.1.

Temperature θ [°C]	Saturated vapor pressure p_{sat} [bar]	Temperature θ [°C]	Saturated vapor pressure p_{sat} [bar]
0.01	0.00611	23	0.02810
4	0.00813	24	0.02985
5	0.00872	25	0.03169
6	0.00935	26	0.03363
8	0.01072	27	0.03567
10	0.01228	28	0.03782
11	0.01312	29	0.04008
12	0.01402	30	0.04246
13	0.01497	31	0.04496
14	0.01598	32	0.04759
15	0.01705	33	0.05034
16	0.01818	34	0.05324
17	0.01938	35	0.05628
18	0.02064	36	0.05947
19	0.02198	38	0.06632
20	0.02339	40	0.07384
21	0.02487	45	0.09593
22	0.02645		

Table E.1: Saturated vapour pressure [61]

Appendix F

Power consumption schedules

On the next pages the power consumption schedules are given for the tropic, artic and temperate zone.

Tropic zone

Part	00:00	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30
300: Primary Ship Systems																								
340: Fresh water & Sanitary Systems																								
370: HVAC Accommodation	54%	54%	54%	54%	54%	54%	54%	54%	54%	54%	38%	38%	38%	38%	54%	54%	54%	54%	69%	69%	69%	69%	85%	85%
400: Electrical System																								
450: Lighting Accommodation																								
700: Joinery & Arrangement Accommodation																								
710: Interior Accommodation																								
800: Nautical, Navigation & Communication Equipment																								
881: Internal Communication																								
883: Entertainment Systems																								

Part	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00	20:30	21:00	21:30	22:00	22:30	23:00	23:30
300: Primary Ship Systems																								
340: Fresh water & Sanitary Systems																								
370: HVAC Accommodation	100%	100%	100%	100%	100%	100%	100%	100%	85%	85%	85%	85%	69%	69%	69%	69%	54%	54%	54%	54%	54%	54%	54%	54%
400: Electrical System																								
450: Lighting Accommodation																								
700: Joinery & Arrangement Accommodation																								
710: Interior Accommodation																								
800: Nautical, Navigation & Communication Equipment																								
881: Internal Communication																								
883: Entertainment Systems																								

Figure F.1: Power schedule of the tropic zone

Artic zone

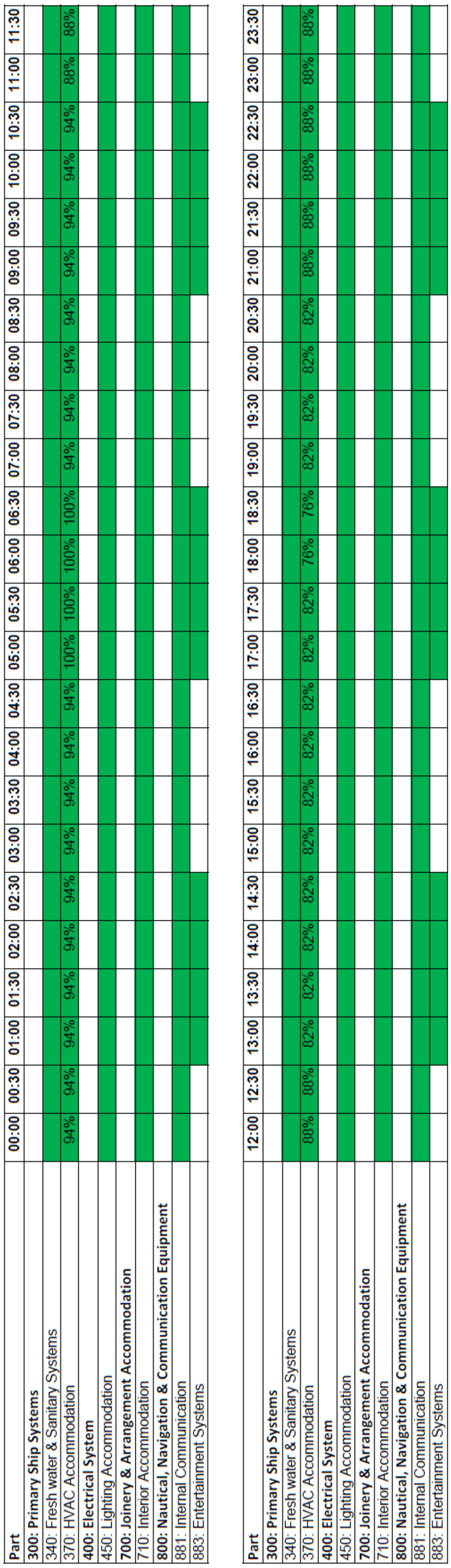
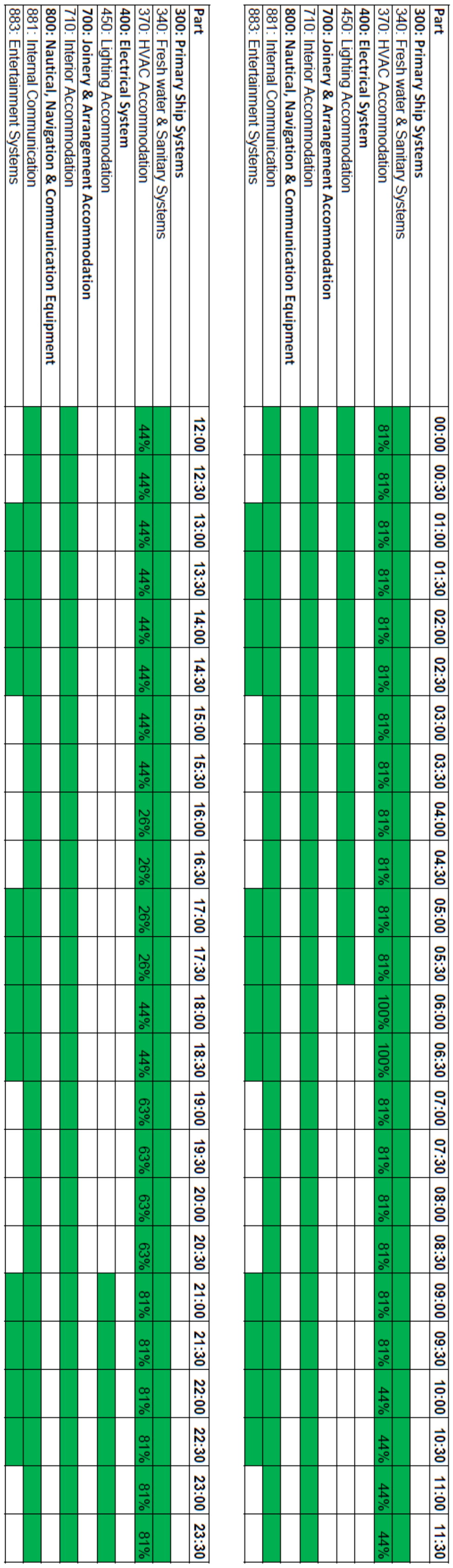


Figure F.2: Power schedule of the arctic zone

Temperate zone



Part	00:00	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00	10:30	11:00	11:30
300: Primary Ship Systems																								
340: Fresh water & Sanitary Systems																								
370: HVAC Accommodation	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	81%	100%	100%	81%	81%	81%	81%	81%	81%	44%	44%	44%	44%
400: Electrical System																								
450: Lighting Accommodation																								
700: Joinery & Arrangement Accommodation																								
710: Interior Accommodation																								
800: Nautical, Navigation & Communication Equipment																								
881: Internal Communication																								
883: Entertainment Systems																								

Part	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00	20:30	21:00	21:30	22:00	22:30	23:00	23:30
300: Primary Ship Systems																								
340: Fresh water & Sanitary Systems																								
370: HVAC Accommodation	44%	44%	44%	44%	44%	44%	44%	44%	26%	26%	26%	26%	44%	44%	63%	63%	63%	63%	81%	81%	81%	81%	81%	81%
400: Electrical System																								
450: Lighting Accommodation																								
700: Joinery & Arrangement Accommodation																								
710: Interior Accommodation																								
800: Nautical, Navigation & Communication Equipment																								
881: Internal Communication																								
883: Entertainment Systems																								

Figure F.3: Power schedule of the temperate zone

Appendix G

General arrangement plan Dockwise Fjell

The general arrangement plan of the reference vessel for cables and wires is given on the next pages. The general arrangement plan has been provided by Dockwise.

Appendix H

Lighting requirements

The lighting requirements according to the Dutch norm NEN1890 can be found on the next page in Table H.1.

Class	Type of lighting	Subclass	Type of task	Standard illuminance [lux]	Examples	Design value (x1.87) [lux]
I	Orientation lighting	A	Perceiving large objects and the movement of persons	50	Storage space, parking garage	± 100
		B	Perceiving of grove details and recognition of persons	100	Hall, staircase, elevator	± 200
II	Work lighting	A	Perceiving of grove details	200	Large construction work, warehouse	± 375
		B	Reading, writing and comparable activities	400	Office, classroom, assembly	± 750
		C	Smaller details than IIB	800	Drawing office, fine assembly	± 1500
III	Special work lighting	A	Perceiving of very small details and weak contrasts on a dark background	1600	Precision work, cadastral drawings, precise inspection work	± 3000
		B	Perceiving at the limit of eyesight	>3200	Operating table	± 6000

Table H.1: NEN1890 requirements for lighting levels [68]

Appendix I

Design model

In this appendix the formulas that make up the design model are given. With these formulas it is possible to build the design model.

Hull and outfitting

Steel accommodation

$$W_{dh} = 0.18 \cdot b \cdot h_j + b \cdot l \cdot (0.05 \cdot N_{Deck} + 0.08) + 0.16 \cdot h_j \cdot l \quad [ton] \tag{I.1}$$

Windows

$$W_{Window} = 0.03 \cdot W_{dh} \quad [ton] \tag{I.2}$$

Primary ship systems

Fresh water system

$$1.5 \cdot \sum A_{Pipe,vert,supply} = \sum A_{Pipe,main,supply} = \sum A_{Pipe,sub,supply} \quad [mm^2] \tag{I.3}$$

$$d_{Pipe,main,supply} = \sqrt{N_{Pipe,sub,supply} \cdot d_{Pipe,sub,supply}{}^2} \quad [mm] \tag{I.4}$$

$$N_{Pipe,sub,supply} = N_{User} \quad [-] \tag{I.5}$$

$$d_{Pipe,vert,supply} = \sqrt{\frac{N_{Deck} \cdot d_{Pipe,main,supply}{}^2}{1.5}} \quad [mm] \tag{I.6}$$

$$N_{Pipe,main,supply} = N_{Pipe,vert,supply} = round\left(\frac{l}{6}\right) \quad [-] \tag{I.7}$$

$$L_{Pipe,sub,supply} = 8 \cdot N_{Pipe,sub,supply} \quad [m] \tag{I.8}$$

$$L_{Pipe,main,supply} = N_{Pipe,main,supply} \cdot b \quad [m] \tag{I.9}$$

$$L_{Pipe,vert,supply} = \frac{N_{Deck} - 1}{N_{Deck}} \cdot h_{Acco} \cdot N_{Pipe,vert,supply} \quad [m] \tag{I.10}$$

$$\begin{aligned} W_{Piping,Fresh,supply} \quad = \quad & \frac{2}{1000} \cdot (N_{Deck} \cdot (W_{Piping,main,supply} + \\ & W_{Piping,sub,supply}) + W_{Piping,vert,supply}) \quad [ton] \end{aligned} \tag{I.11}$$

$$W_{Piping,main,supply} = L_{Pipe,main,supply} \cdot w_{Pipe,main,supply} \quad [kg] \tag{I.12}$$

$$W_{Piping,sub,supply} = L_{Pipe,sub,supply} \cdot w_{Pipe,sub,supply} \quad [kg] \tag{I.13}$$

$$W_{Piping,vert,supply} = L_{Pipe,vert,supply} \cdot w_{Pipe,vert,supply} \quad [kg] \tag{I.14}$$

$$L_{Pipe,sub,return} = L_{Pipe,sub,supply} \quad [m] \tag{I.15}$$

$$L_{Pipe,main,return} = L_{Pipe,main,supply} \quad [m] \tag{I.16}$$

$$L_{Pipe,vert,return} = L_{Pipe,vert,supply} \quad [m] \tag{I.17}$$

$$w_{Pipe,sub,return} = w_{Pipe,main,return} = w_{Pipe,vert,return} = w_{Pipe,fresh,return} \quad [kg/m] \tag{I.18}$$

$$\begin{aligned} W_{Piping,Fresh,return} \quad = \quad & \frac{w_{Pipe,fresh,return}}{1000} \cdot (N_{Deck} \cdot (L_{Pipe,main,return} + \\ & L_{Pipe,sub,return}) + L_{Pipe,vert,return}) \quad [ton] \end{aligned} \tag{I.19}$$

$$W_{fresh} = W_{Piping,Fresh,supply} + W_{Piping,Fresh,return} + W_{fresh,pump} \quad [ton] \tag{I.20}$$

HVAC system

$$\dot{V} = 10 \cdot V_{Acco} \quad [m^3/\text{h}] \tag{I.21}$$

$$\rho = \frac{p}{R \cdot T_{Air}} \quad [kg/m^3] \tag{I.22}$$

$$\dot{m} = \rho \cdot \dot{V} \quad [kg/h] \tag{I.23}$$

$$T_{Mixture} = \frac{\dot{m}_{Indoor} \cdot T_{Indoor} + \dot{m}_{Outdoor} \cdot T_{Outdoor}}{\dot{m}_{Indoor} + \dot{m}_{Outdoor}} \quad [C] \tag{I.24}$$

$$P_{HVAC,heat} = \frac{\dot{m}}{3600} \cdot (h_{Room} - h_{Mixture}) \quad [kW] \tag{I.25}$$

$$h = c_{p,a} \cdot \theta + x \cdot (r_w + c_{p,v} \cdot \theta) \quad [kJ/kg] \tag{I.26}$$

$$P_{HVAC,heat} = 9.43 \cdot 10^{-2} \cdot V_{Acco} \quad [kW] \tag{I.27}$$

$$x = 0.622 \cdot \frac{\phi \cdot p_{sat}}{p - \phi \cdot p_{sat}} \quad [kg/kg] \tag{I.28}$$

$$x_{Mixture} = \frac{\dot{m}_{Indoor} \cdot x_{Indoor} + \dot{m}_{Outdoor} \cdot x_{Outdoor}}{\dot{m}_{Indoor} + \dot{m}_{Outdoor}} \quad [kg/kg] \tag{I.29}$$

$$h_{Mixture} = \frac{\dot{m}_{Indoor} \cdot h_{Indoor} + \dot{m}_{Outdoor} \cdot h_{Outdoor}}{\dot{m}_{Indoor} + \dot{m}_{Outdoor}} \quad [kJ/kg] \tag{I.30}$$

$$\phi = \frac{x}{x + 0.622} \cdot \frac{p}{p_{sat}} \quad [-] \tag{I.31}$$

$$P_{HVAC,heat} = 2.24 \cdot 10^{-2} \cdot V_{Acco} \quad [kW] \tag{I.32}$$

$$W_{HVAC} = W_{AC} + W_{CM} + W_{Piping,HVAC} + W_{Fan,HVAC} \quad [ton] \tag{I.33}$$

$$W_{AC} = 1.9 \cdot 10^{-3} \cdot \dot{V}^{0.6838} \quad [ton] \tag{I.34}$$

$$W_{CM} = 3.8 \cdot 10^{-2} \cdot P_{HVAC}^{0.7003} \quad [ton] \tag{I.35}$$

$$\dot{V}_{Deck} = \frac{\dot{V}}{N_{Deck}} \quad [m^3/\text{h}] \tag{I.36}$$

$$N_{Pipe,main} = round\left(\frac{l}{6}\right) \quad [-] \tag{I.37}$$

$$N_{Pipe,sub} = 2 \cdot round\left(\frac{b}{3}\right) \quad [-] \tag{I.38}$$

$$N_{Pipe,vert} = N_{Pipe,main} = round\left(\frac{l}{6}\right) \quad [-] \tag{I.39}$$

$$\dot{V}_{Pipe} = 3600 \cdot A_{Pipe} \cdot V_{Pipe} = \frac{\dot{V}_{Deck}}{N_{Pipe,main}} \quad [m^3/\mathrm{h}] \tag{I.40}$$

$$d_{Pipe,main} = \frac{1}{30} \cdot \sqrt{\frac{\dot{V}_{Deck}}{\pi \cdot V_{Pipe} \cdot N_{Pipe,main}}} \quad [mm] \tag{I.41}$$

$$\sum A_{Pipe,vert} = \sum A_{Pipe,main} = \sum A_{Pipe,sub} \tag{I.42}$$

$$d_{Pipe,sub} = \sqrt{\frac{{d_{Pipe,main}}^2}{N_{Pipe,sub}}} \quad [mm] \tag{I.43}$$

$$d_{Pipe,vert} = \sqrt{N_{Deck} \cdot {d_{Pipe,main}}^2} \quad [mm] \tag{I.44}$$

$$L_{Pipe,main} = N_{Pipe,main} \cdot b \quad [m] \tag{I.45}$$

$$L_{Pipe,sub} = 3 \cdot N_{Pipe,sub} \quad [m] \tag{I.46}$$

$$L_{Pipe,vert} = N_{Pipe,vert} \cdot h_{Acco} \quad [m] \tag{I.47}$$

$$\begin{aligned} W_{Piping,HVAC} \quad = \quad & \frac{1.1}{1000} \cdot (N_{Deck} \cdot (L_{Pipe,main} \cdot w_{Pipe,main} + \\ & L_{Pipe,sub} \cdot w_{Pipe,sub}) + L_{Pipe,vert} \cdot w_{Pipe,vert}) \quad [ton] \end{aligned} \tag{I.48}$$

$$W_{Fan,HVAC} = 4.02 \cdot 10^{-2} \cdot Q_{Fan}^{0.7078} \quad [ton] \tag{I.49}$$

Electrical system

Power generating system

$$\dot{m}_f = \frac{SFC}{8.64 \cdot 10^7} \cdot \int_0^{24} P_{Load} dt \quad [kg/s] \tag{I.50}$$

$$W_{gen,50Hz} = 2.63 \cdot 10^{-2} \cdot P^{0.9488} \quad [ton] \tag{I.51}$$

$$W_{gen,60Hz} = 2.3 \cdot 10^{-2} \cdot P^{0.9683} \quad [ton] \tag{I.52}$$

$$\Delta W_{gen,50Hz} = W_{gen,50Hz}\left(P_{gen}\right) - W_{gen,50Hz}\left(P_{Peak}\right) \quad [ton] \tag{I.53}$$

$$\Delta W_{gen,60Hz} = W_{gen,60Hz}\left(P_{gen}\right) - W_{gen,60Hz}\left(P_{Peak}\right) \quad [ton] \tag{I.54}$$

Cables and wires accommodation

$$S_{cables} = 2.86 \cdot 10 \cdot A_{floor} \quad [m] \tag{I.55}$$

$$W_{cables} = 8.6 \cdot 10^{-3} \cdot A_{floor} \quad [ton] \tag{I.56}$$

Lighting accommodation

$$P_{Lighting} = \frac{\Phi \cdot A_{floor}}{10^3 \cdot \eta_{Light}} \quad [kW] \tag{I.57}$$

$$N_{Armature} = \frac{10^3 \cdot P_{Lighting}}{P_{Armature}} \quad [-] \tag{I.58}$$

$$N_{Armature} = round\left(2.13 \cdot 10^{-1} \cdot A_{floor}\right) \quad [-] \tag{I.59}$$

$$P_{Lighting} = \frac{N_{Armature} \cdot P_{Armature}}{10^3} \quad [kW] \tag{I.60}$$

$$W_{Lighting} = N_{Armature} \cdot \frac{W_{Armature}}{10^3} \quad [ton] \tag{I.61}$$

Deck equipment

Type of lifeboat	Capacity [persons]	Drop height [m]	Weight lifeboat [kg]	Type of davit	Weight davit [kg]	Total system weight [kg]
LBF 490 C	16	16	3,963	JYF55	5,500	9,463
LBF 580 C	26	17	5,646	JYF55	5,500	11,146
LBF 680 C	33	22	6,440	JYF75	7,500	13,940
LBF 750 C	36	22	7,374	JYF75	7,500	14,874
LBF 850 C	40	25	8,322	JYF90	10,000	18,322

Table I.1: Free fall systems [72]

Secondary ship systems

$$W_{Fifi} = W_{Piping,Fifi} + W_{Fifi,Pump} \quad [ton] \tag{I.62}$$

$$d_{Pipe,Fifi,main} = \sqrt{N_{Pipe,Fifi,sub} \cdot d_{Pipe,Fifi,sub}{}^{\mathbf{2}}} \quad [mm] \tag{I.63}$$

$$d_{Pipe,Fifi,vert} = \sqrt{N_{Deck} \cdot d_{Pipe,Fifi,main}{}^{\mathbf{2}}} \quad [mm] \tag{I.64}$$

Joinery and hotel equipment

$$W_{Joinery} = 1.5 \cdot 10^{-1} \cdot A_{floor} \quad [ton] \tag{I.65}$$

$$W_{Hotel} = \sum N_i \cdot W_i \quad [kW] \tag{I.66}$$

$$N_i = \frac{N_{Crew}}{n_i} \quad [-] \tag{I.67}$$

$$P_{Hotel} = \sum N_i \cdot P_i \quad [kW] \tag{I.68}$$

Nautical, Navigation and Communication Equipment

Internal communication

$$W_{IntCom} = 1.0 \cdot 10^{-3} \cdot N_{Ph} + 2.5 \cdot 10^{-3} \cdot N_{TM} \quad [ton] \tag{I.69}$$

$$P_{IntCom} = 5.0 \cdot 10^{-2} \cdot N_{Ph} + 6.5 \cdot 10^{-2} \cdot N_{TM} \quad [kW] \tag{I.70}$$

Entertainment systems

$$W_{EntS} = 1.587 \cdot 10^{-1} \cdot N_{SatA} + 2.0 \cdot 10^{-2} \cdot N_{Amp} + 3.5 \cdot 10^{-3} \cdot N_{SatRec} + 3.2 \cdot 10^{-3} \cdot N_{TV} \quad [ton] \tag{I.71}$$

$$P_{EntS} = 7.0 \cdot 10^{-2} \cdot N_{SatA} + 1.2 \cdot 10^{-1} \cdot N_{Amp} + 1.8 \cdot 10^{-2} \cdot N_{SatRec} + 2.8 \cdot 10^{-2} \cdot N_{TV} \quad [kW] \tag{I.72}$$

Appendix J

Cost model

In this appendix the formulas that make up the cost model are given. With these formulas it is possible to build the cost model.

Building cost

Hull and outfitting

Steel of the accommodation

$$C_{st} = C_{st,material} + C_{st,installation} \quad [€] \tag{J.1}$$

$$scrap = 12 + \left(\left(\frac{W_{dh}}{1.0 \cdot 10^3} + 100 \right)^{-5.3} \cdot 54 \cdot 10^{10} \right) \quad [\%] \tag{J.2}$$

$$W_{st,gross} = W_{dh} \cdot \left(1 + \frac{scrap}{100} \right) \quad [ton] \tag{J.3}$$

$$C_{st,material} = 1.32 \cdot 10^3 \cdot W_{st,gross} \quad [€] \tag{J.4}$$

$$k = 8.66 \cdot 10^{-1} \cdot \left(45.36 \cdot \left(\frac{l \cdot b \cdot h_j}{10^3} \right)^{-0.115} + 3.5 \right) \quad [\mathrm{h/ton}] \tag{J.5}$$

$$C_{st,installation} = 4.33 \cdot 10 \cdot W_{st,gross} \cdot \left(45.36 \cdot \left(\frac{l \cdot b \cdot h_j}{10^3} \right)^{-0.115} + 3.5 \right) \quad [€] \tag{J.6}$$

Windows

$$C_{Window} = C_{Window,material} + C_{Window,installation} \quad [€] \tag{J.7}$$

$$C_{Window,material} = N_{Window} \cdot c_{Window} \quad [€] \tag{J.8}$$

$$C_{Window,installation} = 5 \cdot 10^2 \cdot N_{Window} \quad [€] \tag{J.9}$$

Primary ship systems

Fresh water and sanitary systems

$$C_{Fresh} = C_{Fresh,material} + C_{Fresh,installation} \quad [€] \tag{J.10}$$

$$C_{Fresh,material} = C_{Piping,Fresh,supply} + C_{Piping,Fresh,return} + C_{Fresh,pump} \quad [€] \tag{J.11}$$

$$C_{Piping,Fresh,supply} = N_{Deck} \cdot (C_{Piping,main,supply} + C_{Piping,sub,supply}) + C_{Piping,vert,supply} \quad [€] \tag{J.12}$$

$$C_{Piping,main,supply} = L_{Pipe,main,supply} \cdot c_{Pipe,main,supply} \quad [€] \tag{J.13}$$

$$C_{Piping,sub,supply} = L_{Pipe,sub,supply} \cdot c_{Pipe,sub,supply} \quad [€] \tag{J.14}$$

$$C_{Piping,vert,supply} = L_{Pipe,vert,supply} \cdot c_{Pipe,vert,supply} \quad [€] \tag{J.15}$$

$$c_{Pipe,sub,return} = c_{Pipe,main,return} = c_{Pipe,vert,return} = c_{Pipe,fresh,return} \quad [€/\mathrm{m}] \tag{J.16}$$

$$\begin{aligned} C_{Piping,Fresh,return} \quad = \quad & c_{Pipe,fresh,return} \cdot (N_{Deck} \cdot (L_{Pipe,main,return} + \\ & L_{Pipe,sub,return}) + L_{Pipe,vert,return}) \quad [€] \end{aligned} \tag{J.17}$$

$$C_{Fresh,installation} = 1.38 \cdot 10^2 \cdot l \cdot (b + h_{Acco}) \quad [€] \tag{J.18}$$

HVAC Accommodation

$$C_{HVAC} = 2.1 \cdot 10^5 \cdot \left(\frac{l \cdot b \cdot h_{Acco}}{1.2 \cdot 10^3}\right)^{0.65} \quad [€] \tag{J.19}$$

Electrical system

Power generating systems

$$C_{gen,material} = 9.25 \cdot 10^3 \cdot P^{0.62} \quad [€] \tag{J.20}$$

$$C_{gen,installation} = 1.0 \cdot 10^3 \cdot P^{0.55} \quad [€] \tag{J.21}$$

$$\Delta C_{gen,material} = C_{gen,material}\left(P_{gen}\right) - C_{gen,material}\left(P_{Peak}\right) \quad [€] \tag{J.22}$$

$$\Delta C_{gen,installation} = C_{gen,installation}\left(P_{gen}\right) - C_{gen,installation}\left(P_{Peak}\right) \quad [€] \tag{J.23}$$

$$\Delta C_{gen} = \Delta C_{gen,material} + \Delta C_{gen,installation} \quad [€] \tag{J.24}$$

Cables and wires accommodation

$$C_{cables} = 148.23 \cdot S_{cables}^{0.8469} \quad [€] \tag{J.25}$$

Lighting accommodation

$$C_{Lighting} = N_{Armature} \cdot C_{Armature} \quad [€] \tag{J.26}$$

Deck equipment

Type of lifeboat	Capacity [persons]	Drop height [m]	Type of davit	Total system cost [€]
LBF 490 C	16	16	JYF55	82,000
LBF 580 C	26	17	JYF55	84,000
LBF 680 C	33	22	JYF75	94,000
LBF 750 C	36	22	JYF75	102,000
LBF 850 C	40	25	JYF90	123,000

Table J.1: Cost of free-fall systems [72]

Secondary ship systems

$$C_{Fifi} = C_{Fifi,material} + C_{Fifi,installation} \tag{J.27}$$

$$C_{Fifi,material} = C_{Piping,Fifi} + C_{Fifi,Pump} \quad [€] \tag{J.28}$$

$$C_{Piping,Fifi} = N_{Deck} \cdot (C_{Piping,Fifi,sub} + C_{Piping,Fifi,main}) + C_{Piping,Fifi,vert} \quad [€] \tag{J.29}$$

$$C_{Piping,Fifi,sub} = L_{Pipe,Fifi,sub} \cdot c_{Pipe,Fifi,sub} \quad [€] \tag{J.30}$$

$$C_{Piping,Fifi,main} = L_{Pipe,Fifi,main} \cdot c_{Pipe,Fifi,main} \quad [€] \tag{J.31}$$

$$C_{Piping,Fifi,vert} = L_{Pipe,Fifi,vert} \cdot c_{Pipe,Fifi,vert} \quad [€] \tag{J.32}$$

Joinery and hotel equipment

$$C_{Joinery} = C_{Joinery,material} + C_{Joinery,installation} \quad [€] \tag{J.33}$$

$$C_{Joinery,material} = 7.5 \cdot 10^2 \cdot A_{floor} \quad [€] \tag{J.34}$$

$$C_{Joinery,installation} = 1.25 \cdot 10^4 \cdot A_{floor}^{0.55} \quad [€] \tag{J.35}$$

Nautical, navigation and communication equipment

Internal communication

$$C_{IntCom} = 1.0 \cdot 10^2 \cdot N_{Ph} + 1.75 \cdot 10^3 \cdot N_{TM} \quad [€] \tag{J.36}$$

Entertainment systems

$$\begin{aligned} C_{EntS} &= 1.75 \cdot 10^4 \cdot N_{SatA} + 5.0 \cdot 10^2 \cdot N_{Amp} + \\ &\quad 1.0 \cdot 10^2 \cdot N_{SatRec} + 2.0 \cdot 10^2 \cdot N_{TV} \quad [€] \end{aligned} \tag{J.37}$$

Fuel savings

$$T_{Trip} = \frac{S}{V_S} + \frac{S_{Port}}{V_{S,Port}} + T_{Port} \quad [\mathrm{h}] \tag{J.38}$$

$$m_{f,Trip,acco} = 3.6 \cdot T_{Trip} \cdot \dot{m}_f \quad [ton] \tag{J.39}$$

$$N_{Trip} = \frac{24 \cdot (365 - T_{off})}{T_{Trip}} \quad [-] \tag{J.40}$$

$$m_{f,Year,acco} = m_{f,Trip,acco} \cdot N_{Trip} \quad [ton] \tag{J.41}$$

$$C_{Fuel,Trip,acco} = m_{f,Trip,acco} \cdot c_{Fuel,acco} \quad [€] \tag{J.42}$$

$$C_{Fuel,Year,acco} = m_{f,Year,acco} \cdot c_{Fuel,acco} \quad [€] \tag{J.43}$$

$$C_{adm} = \frac{\Delta^{\frac{2}{3}} \cdot V_S^3}{P_D} \quad [\frac{ton^{\frac{2}{3}} \cdot kts^3}{kW}] \tag{J.44}$$

$$\delta P_D = P_{D,Manned} - P_{D,Unmanned} \quad [ton] \tag{J.45}$$

$$m_{f,Trip,size} = \delta P_D \cdot SFC \cdot T_{Trip} \cdot 10^{-6} \quad [ton] \tag{J.46}$$

$$m_{f,Year,size} = m_{f,Trip,size} \cdot N_{Trip} \quad [ton] \tag{J.47}$$

$$C_{Fuel,Trip,size} = m_{f,Trip,size} \cdot c_{Fuel,size} \quad [€] \tag{J.48}$$

$$C_{Fuel,Year,size} = m_{f,Year,size} \cdot c_{Fuel,size} \quad [€] \tag{J.49}$$

$$C_{Fuel,Trip} = C_{Fuel,Trip,acco} + C_{Fuel,Trip,size} \quad [€] \tag{J.50}$$

$$C_{Fuel,Year} = C_{Fuel,Year,acco} + C_{Fuel,Year,size} \quad [€] \tag{J.51}$$

Manning cost

$$C_{Manning} = N_{Crew} \cdot c_{Crew} \cdot \beta \quad [€] \tag{J.52}$$

Insurance cost

$$C_{Insurance} = C_{P\&I} + C_{H\&M} \quad [€] \tag{J.53}$$

Depreciation cost

$$C_{Dep} = \frac{C_{Building} - R_{Acco}}{T_{Dep}} \quad [€] \tag{J.54}$$

$$R_{Acco} = 2.4 \cdot 10^2 \cdot \delta W \quad [€] \tag{J.55}$$

Interest cost

$$C_{Int} = 0.5 \cdot L_{Rate} \cdot C_{Building} \cdot I_{Rate} \cdot (T_{Int} + 1) \quad [€] \tag{J.56}$$

Appendix K

Particulars reference vessel

The particulars of the reference vessel are given on the next pages.

Table K.1: M-Borg hull specification

Hull Particulars	Unit	Design
L	$[m]$	134.50
L_{PP}	$[m]$	127.20
L_{WL}	$[m]$	129.79
B	$[m]$	16.50
D	$[m]$	9.80
T	$[m]$	7.00
∇	$[m^3]$	11694
Δ	$[ton]$	11986
DWT	$[ton]$	8950
A_{WL}	$[m^2]$	1886
S_A	$[m^2]$	3363
C_B	$[-]$	0.796
C_M	$[-]$	0.997
C_P	$[-]$	0.798
C_{WP}	$[-]$	0.880
LCB	$[m]$	63.66
LCF	$[m]$	66.64
KB	$[m]$	3.69
BM	$[m]$	3.26
LCG	$[m]$	63.66
KG	$[m]$	6.50
$Tonnage$	$[GT]$	6540

Table K.3: M-Borg propulsion specification

Hull Particulars	Unit	Design
Main engine		Wartsila 8L32
P_B	$[kW]$	5280
Ne	$[r/min]$	600
Generator		
P_{gen}	$[kW]$	4100
N_{gen}	$[r/min]$	1800
Gearbox		
Reduction	$[-]$	4.136
Propeller		CPP
Blades		4
D_p	$[m]$	4.30
N_p	$[r/min]$	145
A_e/A_0	$[-]$	0.557

Appendix L

General arrangement plan reference vessel

The general arrangement plan of the reference vessel is given on the next pages.

Appendix M

General arrangement plan unmanned reference vessel

The general arrangement plan of the unmanned reference vessel is given on the next pages.