Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Gaute Aanesland Jørgensen

Applying Tradespace Exploration in the evaluation of cruise ship design and operation, in the wake of the Covid-19 pandemic

Master's thesis in Marine Technology
Supervisor: Professor Stein Ove Erikstad
June 2022

NTNU
Kunnskap for en bedre verden

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Det skapende universitet

Master Thesis in Marine Systems Design - Spring 2022

Stud. techn. Gaute Aanesland Jørgensen

"Using Tradespace Exploration in evaluation of cruise ship design and operation, in the wake of Covid-19 pandemic"

Background

Due to the spread of Covid-19 virus in cases like "Diamond Princess", the cruise ship industry halted in 2020, with uncertainty related to when the cruise industry could resume. As of 2022, it is still unclear what impact this pandemic will have on the industry. The Covid-19 pandemic might lead to improvements in the way cruise ships are built or operated, leading to better infection control procedures. Ship designs might also be evolving due to the recession, only the best cruise ship designs will last. The Covid-19 pandemic clearly showed that the cruise industry was not prepared for pandemic. Maybe this is the time for change.

Overall aim and focus

This master thesis aims to develop an evaluation model for cruise ship design and operation, with respect to pandemic preparedness.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide background of the status and important trends in the cruise ship industry before and during the Covid-19 pandemic.*

2. *Develop a system model with respect to pandemic, based on:*
   a. *Stakeholder needs*
   b. *Function structure - Overall and sub functions*
   c. *Form elements*

3. *Establish changes in function structures due to Covid-19 pandemic*

4. *Propose an evaluation model for pandemic preparedness, and evaluate it in different future pandemic scenarios*

5. *Discuss and conclude*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor

The work shall follow the guidelines given by NTNU for the MSc Project work.

It shall correspond to 30 ECTS, which is 100% of one semester.

Stein Ove Erikstad
Professor/Responsible Supervisor

Abstract

In this thesis, we investigate pandemic preparedness in cruise ships. Prior to the Covid-19 pandemic, the cruise industry was in continuous growth, year after year. The Covid-19 pandemic showed that the cruise ship industry was not prepared for a pandemic. Changes in both the design and operation will be needed due to combat this issue. This master's thesis aims to develop an evaluation model for cruise ship design and operation, with respect to pandemic preparedness.

An evaluation model for cruise ship design and operation with respect to pandemic preparedness is developed in this master's thesis. It employs a system design approach. The needs of stakeholders were investigated, and a cruise ship's function structure was created. Specific measures were then determined based on these design methods and health experts. In order to assess cruise ship preparedness based on these measures, Tradespace exploration and epoch era analysis was applied. The measures proposed needed to be mapped to utility attributes that could be applied to the tradespace exploration. Based on the results, the model proved to be an efficient means to evaluate cruise ship preparedness. It was also shown to be applicable to a real-world environment.

Lastly, the results indicated that the model could be tailored for specific cases for cruise liners. This master's thesis developed a model that can be used to evaluate cruise ship preparedness from a design and operation perspective. It will be necessary to provide additional data for this model to accurately assess preparedness, this could be provided by a decision-maker such as a cruise ship owner while tailoring the model to their specific ships and stakeholders.

Sammendrag

I denne oppgaven undersøker vi pandemiberedskap i cruiseskip. Før Covid-19-pandemien var cruiseindustrien i kontinuerlig vekst, år etter år. Covid-19-pandemien viste at cruiseskipindustrien ikke var forberedt på en pandemi. Endringer i både design og drift vil være nødvendig for å bekjempe dette problemet. Denne masteroppgaven har som mål å utvikle en evalueringsmodell for cruiseskipdesign og drift, med hensyn til pandemiberedskap.

En evalueringsmodell for design og drift av cruiseskip med hensyn til pandemiberedskap er utviklet i denne masteroppgaven. Den bruker en systemdesigntilnærming. Behovene til interessentene ble undersøkt, og et cruiseskips funksjonsstruktur ble opprettet. Spesifikke tiltak ble deretter bestemt basert på disse designmetodene og helseeksperter. For å vurdere cruiseskipsberedskapen basert på disse tiltakene, ble Tradespace exploration og epokeanalyse brukt. De foreslåtte tiltakene måtte kartlegges til nytteattributter som kunne brukes i tradespace exploration. Basert på resultatene viste modellen seg å være et effektivt middel for å evaluere cruiseskipsberedskapen. Det ble også vist å være anvendelig for et virkelig miljø.

Til slutt indikerte resultatene at modellen kunne skreddersys for spesifikke tilfeller for cruiseskip. Denne masteroppgaven utviklet en modell som kan brukes til å evaluere cruiseskipsberedskap fra et design- og operasjonsperspektiv. Det vil være nødvendig å gi ytterligere data for denne modellen for å nøyaktig vurdere beredskapen, dette kan gis av en beslutningstaker som en cruiseskipseier mens modellen skreddersys til deres spesifikke skip og interessenter.

Preface

This thesis marks the end of my masters degree from Norwegian University of Science and Technology (NTNU). Over the past 5 years i have studied at the Department of Marine Technology, specializing in Marine System Design. The thesis was written during spring 2022, a task representing 30 ECTS. My thesis focuses on developing a model that can be applied to evaluate cruise ship pandemic preparedness.

Gaute Aanesland Jørgensen
Trondheim 10/6/2022

Acknowledgement

I would first and foremost express my deepest gratitude towards my supervisor, professor Stein Ove Erikstad at NTNU, for valuable conversations and his guidance this past year, with weekly guidance to ensure good progress through the entire semester. I also wish to express my appreciation to Kai Levander, for his guidance and advice during this process. I also want to thank my family for continued support over the last 5 years.

Lastly i am grateful to my fellow students at A2.011, for valuable discussions during the master's thesis, as well as all the memorable moments over the last 5 years.

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Chapter 1

Introduction

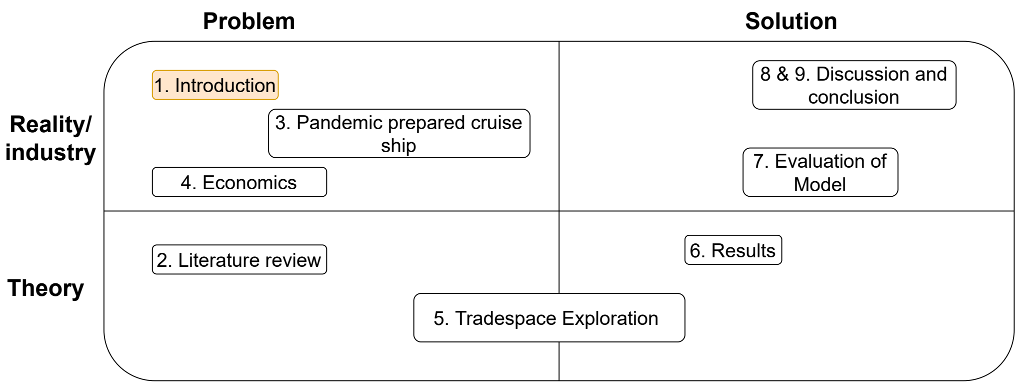


Figure 1.1: Overview of where the current chapters are located, in relation to theory vs industry, and problem vs solution. This figure will be presented in the beginning of each chapter, with the current chapter highlighted in yellow.

1.1 Background

In February 2020 Covid-19 pandemic struck its first cruise ship victim, the "Diamond Princess". The ship is operated by Princess Cruises, and during a Western pacific cruise, they detected Covid-19 on board [37]. They began screening the passengers, and the number of Covid-19 cases rose quickly. The situation resulted in the ship being quarantined by the Japanese authorities, and all its passengers and crew were to remain on the ship for 14 days. The incident resulted in 712 infected, out of the 2666 passengers and 1045 crew, with an estimated 7 to 14 deaths [32]. The virus spread quite fast on the ship, the ship itself even made headlines and stayed high up on Covid-19 tracking websites, based on countries, where "Diamond Princess" was regarded on multiple websites as its own country due to the high numbers compared to other countries. During the ship's worst times, the ship was involved with more than half of the total Covid-19 cases outside of china [33].

"Diamond Princess" exposed the cruise ship industry's weakness in handling viruses. Coronavirus is not the first outbreak to demonstrate the vulnerabilities of combining viruses with high levels of people and close quarters found on cruise ships, but it is the most serious threat to the cruise ship industry in a long time. Cruise ship operators, as well as much of our society, underestimated the impact of Covid-19 at first. Several outbreaks occurred among many different cruise ship operators before the situation finally settled, and the cruise ship industry was put on hold for the foreseeable future. Around September of 2021, there seemed to be a bright future for the industry again, since cases were dropping, vaccination rates were rising, some cruises were resuming, and overall the mood was positive in the industry. Several countries will be in their third, or fourth lockdown when this paragraph is written in June 2022. Again, cruises and vacations are slowly returning, but the cruise ship industry's future is uncertain.

The cruise industry is in need of change as a result of events like these. Cruisers need to feel safe when taking cruises, and with the current circumstances, that is not a guarantee right now, or if the next pandemic hits.

1.2 Objective

This master's thesis aims to develop an evaluation model for cruise ship design and operation, with respect to pandemic preparedness
The scope and main activities of the master's thesis will include;

1. Provide background of the status and important trends in the cruise ship industry before and during the Covid-19 pandemic.
2. Develop a system model with respect to pandemic, based on:
   (a) Stakeholder needs
   (b) Function structure - Overall and sub functions
   (c) Form elements
3. Establish changes in function structures due to Covid-19 pandemic
4. Propose an evaluation model for pandemic preparedness, and evaluate it in different future pandemic scenarios
5. Discuss and conclude

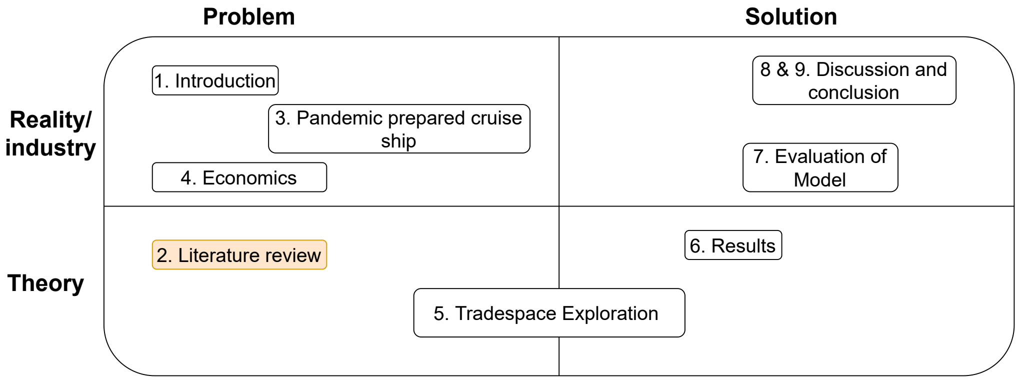
1.3 Structure of the Report

The structure of this master's thesis is as follows:

- **Literature review**
  Chapter 2 presents a literature review on the theory for design process methods and system design. It presents the theory for the design process, as well as different decision-making processes.
- **Pandemic prepared cruise ship**
  Chapter 3 presents a overall introduction to cruise ships, and the affects Covid-19 have on the them. A stakeholder analysis is completed, functional structure of cruise ship is found, and measures for pandemic preparedness is presented.
- **Economics**
  Chapter 4 presents the economical aspects of the proposed measures. It introduces CAPEX, OPEX and VOYEX, and covers cost benefit analysis.
- **Tradespace exploration**
  Chapter 5 presents the use of trade space exploration, and presents epoch era evaluation, and presents how the epochs are weighted in the tradespace exploration. Additionally this chapter presents feasibility in the tradespace exploration.
- **Results**
  Chapter 6 presents the results of the tradespace exploration, and the epoch era analysis.
- **Evaluation of model**
  Chapter 7 presents examples to validate the model developed and test how it would perform on "real world" cruise ships.
- **Discussion**
  Chapter 8 provides a discussions of the findings from both the tradespace exploration, with epoch era analysis, and from the validation of the model.
- **Conclusion and Further work**
  Chapter 9 provides a conclusion to the master's thesis, it also provides considerations for further work.

Chapter 2

Literature Review



2.1 Design Process

A design process is a useful tool in an approach to finding a suitable solution to a problem. As described in [20] " The most common way to describe the ship design has been by a spiral model, capturing the sequential and iterative nature of the process."(Kai Levander). The design spiral is usually accredited to Harvey Evans 1959 [9]. The visualization is used to show the sequential and iterative approach as Kai Levander described. The design spiral is often criticized, as in Levander's work, where he describes a better approach, "This model easily locks the naval architect to his first assumption and he will patch and repair this single design concept rather than generate alternative. An approach that better supports innovation and creativity should be used. The design should start from the mission specified for the ship. There are two types of input data, demands that must be followed and preferences that describe goals" (Kai Levander, 2007). The system-based approach is described as a better alternative, where the focus should be on a solution based on functional descriptions, which are based on requirements.

2.1.1 System design

System design is a process of mapping between three different design domains[24] [4] [22]. A function form mapping model is applied, where the mapping is a representation of mapping from the function space to the form space. Where the function space describes the needs and requirements and the form space represents the final description of the ship. In a ship design task, these three domains will eventually complete the design process. When the physical and the functional domains include a description of the function and the form that satisfies the needs domain, this process is complete. This process is illustrated in Figure 2.1. The needs domain details the stakeholder's needs. The functional domain details the objective of the vessel, it includes a description of functions that the ship will have. The Physical domain is a depiction or description of the physical form of the ship.

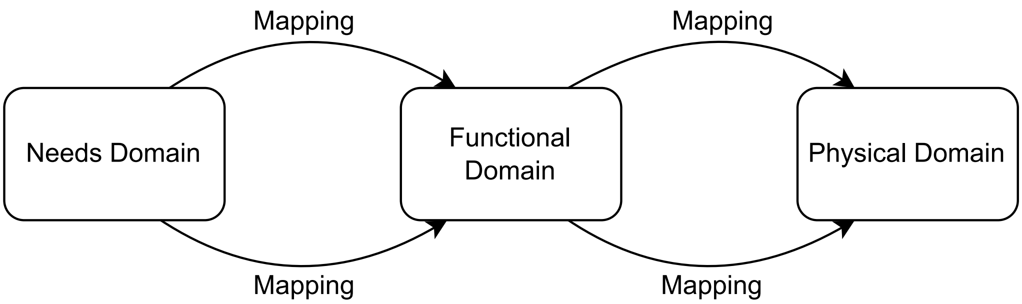


Figure 2.1: Illustration of system design as a mapping process

Source: [24][4][22]

Suh [22] notes that the design process is a continuous mapping from a domain to a domain, where the main goal is to answer the questions *"What we want to achieve"* and *"How we want to achieve it"*. The needs domain is a domain including the value that the design gives. This value is based on the needs of the stakeholders and ensures that the final descriptions of the physical ship, provide value to the stakeholders, not just a given capability without meaning.

Form follows Function

From [25], Engineering Design, and the use of [20], System Based Ship Design, we can gather the first steps of the conceptual design phase. As depicted below, the image from Levander shows how the mission should be the focus, giving certain functions, that again will provide the given form. A well-known design philosophy within building architecture is that form follows function [38] In theory, the building's form should reflect the building's function, and be a bi-product of the function. The principle in [25] and [20] is to also base the structure of a ship on its functions, and that the form of the ship will be based on these functions. A good form follows a function design concept that requires establishing a stable and good function structure.

Mission → Function → Form → Performance → Economics

Figure 2.2: Illustration of the conceptual design phase

Source: [20]

It is also adopted in Ship Design: methodologies of preliminary design with the following statement: "*A ship is designed to serve specific requirements of her owner or a mission of an authority or society, disposing of certain functional characteristics, specific hull form and powering, space and weight distribution, while demonstrating certain technical and economic performance*" [26]. It is evident that the use of form follows function is necessary to design a good concept or early-stage ship. The early stage of the concept carries with it inherent risks and uncertainty. Increasing uncertainty is strongly correlated with increasing complexity. Gaspar et al. [12] focus on five aspects of complexity in system design, Structural, behavioral, contextual, temporal, and perceptual aspects. Form function mapping is derived from technical analysis, combined with a standard ship design approach. A depiction of the five aspects of complexity is shown in Figure 2.3. Due to the five aspects of complexities presented, it is difficult to measure the value of one solution over the others [11]. From Ebrahimi et. al[8], the findings show that although, the increase in complexity gives higher uncertainty, it also gives a strong correlation with competitiveness in the market. They also found that the ship designers in the bast put a lesser focus on costumer needs.

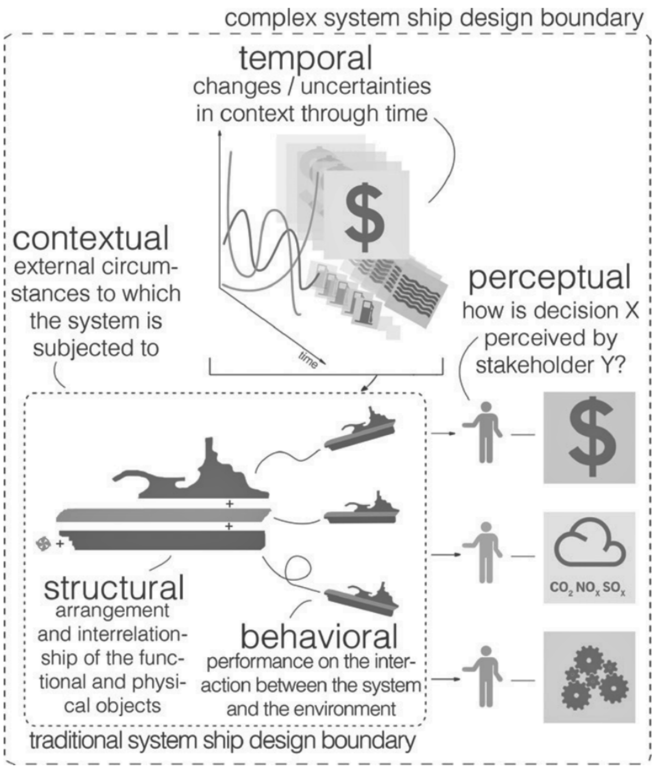


Figure 2.3: Five aspects of complexity in ship design

Source: [12]

2.2 Decision making

In a design process, different design alternatives can be difficult to measure against each other. Which design is the best one? The choice is often difficult to obtain, and the different possibilities of a design solution can often be endless. In order to evaluate one design against another, it is needed to evaluate the positives vs the negatives of these designs. Gaspar et al.[12], solve these issues by the use of epoch-era analysis. The use of deterministic mathematical programming guide the design and the decision-making. Gaspar et al.[12], describe a multi-objective decision-making process as first establishing key constraints for the design. Determine the main stakeholders, and determine the value of certain aspects of the design. The term value has increased in popularity in the design industry over the last few years. Ulstein, tries to raise awareness for the consideration of commercial and operational aspects, when making design decisions. They also in (2015) tries to advocate for the better consideration of the term "value" in the decision process. The engineering design has previously been accompanied by success in a reduction in cost and high-performance requirements. The shift from only focusing on performance requirements and the cost-related properties of ships has been transforming over the last couple of years. As Garcia [10] has shown, the consideration of the value of the ship is as just important. Including the value of the ship in the design process, allows for a more integrated decision throughout the entire process. This allows the designers to evaluate a design in earlier stages, without restricting the design with early-stage decision constraints.

However, the consideration of value does come with some drawbacks. The term value does not have a given definition, and it is highly subjective. Value for one stakeholder can be irrelevant for the next. Understanding the functional requirements of the ship, as well as the needs of the stakeholders is therefore imperative to make good decisions based on value. Understanding the stakeholder's needs and expectations will therefore become a huge part of the decision process. This can often be described as one problem. How do you measure value for all the stakeholders? The value measuring can be done in multiple methods, the use of utility is often used, as it provides a measurable method, as well as reflect the value through the use of utility measures. The higher utility provides higher value for the stakeholders. Some utilities will be valued higher by some stakeholders than others, but assigning a total "Utility score", including the different utilities of the ship, and the value these provide to the different stakeholders, the entire ship can be valued against another with a different set of utilities. For a supply vessel, the utilities can be equipment options, size options, free deck area, etc. The utilities will be based on the ship's mission and its function.

2.3 Multi-objective decision making

The available measures, and the combinations of these, will create a very large space of possible solutions. To limit the amount of spaces, as well as evaluation the best ones, the use of multi-objective decision making can be an appropriate approach. Multi-Attribute Utility Theory methods, aims to determine the the overall utility of a solution. This will be based on given criteria called "attributes" [18]. Similar to the term value, the term utility will describe the stakeholders satisfaction with a certain outcome. According to Ross et. al(2009) [23], the use of Cost Benefit Analysis (CBA) is a widely accepted method for appraisal of projects. "*CBA seeks to enumerate all direct costs and benefits to society of a particular design, assigns them monetary equivalents, ... and adds them to a single number*" [23]. The CBA aims at assigning a value to a concept, and compare that value to the cost of that CBA. Due to the need to both evaluate and generate design concepts in this thesis, the method called Multi Attribute Tradespace Exploration (MATE) was considered. The MATE process is described by Ross et. al(2006) [28], which describes a value-based decision method through the use of tradespace exploration. A illustration of Ross et. al (2006) [28] tradespace exploration is depicted in Figure 2.4.

2.3.1 Tradespace exploration

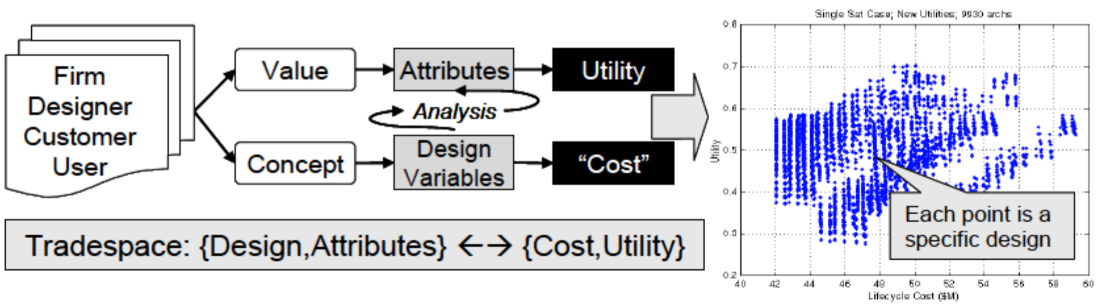


Figure 2.4: Tradespace analysis from Ross et.al, showing the tradespace design process

Source: [28]

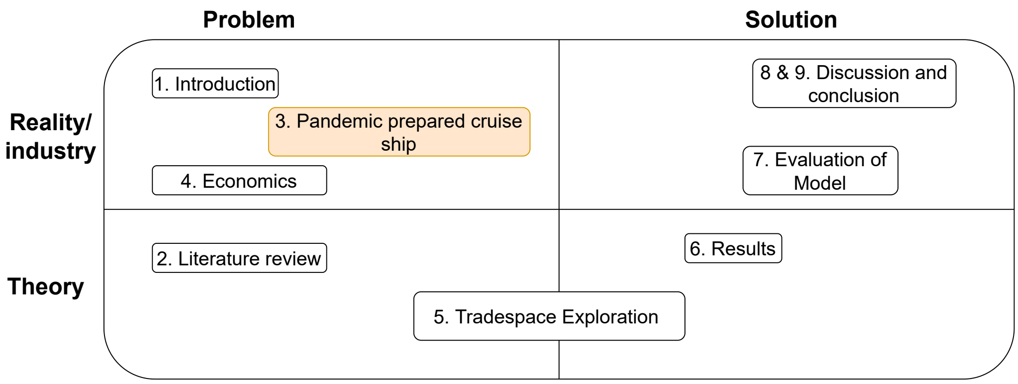
Figure 2.4 Shows the process, where the stakeholders value is mapped to different domains as mentioned in Section 2.1.1, it connects the needs to function. The methodology presented by Ross et. al(2006)[28], shows how the value perceived by the stakeholders, should give the attributes the method is using for its decision making. These attributes will then be given utility, and together with the design variables and cost, be able to generate the tradespace. The tradespace, depicted in Figure 2.4, compares the perceived utility of the concept, against the cost, where each marker is a unique design concept. The higher the point, the higher the perceived utility, and thus value. Comparing a vertical line, the higher point will have higher utility compared to a lower point on the same vertical axis, but with the same cost. This method can therefor help decision makers evaluate design concepts, as well as generate them based on attributes. From Ross et. al [23], *"MATE is intended for both concept generation and concept evaluation, while CBA is only intended for concept evaluation."*. Based on these findings, the methodology of using tradespace exploration was adopted in this thesis as it fits the need to both generate and evaluate concepts. To evaluate the designs against each other on a systematic way, the pareto front will be used. It shows the leading edge of the tradespace, depicting only the highest utility concept, at each price point. *"The Pareto front is defined as the set of non-dominated solutions, where each objective is considered as equally good"*[30]. Non-dominated means that there is no other designs that dominates the design for the same cost. For additional reference material for the these decisions in the thesis, Gaspar et. al[12], was also used as a basis and guidance.

2.3.2 Epoch Era analysis

Tradespace is highly dependent on the preference of stakeholders, the perceived value for the stakeholder will come with inherent uncertainty in regards to future changes. Tradespace can map the value perceived by the stakeholders at a given time, but it lacks the ability to adapt to changes in the future. To combat this, the use of Epoch-Era analysis will be used. Monte Carlo Simulation is another possible method to examine the effects of uncertainty in the future. However, based on the findings in Rader et. al(2010)[27], *"EEA is better suited when a contextual framework can help highlight the effects of uncertain future contexts"*, the decision of using Epoch era analysis was made. This decision was also based on the general findings in and in Gaspar et. al[12]. Both CBA and epoch era analysis achieve the same goal, however the epoch era analysis is more suited in this thesis. Epoch Era is [29] divides uncertainty into structured future scenarios, into epochs and eras, where a era consists of a subset of epochs. The use of epoch era analysis allows the decision maker to evaluate a concept in multiple future scenarios, and thus reduce the uncertainty in the decision making.

Chapter 3

Pandemic prepared cruise ship



In this chapter the cruise industry prior to Covid-19 will be presented. The economical state of the industry will also be shown. A stakeholder assessment will be completed, and functional structure of a cruise ship will be presented. The chapter will also depict changes in these functional structures, and a list of possible measures will be displayed. Lastly, KPIs will be generated based on the presented measures.

3.1 Initial market analysis of cruise ship industry

3.1.1 Trends

In order to comprehend the cruise industry, it is important to examine some trends in the industry before Covid-19. The cruise industry was severely affected by the pandemic, but just a few years ago, the outlook was quite different. Following are the graphs that show the cruise industry's outlook for 2019, prior to Covid-19.

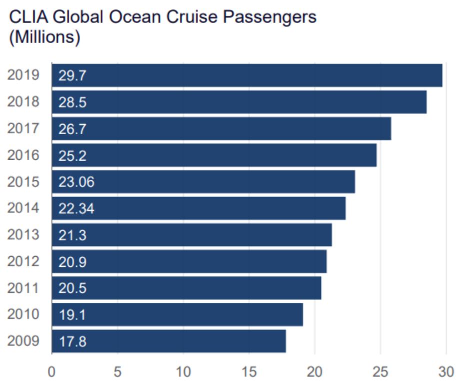


Figure 3.1: Passengers on cruises

Source: [3] - STATE OF THE CRUISE INDUSTRY OUTLOOK

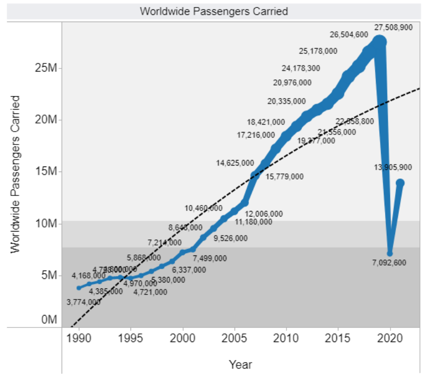


Figure 3.2: Trends in cruise ship industry

Source: [7] - Growth of the Ocean Cruise Line Industry

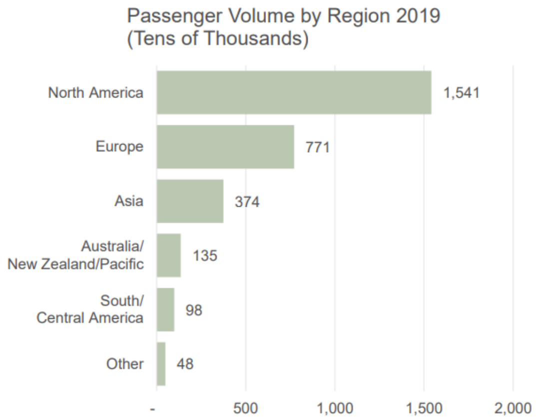


Figure 3.3: Market region

Source: [3] - STATE OF THE CRUISE INDUSTRY OUTLOOK

The global cruise industry has seen large growth over the last 30 years, as shown by Figure 3.2. At its peak, the cruise industry catered to around 30 million passengers yearly, with prospects aiming even higher in the future [3]. The cruise industry showed rapid growth each year, at around a 6% increase in passengers each year. The cruise duration is at a stable 7 days, with a stable average age of 46.7 years old [2]. The age groups have also seen a stable trend, showing good market utilization. The capacity of cruise ships have have also been increasing since the 1970s, with the largest being built in 2018, Symphony of the Seas, having a capacity of almost 7000 passengers. Compared to the maximum capacity in the 1970s, of around 2000 passengers, this growth is huge. This is clearly illustrated in Figure 3.4 The passenger segment is the largest in Northern America, as shown in Figure 3.3. One explanation for the North American domination of the cruise segment can be explained by the destinations these cruises take. As shown in Figure 3.5, the clear number one area is the Caribbean, with Asia and the Mediterranean coming in second and third respectively. The second-largest passenger volume is from Europe, with Asia coming in third.

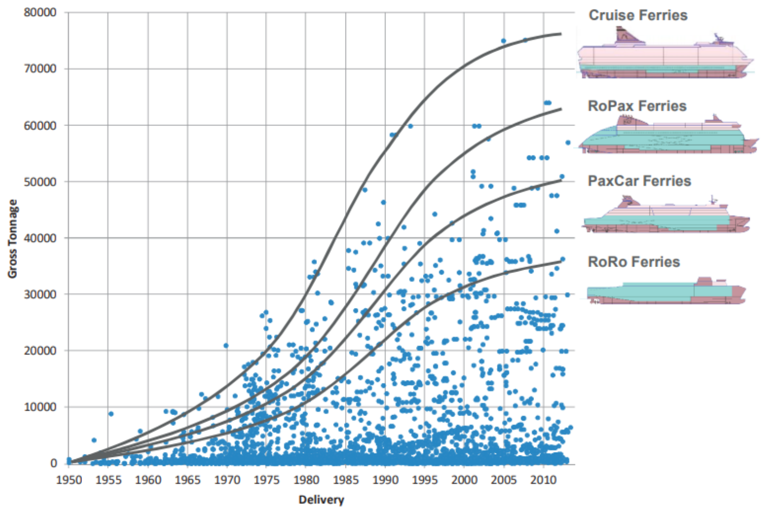


Figure 3.4: Growth in capacity

Source: ([20]) - System Based Ship Design

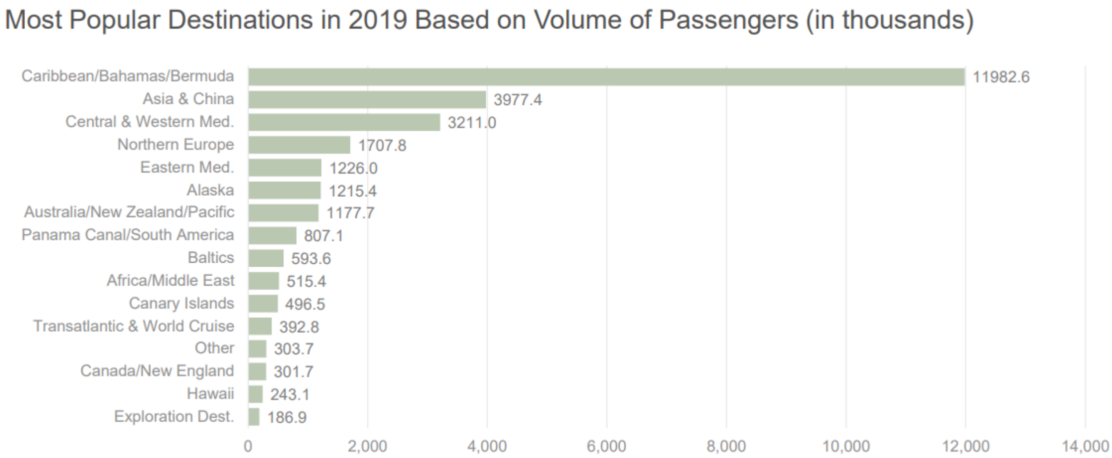


Figure 3.5: Destinations

Source: ([3]) - STATE OF THE CRUISE INDUSTRY OUTLOOK

New market segments have also popped up, like expeditionary cruises. This segment showed bullish growth in the years prior to Covid-19, with 41 new expedition ships being delivered between 2019 and 2023. This will result in a doubling of market capacity, compared to 2018 figures. This segment has also seen several different cruise operators jumping into the segment. These 41 ships will be delivered to 17 different operators, with several of them having this being their first expeditionary cruise ship. *"This (trend) has been driven by demand for cruise holidays which take guests to destinations, for authentic, in-depth experiences"*, comments CLIA Vice president of Strategic Communications Julie Green [17]. Expeditionary cruises are not a new concept, but the way it have been done has changed a lot over the last few years. Previously these cruises would use ships built for other purposes, thus compromising on comfort or luxury. The growth we are seeing in expeditionary cruises right now is largely due to the specially built cruise ships, no longer compromising on either comfort or the luxury aspects of expeditionary cruises.

Figure 3.6: Economic Impact

Source: ([3]) - STATE OF THE CRUISE INDUSTRY OUTLOOK

3.1.2 The economic impact of Covid-19

As mentioned in the previous paragraphs, the cruise market prior to 2019 looked bright. The economic impact of the cruise industry is as shown in Figure 3.6. Over a million jobs, 50 Billion dollars in wages and salaries, and an estimated worldwide output of 154 Billion dollars. The cruise ship industry is a large part of the global economy, and also a large part of global tourism. The ever-growing trends in passengers, new market segments, and the overall economic impact of the cruise industry took a hard hit at the start of 2020. The overall impact of Covid-19 on the cruise industries is yet to see, but the short-term impacts have been immense. The early estimates for 2020 compared to 2019 shows a loss of over 50% in these three categories, a loss of over 518.000 jobs, a loss of over 23 Billion dollars in wages, and a loss of over 77 Billion dollars in global economic impact. The shares of at least the three largest cruise operators fell approximately 70% - 80% in April, compared to the start of the year [19]. Largely due to the situation with the halt in global travel and tourism, but also due to the reputational damages caused by "Diamond Princess", and the correlation between cruise ships and the Covid-19 outbreak [31].

3.1.3 Changes already implemented by cruise operators

During the second part of 2021 several cruise ship operators resumed some of their cruises. All of these cruises shared a few changes, compared to the cruise operations prior to Covid-19. Due to the bad press surrounding cruses and the further spread of Covid-19, the cruise industry had to introduce changes. Let's take a closer look at some changes the industry has already implemented. They often have mandatory mask usage outside of restaurants or bars. The use of HVAC has been updated to no longer recirculate air as much as possible. This is often done on newer ships where the intake and outlet of the HVAC system are on different sides, allowing for clean air intake. In reduced capacity, most cruises have reduced their capacity, to improve the overall distance between people, often up to 50% reduced capacity. They have introduced social distancing as much as possible, allowing for smaller venues of people, and smaller groups. Some cruise operators have changed their operational profile, focusing on just one turnaround port, allowing for an entire empty ship for several hours, with no passengers on board [5].

Guest screening is mostly used by the operators, allowing them to know if anyone is sick in advance of the departure. Some have introduced high-risk areas, resulting in passengers from those areas with high infection rates not being permitted on board. Temperature screening has also been used sometimes. The cruise operators stagger the embarkations, resulting in less queuing and increased social distancing. The buffet is often changed with the passengers choosing their food instead of self-serving, and instead by staff. Standard dining times were increased and sometimes referred to as "open times", meaning the passengers receive a specific time for their party, again, resulting in a more staggered eating situation with more social distancing. And lastly, the use of different apps or other tracking measures has been implemented to keep better track of the passenger's movements and contact points [14].

Regarding crew those routines have also changed, they have to go through preliminary screening before leaving their home country, often including swab tests for Covid-19. when arriving at their desired departure country they often have to undergo a second Covid-19 PCR test before being allowed to embark. The crew on board often undergoes a quarantine as well. And the crews are monitored with weekly or monthly Covid-19 tests and temperature screening. Another big part that is being dealt with by the cruise operators is the larger logistics problems regarding the crew, with increased times for embarking and disembarking, the changes in logistics are immense and challenging, and good solutions to these problems are still being discovered.

3.2 Stakeholder assessment

The performance of a ship design can be measured by how well it meets stakeholders expectations and requirements. It is therefor important that we have a good overview of the stakeholders involved in our design. With these stakeholders, and their needs, we can then ensure that the design of our solution meet these needs and requirements, and we can design with these in minds. A stakeholder can be defined as: "*A stakeholder is a party that has an interest in a company and can either affect or be affected by the business.*" [16]. From this definition we can understand that the stakeholders can be affected by the company, but the stakeholder can also affect the company. These stakeholders can have aligning needs, but they can also be conflicting, so even though a group of stakeholders want to see a project implemented, it is not necessarily the same stakes at stake, resulting in a reduced likelihood of project success. It is therefor important to identify these needs, and understand these, to achieve goals and requirements for the project, that matches stakeholder needs.

This thesis focuses primarily on the needs regarding safety and the requirements related to Covid-19, but also takes into account broader needs. The stakeholders below are represented in the following list. In some cases, stakeholders have been grouped to keep a good overview, and examples of certain stakeholders in those groups will be given.

- **Customers**
  Who: The cruisers, the passengers

  Needs: Wanting to be on the cruise, and have the best experience possible. Not have to worry about Covid-19, safest trip possible, hassle free travel, costumer satisfaction, brand loyalty, costumer privacy, cost of travel, brand awareness
- **Suppliers**
  Who: Several different suppliers, can be: Tour operators, food delivery, local ports, transportation, shipyard etc
  Needs: Financial stability, earning potential, reputation, trust, communication, contract stability, acceptable deliverable time frames, flexibility, predictability, pay on time.
- **Shareholders**
  Who: Financial shareholders/investors
  Needs: Financial impact, earnings/results, reputation of company, short term profit, long term profit, minimize risk, influence
- **Competitors**
  Who: Other cruise liners competing to earn the customers
  Needs: Financial impact, reputation of competitors, reputation of company, trust, communication, information, ticket sales
- **Employees**
  Who: Crew, personnel, costumer service, managers etc. These employees are often divided into two sections: seen by cruisers or not.
  Needs: Pay, job security, health and safety, work hours, work environment, benefits
- **The responsible for the passengers while sailing**
  Who: The captain
  Needs: Safe travels, hitting timelines, steady sailing, no corona on board, minimize risks of infection, crew safety, readiness for infections and other hazardous events, communication, trust, predictability
- **Port authority**
  Who: The port authority, and they will work as a supplier when the cruise liner is at port

Needs: Reduced risk of infection, safety, communication, trust, flexibility, predictability etc

- **Local community**

  Who: Local shops, local tourist attractions, local restaurants, local governments etc

  Needs: Safety, reduced risk of infection, tourism impact, environmental impact of the cruise ship being there, economical impact on local businesses, ports, events, Investments done to local ports and the community

- **Governmental regulators**

  Who: Countries or government can decide on laws and regulations related to the use of ships, either locally or globally if the cruise liner is flagged under their country.

  Needs: Safety of passengers, environmental impacts, financial impact, safety of crew, reputation, earnings, taxes, city planning etc

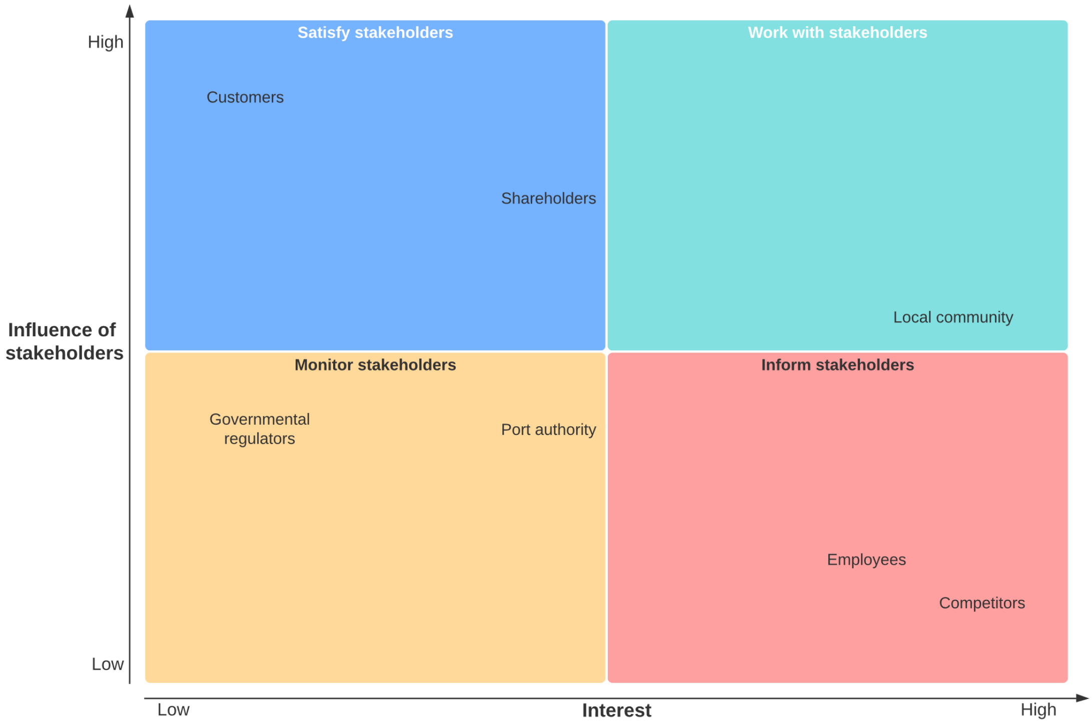


Figure 3.7: Stakeholder matrix

The stakeholder matrix illustrates the position of the stakeholders. In this case, the document gives an understanding of how to deal with each stakeholder group. The stakeholder matrix for the stakeholder groups mentioned previously is shown in Figure 3.7. A stakeholder's power or influence is mapped to its interest in the company in this matrix. It is best to work with a stakeholder with high interest and influence, as shown by the green square in the upper right corner. In this case, the cruise operators should work with the local communities in order to meet this requirement, since both will benefit from a good and close collaboration. Stakeholders should be satisfied if their influence is high but their interest is low. These stakeholders are shown in the upper left corner, in blue, and cruise operators should satisfy these stakeholders and customers. There are some customers who base their choices on loyalty to a brand, so it is possible to map them in the upper right corner, but for the average customer, choosing a cruise liner often has to do with their needs, and thus fits in this corner. The shareholders should also be satisfied, since they often have financial interests in the company, but that is also their main interest. Some shareholders will obviously have more interest in the company then others, however, a large majority have a medium interest, so being satisfied is an adequate strategy for shareholders, even if they are close to the green corner in terms of their interest.

When the influence of the stakeholders are generally low, but the interest is high, the stakeholders should be informed, illustrated in Figure 3.7 as the bottom right corner in red. Although these stakeholders can increase the company's influence, they usually have a small impact, so it's important to keep them informed through good communication in order to ensure their best use. In the case of cruise liners, these stakeholders include their competitors and employees. Employees are a broad term, and different employees will have different influences, but the average influence of an employee is relatively low. Generally speaking, the captain will have quite a high influence, but for the rest of the crew, the cruise liner can easily change employees, and often does depending on which country has the lowest labor costs. During the Covid-19 pandemic, cruise liners realized that their crews were less changeable than previously thought. Maintaining a good relationship with the crew has become increasingly important due to the logistics of embarking, and turnaround days, and so the employees have gained influence over the cruise lines. Lastly the bottom left corner, illustrated by the yellow color, where the interest is low and the influence is also low. Generally, government regulators are quite influential, but have little interest in any particular cruise liner company. Instead, they are interested in the cruise industry as a whole, therefore they should be monitored. In the same way, port authorities often have more interests in certain cruise liners because they generally deal with fewer cruise liners in general, but they should still be monitored, unless either their influence or interest in one cruise liner increases.

3.3 Function structure of a cruise ship

Kai Levander argues that ship functions can be placed into two categories: the functions pertaining to the ship and the functions pertaining to the payload [20]. In Figure 3.8, you can see the subdivided functions concerning the ship. We can see that the payload systems are generally divided into three sections, Cargo spaces, cargo handling, and cargo treatment. Since the ships studied in this master's thesis will mainly carry passengers, the payload structure will differ somewhat Figure 3.8. However, the overall principles will remain unchanged. Secondly, ship function entails everything related to the ship, such as the structure or hull of the ship, the ship equipment, the accommodation or hotel onboard, and the machinery and tanks. In this master thesis, this sub-function pertains primarily to cruise ships, with just a little more focus on accommodation compared to let's say a cargo ship.

The theory behind the use of this function structure is that when we sum up the space and are used for each of these sub-divisions of ship functions and payload functions, that will be the overall gross tonnage for the system [20]. This function structure also allows the design of the ship to better suit the actual function the ship will have, and as mentioned in chapter 2, the form should follow function. Another benefit of having a solid ship function structure is that when something as detrimental to the cruise industry as Covid-19, which seemingly changes everything about the cruise ship and its functions, we can simplify the ship into all these sub-functions and focus on the changes Covid-19 can have on these functions, and thus study the changes on the ship as a whole.

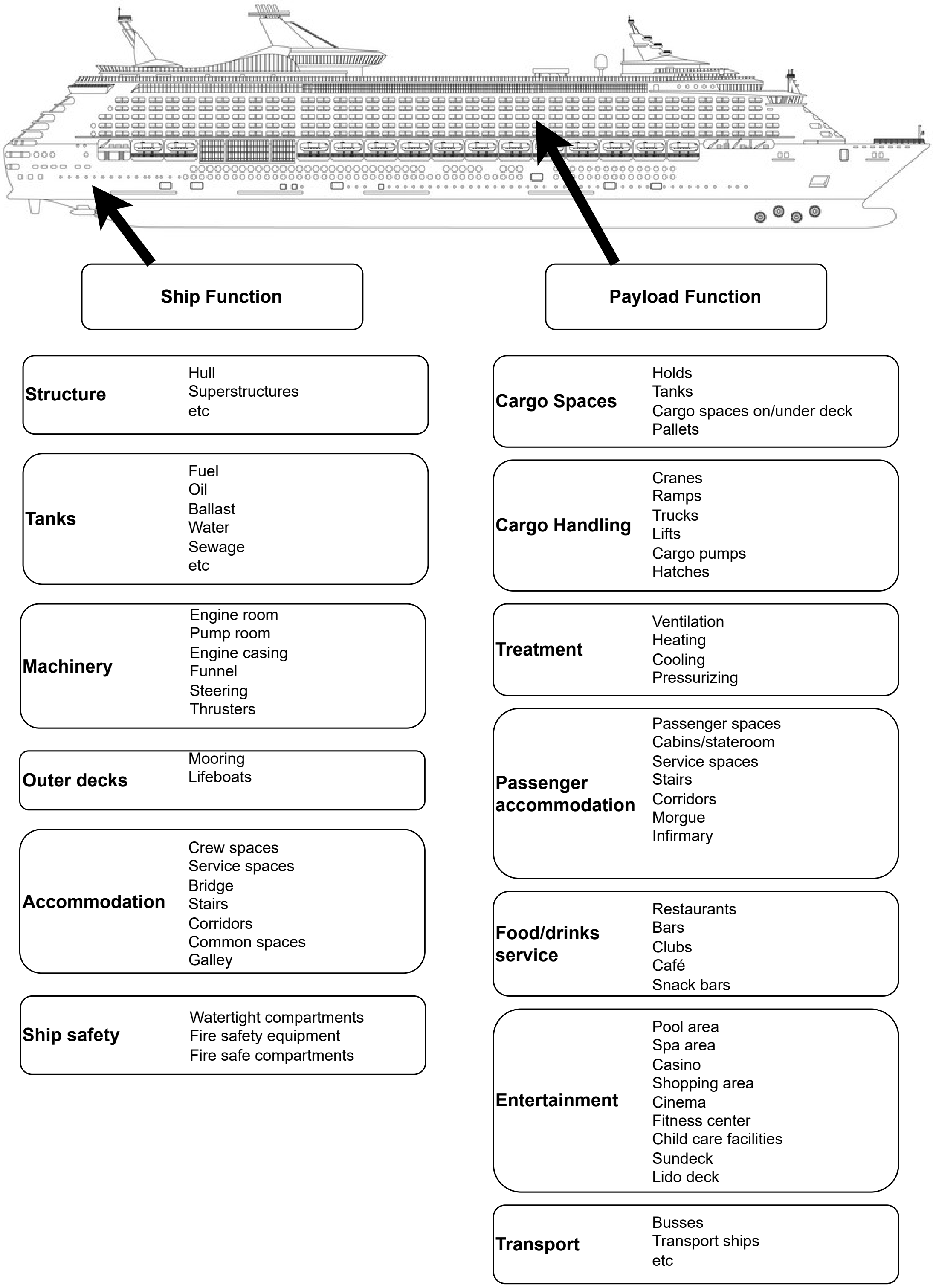


Figure 3.8: Function Structure of a Cruise ship based on Levander's function structure of a container ship

Source: [20] - System Based Ship Design

The structure proposed for a cruise ship can be shown in Figure 3.8. It shows the same structure as shown in Figure 3.8. There will be a generalized function structure for the major cruise ship types, with minor changes needed for expedition cruise ships, small, medium, and large ships. Due to this master's thesis taking a general approach to developing a model, these specific changes will be outside the scope of this master's thesis.

Ship functions

As mentioned previously this is the function of the ship itself. We note that to Figure 3.8there are six sub-functions in this section.

Structure-function is responsible for the hull and superstructure of the ship, it's the framework of a ship. This function is responsible for the main shape, rigidity, and also fluid dynamics regarding how the ship moves through the water.

Tanks function is where all the fuel, oil, ballast, etc are kept. They are kept in tanks, and they affect everything from piping to the weight, as well as the stability of the cruise ship.

Machinery is where the main engine is situated, as well as the different pumps required, the casing for the engine, and also the funnel. This function will also include the thrusters as well as the steering system. This ship function's main objective is to give the ship maneuverability, as well as provide the power needed for auxiliary devices.

Outer decks function is in this thesis regarded as the mooring function, as well as the placing of the lifeboats and the surrounding subsystems regarding those. For cruise ships, the outer deck function could also include the sundeck and outside walkways, etc, however, these will be regarded as a payload function, due to it being connected with the payload of the cruise ship, and the passengers.

The accommodation function is everything connected to the accommodation of the crew. This includes service spaces, the bridge, stairs, corridors connecting everything and the common spaces, and the galley. This function is meant to accommodate the crew in the best possible way, and due to the longevity of the stays some of the crew endures on a cruise ship, this function is vital to the crew's satisfaction. This function will also include entertainment for the crew, like a crew bar or a crew hot tub.

The ship safety function is everything regarding the structural safety of the vessel, like fire protection systems like sprinklers, or the watertight compartments, and their layout.

Payload Functions

For a cruise ship, the payload will be the passengers themselves. But for this function, we will also be including the sub-functions needed to accommodate and service the passengers as well. The payload sub-function can be subdivided into seven sub-functions again, and these are shown in

Figure 3.8.

Cargo spaces function would be the needed area and volume to accommodate the cargo needed for a round trip of the cruise ship, this would consist of space on and under the deck, as well as different tanks. It is important for this function to be able to be utilized the best and quickest when the ship is in port, as the time to be supplied is often a logistical and time-sensitive issue for the cruise operators.

Cargo handling functions would be the systems related to handling the cargo. Such as cranes, ramps, trucks available, lifts, and different pumps and hatches. the main function is to allow a good and stable flow of deliverables while in port, as well as from the different cargo holds and areas, to the needed services the cruise offers while sailing, such as the flow of ingredients from the cargo holds to the galley.

Treatment functions are the different treatment systems for the air inside the cruise ship. Such systems as the HVAC systems, ventilation, heating, and cooling systems, and different pressurizing systems.

Passenger accommodation or hotel would be the cabins for the passengers, as well as the support systems for them, like service spaces, stairs, corridors, and other passenger spaces. This function will also include other specific passenger spaces like a morgue and an infirmary.

The food/drink service function will include the space and area needed to serve the passengers food and drinks. Systems such as restaurants, bars, clubs, cafes, or snack bars, but also the spaces connected to the lido deck, with its bars and snack bars.

Entertainment function is everything the cruise operator wants to offer its passengers, like a pool area, spa center, casino, shopping area, cinema, childcare facilities, and a lido deck. These systems will be connected to the needs of the target group the cruise operator aims for with its cruise ship and will therefore be customized to each specific cruise ship and its operational area or target group.

Transport function will be everything needed to transport the passenger from or to the ship for embarking, or for any organizational trips the cruise operator wants to offer at any of the ship's planned ports.

3.4 Changes in function structures

Covid-19's impact on cruise ships can now be mapped with a clear understanding of the function structure of a cruise ship. The effect on Covid-19 can be explored, regarding each of the sub-functions, both regarding ship function as well as payload function. Even functions that seem unaffected by the Covid-19, such as most ship functions, actually have an impact that can be quite significant.

3.4.1 Changes in stakeholder needs due to Covid-19

In order to identify changes in functions, it is first necessary to understand the changes in stakeholder needs. Covid-19 presents a number of changes from previous years, with the most impactful change being the focus on the safety and health of passengers. Having a sense of security is important. The passengers need to feel that they are being well taken care of by the cruise operator when it comes to personal safety in relation to the spread and the possibility of getting infected with Covid-19. A second major change is an emphasis on quarantines, both for the crew and passengers. Other changes in needs will be explored in the list below, where these needs are more general because multiple needs affect a wide range of stakeholders.

- Personal safety for crew and passengers
- Quarantines, avoid for passengers, needed for the cruise operators
- Reduced risk of infection is a new need for the governmental regulators, the local community, the port authority, the employees and the passengers.
- The focus on minimizing risk is more important for the shareholders, but also for the passengers as well.
- The need for trust is overall a new need for all of the shareholders
- The need for communication and information for the passengers, employees, port authority and the local community is elevated.
- Predictability but also flexibility will also be a more important need for most of the stakeholders, in regards to the need for fast changes if infections occurs, either on the ship, before embarking of either passengers or crew, or within the different suppliers or port authorities connected with the cruise operator.
- A need for financial stability is also rising for the shareholders, but also for the competitors and suppliers. Covid-19 has, without a doubt been a difficult year for the cruise industry, as mentioned in Section 3.1.2, it has also been challenging for the cruise operators' suppliers and port authorities.

3.4.2 Changes in Ship functions due to Covid-19

Likewise, as the requirements of stakeholders have changed since the era of Covid-19, the structure of the functions will also change. Observing changes in the ship's sub-functions, it appears that the changes are not as direct as changes in the payload functions. This section looks at the changes that could be made to the ship's functions.

Structure The structure of the ships already built will probably not change, however, for new ships, changes in operational profiles seem inevitable to avoid unnecessary risk for infections. the overall hull of the ship, and especially the bulb is often designed for a certain service speed, this is based on the previous experience by cruise ship operators, but it is also often based on being able to cover multiple ports during a trip and cover longer distances. Therefore changes in how and where the cruise ship will travel, and what ports to visit, will affect the most optimal design for that cruise ship. As mentioned in Section 3.1.3, that has already been implemented by cruise operators, although those have been temporary changes. The effect of the changes in operational profiles is however necessary to explore in the future, as the future regarding Covid-19 continues to be uncertain, but also the possibility for other pandemics.

Tanks might need to load the ballast tanks differently due to lower demand of passengers, or where they are placed, or due to the change in the operational plan.

Machinery might change due to changes in operational profile, the engine room and pump room especially. The funnel might change due to new layout in fire safety

Outer decks might be changed, due to being divided into "quarantine zones", so quarantined passengers can reach the lifeboats as well. In the event of an outbreak, and another safety issue resulting in the abandon ship order, the use of designated lifeboats for the Covid-19 infected should be utilized. The cruise operator might have a plan for this in the event of an outbreak, and they might also choose to let the safety issue resulting in abandon ship command be more critical for the overall safety of the crew and passenger, and therefore let every passenger use every lifeboat, without designated lifeboats.

Accommodations will most likely change, Increase or decrease in different crews, doctors and nurses may be needed, more staff to cover if a virus spreads, less flexibility in changing staff, and so on. Maybe separating the crew into different cohorts, or different zones of the ship also might influence the layout of corridors and stairs.

In regards to **safety**, watertight compartments or fire safety might be used as a basis for quarantine zones. With the watertight compartment, and the fire safety zones containing closed HVAC systems. Some cruise operators have already changed the layout of the HVAC system where possible, but in the event of a large outbreak, the use of these zones as quarantine zones should be utilized by the cruise operator.

3.4.3 Changes in Payload functions

With Covid-19, there will be a direct impact on the payload functions. Many of the changes in needs for the stakeholders, either directly or indirectly, are aimed at the passengers. Now let's examine the changes that could affect or be made to payload functions. The changes will have different goals, but there are different approaches to reducing the overall impact of Covid-19 on cruise ship operators depending on the goals. There are three phases to their plan for reducing impact. The first phase is to reduce the likelihood of infections entering the ship. Next, they need to increase the probability of containing the infected. Lastly, they need to minimize the impact of infection on passengers and crew.

Cargo space holds, might be affected by a change in operational profile, or by how the crew is separated into cohorts or shifts, might need more storage space due to longer sails due to a pandemic, skipping ports, or just using one main port for embarking and disembarking.

Cargo handling might need to change due to an increase or decrease in use, due to changes in the operational profile, or changes in capacity. As mentioned most ships starting up will run at around 50% capacity. Therefore the cargo handling will change to accommodate for that as well. Crew members might have to work in cohorts, having to have separate cargo handling systems for each cohort.

Treatment needs to be scaled up to accommodate quarantine zones, or be divided into cohorts. This might need a refit of the treatment system, but this depends on the specifics of each ship. The HVAC system might need to be altered as some cruise operators already have done, to ensure that only clean air is on the intake side. An overall reduction in recyclable air would be a benefit for the treatment system.

Passenger accommodation/hotel might need to change for better optimization of cohorts, and due to changes in schedules or operational profiles. The ship will likely start up with reduced capacity, having more rooms available, allowing for more social distancing. For a more permanent solution, the designs of the cabins, and the sizes of these might need to be altered for better optimization of available space and the safety of the passengers.

Food/drink services need to accommodate fewer people but at wider hours, more spread in breakfast and dinner, and so on, due to reduce the risk of contamination between cohorts. Some cruise ship operators are already doing this, and it would have to be a standard thing for cruises to have as safe restaurants and bars as possible. Allowing for more social distancing, which is necessary to reduce the probability of escalation of infections if a crew or passenger is infected.

Entertainment might suffer from the same changes as food services, and due to changes in the schedules or the operational profile. Some entertainment will need to be put on hold during the pandemic as well. This will again be specific to what entertainment systems a certain cruise ship operator has implemented, but in general, they need to accept wider opening, fewer people, and smaller groups.

Most cruise operators have halted the use of organized tours from the ship, and some are only halting the use and deals with external tour agencies, only offering the cruise operators designated tours. this would allow them to better monitor the passengers and the crew the passengers would meet. Again, this is very specific for a certain cruise operator, and for the ship's designation, but the general rules for changes for this sub-function would be to reduce group sizes, increase the distance between the passengers, and thus overall reduce the probability of infection happening during transportation.

3.4.4 Support functions for a cruise operator

A cruise ship is not a closed environment but is driven by local communities, port authorities, travel agencies, tourist attractions, tour guides, etc. Therefore, the need to evaluate these support functions would need to be explored. While considered outside the scope of this thesis, it will be necessary for the master's thesis. Despite the optimal design and utilization of a cruise ship, if the support functions fail in regards to Covid-19, then that will negatively impact not only the cruise ship but also the cruise operator. There is a need to optimize the entire value chain surrounding cruise ships. In fact, ship-related issues may even be solved by outside functions or systems.

3.5 Measures

Since this thesis is only looking at the design aspect of Covid-19 prepared cruise ships, it will not focus on how effective measures are. This thesis will base its work on measures proposed by the health sail panel, in its 69-page report from 2020 [14]. This thesis will therefore not discuss the effectiveness of any of these measures proposed, and it will not focus on the health aspect of Covid-19. This is adequate as this is a Systems engineering thesis, and that will therefore be outside the scope of this thesis. The panel evaluates 20 topics, divided into 74 points. Of these, 14 will be used as potential measures for a cruise ship in this thesis. As supporting sources and working as an updated source, the use of another report done by EU HEALTHY GATEWAYS was also used. This report is from April 2022 and will be the last health-related paper to be used in this thesis [36]. These two papers combined were used to confirm the validity of the measures proposed for this thesis and these proposed measures are shown in Figure 3.9.

Figure 3.9 is divided into 2 sections, ship changes, and operational changes. Ship changes will be the measures that will or could have an impact on the structure and the design of the ship. They would alter the ship in a physical way. While the Operational changes will alter the operational aspects of the ship. It is important to focus on both the physical changes as well as the operational changes for a cruise ship [35][13]. Due to the nature of cruise ships, the operational aspects of the ship greatly affect the payload. since the payload of a cruise ship is the passengers, and since the passengers are one of the most impactful stakeholders, as well as have the ability to greatly affect the other stakeholders, the operational aspect of a cruise is needed to examine. The physical aspects of the ship is also needed to consider, since they will alter the physical functions of the ship, affecting the stakeholders. The main stakeholders, as found in Section 3.2, are the passengers and the shareholders. Physical altercations could affect the entire design of the ship and thus could have a great impact on the shareholders. This would also affect the passengers since they are the ones these changes would affect while on a cruise.

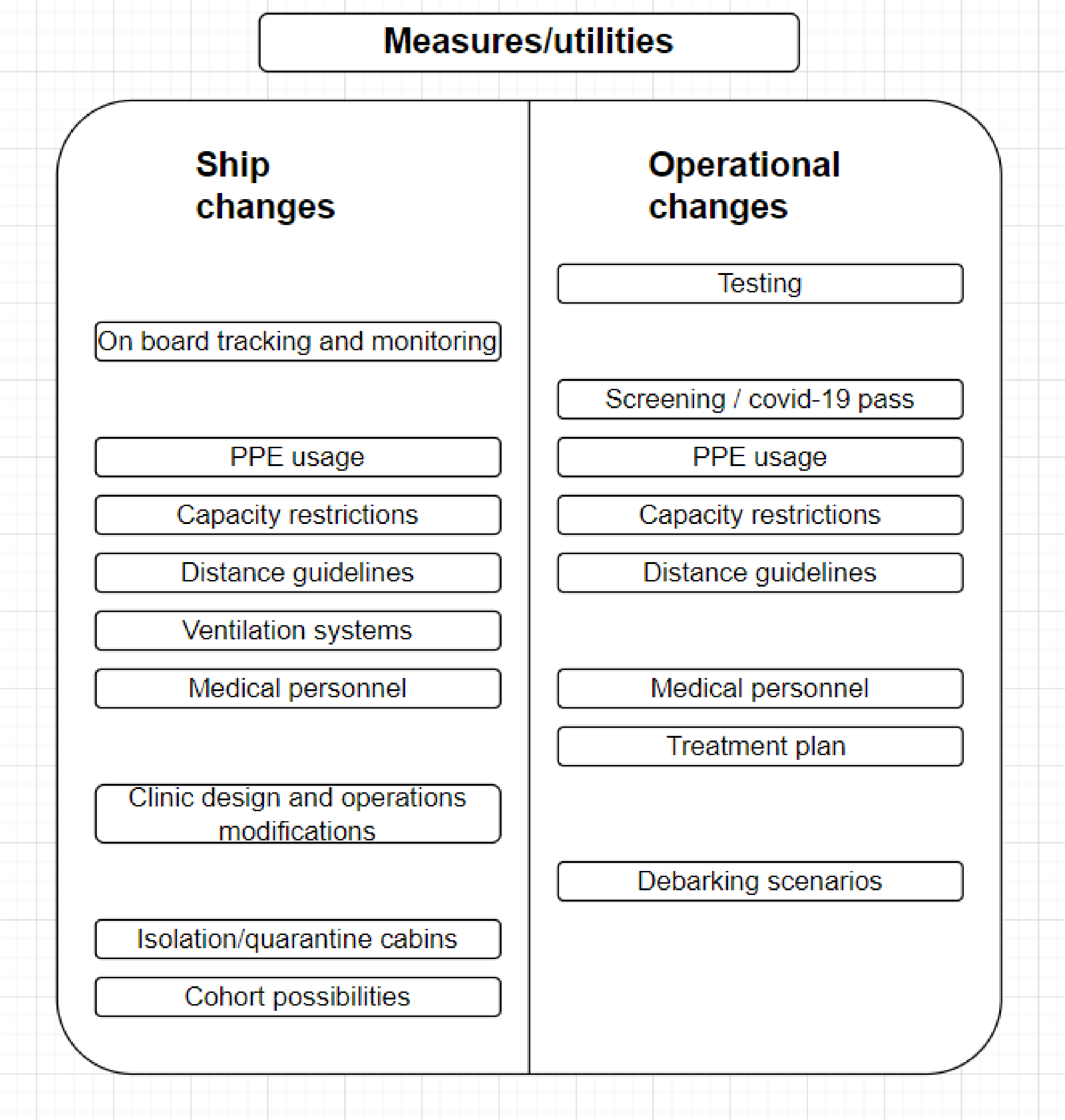


Figure 3.9: Measures proposed for pandemic preparedness of cruise ships

From Figure 3.9 it is clear that a lot of the measures proposed, would alter both the ship and the operational changes of the cruise ship. Some changes, like the testing, could be done without having to alter the design of the ship. While other changes, like the ventilation systems, can be altered, without interfering with the operational aspects. Of course, some types of testing, and some types of ventilation systems could alter both, but for this theses, these will be disregarded. This thesis will focus on how the general cruise ship could handle a Covid-19 similar pandemic, it is therefore done in a general term, and very specific alternatives do not need to be considered.

3.6 Key performance indicator

Key performance indicators can be described as: "Key performance indicators (KPIs) refer to a set of quantifiable measurements used to gauge a company's overall long-term performance" [15]. They can measure a company's success compared to other targets. In this master's thesis, they can also be used to measure the success of a cruise ship compared to specific criteria. Some of the criteria used have been mentioned briefly previously but will be elaborated on later in this section. Trying to evaluate a ship's value compared to another can be difficult and complex, especially when also assessing the operational aspects, the support systems, and the company and the organizational aspects in regards to safety concerning Covid-19 infections. KPIs can help with this complex task, making quantitative comparisons possible. If it is possible to calculate some KPIs for each ship, it is possible to use those when comparing ships. This can be useful for the companies when designing new ships after the Covid-19 pandemic. It can be helpful for the customers or passengers. It can be helpful to understand better the problems a cruise line faces concerning reducing the probability of infections etc. Compared to another cruise line. The possibility to quantitatively measure the resistance of a ship to Covid-19 can also be helpful for the government in regards to further regulations and, in general, can be quite advantageous for all the stakeholders identified in Section 3.2. This needs to be done in a structured way to ensure that the quantitative method works[1].

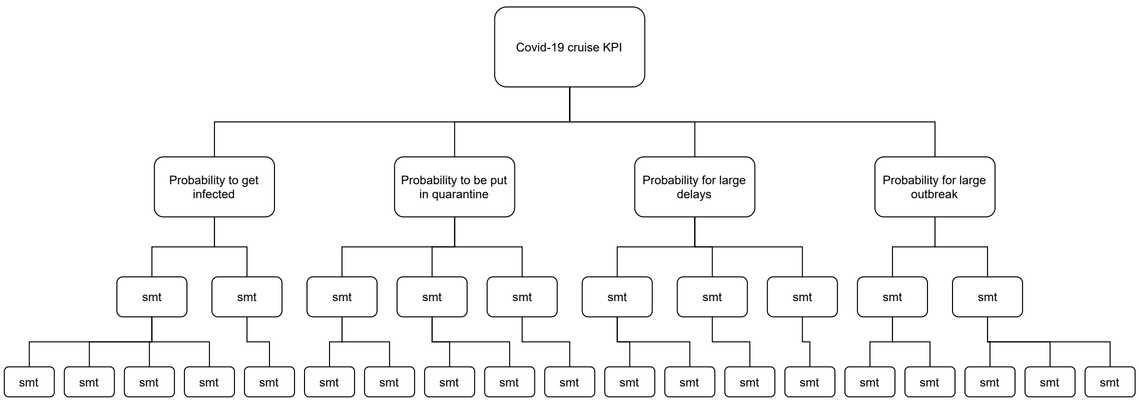


Figure 3.10: Example KPI tree for a pandemic related cruise ship operation

A KPI can be broken down into several sub-parts, eventually and hopefully achieving a measurable part, that will lead to a certain KPI. This can be shown in Figure 3.10. Here four KPIs are suggested. The probability of getting infected, this KPI is aimed at the passenger, to make the passengers easier spot what ships are safer than the others. It is also aimed at the governments and the cruise operators, to give e clear indicator of what ship is best suited. The second KPI suggested is the probability to be put in quarantine, this again is aimed at the customers or passengers, but also regarding the crew and thus the cruise ship operators. The third suggested is the probability of large delays, this one is aimed at port authorities and governments, and also the cruise operator. Knowing this KPI will give these stakeholders a large advantage when planning and making logistical plans. it would also satisfy multiple needs, like flexibility and predictability. The last KPI suggested is the probability of a large outbreak. This would be aimed at the cruise operators and the government, but also the passengers, and the other stakeholders.

As shown a KPI tree can give a good overview of the measurable parts regarding the impact of Covid-19 on cruise ships. But, as also shown in Figure 3.10 it can be very complex, especially when trying to quantify these KPIs and the sub-parts that are used to calculate the KPIs. Due to the complexity and especially regarding the complexity involved with calculating the sub parts for the KPIs, developing this KPI three will be the main focus of the master's thesis, and is therefore outside the scope of this thesis. However, some suggestions for the inputs needed to calculate these KPIs will be discussed. The same goes for some of the criteria that will be measured.

To evaluate and calculate KPIs some inputs are needed, examples of how the data used for these calculations can be shown in the list below.

- General arrangement or similar. This would be used against certain criteria measurable and based on the ship function and payload functions mentioned in Section 3.3, and especially the changes in function structure. An example would be to check whether the fire zones could be used as quarantine zones, or if that is not applicable to that certain ship. Another example could be checking whether the HVAC system is only getting airflow from clean air, and not using recycling.
- Questionnaire used to ask critical questions to the cruise ship operators regarding Covid-19 implementations done to secure the safety of its passengers. Again, these would be checked against certain criteria. the suggestion at this point is to check against the recommended implementations made by the Healthy sails panel, or against the guidelines provided by Healthy GateWays on behalf of EU[14] [36]. This was a thorough report on what would be effective for cruise ship operators to implement against Covid-19. In this report, they suggested 74 recommendations, which would be an excellent basis for developing criteria to base some of the KPIs[14].
- Questionnaire used to ask critical questions in regard to the operational profiles of the cruise ships, as well as logistics. This would again be used to develop the criteria to measure the KPIs against.
- Data regarding capacity, and other vital information about the ship.
- Information about the testing capacity on board, as well as in the ports planned to enter
- Data regarding the current situation around Covid-19 (new variants like omicron or delta in the area).
- The cruise line operators' emergency plan if an infection occurs.

The collection of the data would be done for a specific cruise ship and would give the cruise ship owner good indications for further use in their analysis of the performance of the cruise ship. When the inputs are gathered, the KPIs can be calculated. This would again give the cruise ship data on how well the cruise ship is performing, related to a pandemic. Underneath is a list of the proposed KPIs for a pandemic prepared cruise ship:

- Passenger infection ratio
- Passenger death ratio
- Passenger missed days ratio
- Average quarantine stay
- Average delay time
- Average unavailability
- Number of crew infected
- Number of Isolation cabins used
- Probability of getting infected during the cruise
- Probability of great delay during the cruise
- Probability of delayed disembarking
- Probability for a large outbreak

These KPIs would be good to measure the performance of the ship while in operation. However, in this thesis, it is needed to have KPIs that can be used to evaluate the designs as well as the operational aspect. It is needed to connect the use of KPIs to the measures provided in the previous section. The use of KPIs is often used while in operations. For this thesis it is therefore needed to modify the proposed KPIs, to adapt to the measures that also affect the design. This is done to be able to evaluate different designs against each other, without having to rely on the live collection of data from the operational aspects. The new modified KPI three is shown in Figure 3.11.

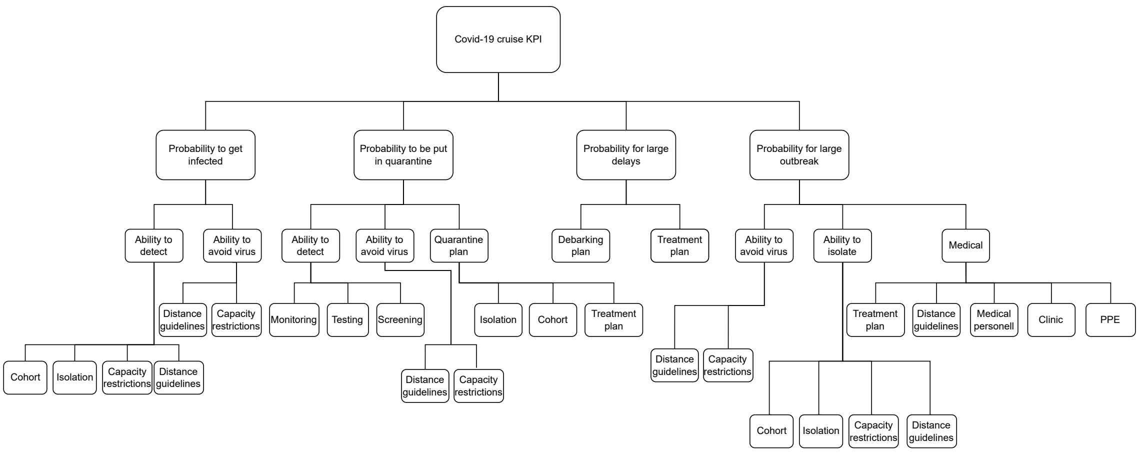


Figure 3.11: Modified KPI tree to show the usefulness in the evaluation process

Figure 3.11 shows an overview of the connections the four main KPIs, and thus the main KPI, connects to the proposed measures. It gives a good sketch of the connections between the measures and the end KPIs. Whit this connection established, it is possible to use these measures in a further analysis to establish a general model for evaluating the design and operational aspects of a cruise ship, related to pandemic preparedness. These modified key performance indexes need to be based on the function criteria for the cruise ship, the function structure, as well as having the possibility to be connected to the value it provides to the stakeholders.

The chosen measures, and the chosen KPIs, include the function structure from Section 3.3, within them. The changes in function structure presented in Section 3.4, lays the foundation for how the measures will adapt to the larger ship system, and these KPIs need to address that. One of the KPIs, and also the measures should include e.g. ship safety, represent that the changes in the use of fire safe compartments, could affect the pandemic preparedness of the ship, and the measure of both isolation and cohorts include these. Accommodation function under both ship function and payload function in Figure 3.8, will be included in the distance guidelines, where the layout of the corridors, common spaces etc, affects how the ship performs in an pandemic evaluation. Treatment function is included directly into the ventilation system measure. The measure of testing, Personal protective equipment(PPE) and clinic, will include the function of cargo handling, as well as transport. These were a few examples of the relationships between the KPIs and the function structure, a complete relationship matrix can be show in Figure 3.12. The matrix shows the relationship between the measures/KPIs and the functions of a cruise ship.

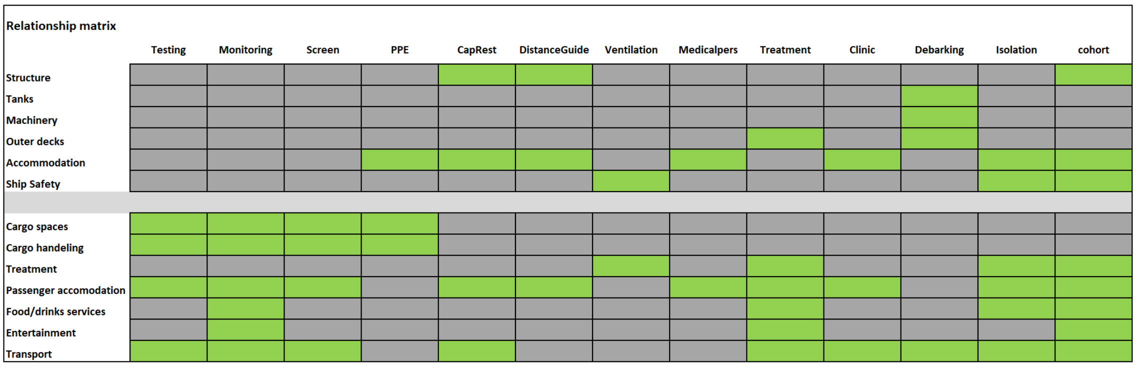
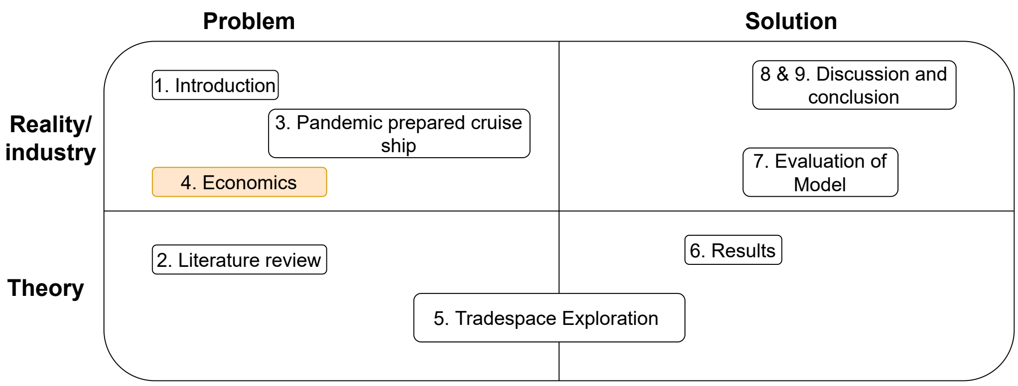


Figure 3.12: Relationship matrix between the measures and the functions

Chapter 4

Economics



To be able to evaluate a cruise ship's design capabilities against others, it is also necessary to consider the economical aspect of the design. A typical cruise ship will have a lot of equipment, design functions, and also operational functions, and in this thesis, the relevant costs of all these will not be elaborated. The relevant costs will be related to the mentioned ship functions and equipment, which is connected with the measures needed to evaluate the cruise ship in regard to pandemic preparedness. It is also important to mention that these breakdowns will not be in great detail, as the main goal of this thesis is to provide a broad evaluation tool that is based on a general cruise ship. Therefore the costs related to these measures will be broad and approximations, often based on ranges for typical ships. A brief preliminary CBA analysis will be done as a guide for the general model for evaluating pandemic-related cruise ships. Another note to mention is that the costs of many of these measures can be difficult to even approximate, due to the costs relating to a pandemic for cruise ships on the scale of Covid-19, is new, and the costs are less researched at the time of writing this thesis in 2022.

4.1 Cost-benefit analysis

CBA, or cost-benefit analysis is a method for appraising large-scale projects. It is one of the most widely used methods in the industry[23]. From the article of Ross. et al, the quote "*CBA seeks to enumerate all direct costs and benefits to society...of a particular design, assigns them monetary equivalents...*"[23] explains the main goal of a CBA. The goal is to value a design solution value, vs its cost. This will be done in this thesis, by gathering broad values for the costs related to a typical cruise ship design. Then add the costs related to the specific design solution being evaluated. This specific solution will have its costs based on the standard cost of a typical cruise ship and add the costs for each tier of measures included in the design, based on the measures presented in Section 3.5 .

4.2 CAPEX

CAPEX, or capital expenditure, is a term widely used in the shipping industry. It is the capital expenses, everything correlated to the acquiring of a ship. It is a cost that occurs in the initial phase of operation. These costs will be large, and will typically consist of the cost of labor for building a ship, materials, and design costs. The cost of acquiring a property, and in this case, a large cruise ship, would be classified as a capital expenditure. In this thesis, the type of cruise ship can vary, and thus the costs related to acquiring a general cruise ship for this model will also vary. The typical prices of cruise ships build can range from a couple hundred million dollars, to upwards of 1.5 billion dollars [21]. A normal size cruise ship of around 2000-3000 passengers will cost around $550 million[6]. As mentioned previously, this thesis will take a general approach to evaluate a cruise ship, and will therefore use a ship of around 2000-3000 passengers as standard. The economical aspects will also suit this type of ship, but due to the generalizations, a cruise ship operator or a cruise ship designer should have no problem having a specific model suited for their specific costs and ship type.

4.3 OPEX

OPEX is the operational expenditures related to an organization or business. OPEX is a financial term for expenses that are used for the day-to-day operations of a business. For a cruise ship company, the operational expenses will be such as salaries, insurance, payroll, marketing, costs of goods, utilities, taxes, etc. These expenses will be small compared to the larger sums of the CAPEX, but due to the lifespan of a ship, these expenses start to add up. Considering a cruise ship's life span of typical 30 years, with several overhauls retrofitted at later dates, the operational costs cover a large part of the total costs related to a cruise ships lifetime. For cruise ships, the operational expenditures over the lifetime of the ship can sometimes be several times larger than the capital expenditures. Annual costs, can range from tens of millions of dollars to several hundred million dollars per cruise ship.

4.4 VOYEX

VOYEX is a shipping-specific term, coined by Ullstein. It separates the costs connected with the voyage of the ship, from the otherwise operational expenses, the OPEX. These voyage-related expenses will typically be fuel costs. These expenses can vary and might be independent of operational costs. A ship can have operational costs without voyage costs when it lays in berth. Due to the nature of the measures chosen in Section 3.5, none of the chosen measures will affect VOYEX directly on a measurable scale. Measures such as debarking, treatment plan, and capacity restrictions will contribute to changes in voyage-related expenditures, however, due to the general aspect, this will for this general model not be considered. If this model was to be applied to a specific case for a cruise ship owner or designer, these costs would be needed to explore.

4.5 Economical breakdown of measures

As mentioned in Section 3.5, some measures will change the physical aspect of the ship, while others might only alter the operation of the cruise ship. This will be the same for some of these measures. Some will alter the capital expenditures, while others will affect the operational costs, and some will affect both. With an assumed lifespan of 30 years, these costs add up to the overall cost of these ships. To be able to accurately evaluate one ship versus another, it is needed to look at the entire lifespan of the ships, especially where these measures affect it. However, since cruise ships often gets retrofitted several times through its lifespan, mostly to keep up with the berth standard, as well as the competition, considering these costs for a time period of 30 years is not needed. Pandemic related measures will also change over the years, and the research done after Covid-19, will bring much greater insights into the needed measures for cruise ships. Due to most cruise ships being overhauled several times, and the risk of these measures being redundant before this time frame, and have the option to be changed during the overhauls, a lifespan of 10 years will be used to calculate the costs related to each measure. This will ensure that the measures have some longevity to them, and thus includes the operational aspects, while also not overcompensate for a high cost that becomes redundant and replaced in 5-10 years.

4.5.1 Approximations of costs of measures

Below is a brief approximation for the costs of each measures used for the general evaluation model in this thesis. The measures will be divided into three tiers, tier 0, tier 1, tier 2. These tiers will be shown clearly later in Figure 5.1

Testing

Testing equipment for a typical 2000-3000 passenger cruise will depend on the frequency of testing. A typical cruise ship will change its passengers weekly, so the testing equipment would be needed for approximately 130.000 passengers. The cost of test for a virus may range from couple of cents, to several 100 dollars, depending of the state of the pandemic. It will also change over the time period, and during the years of no pandemic these costs will be low. A rough estimate for the ranges of this OPEX will be \$250.000 each year per tier. Increasing the measure of testing from tier 0 to tier 1 should cost \$2.500.000, over the 10 years.

Monitoring

Monitoring the passengers before or after infection will be affected by the passenger size, as well as the tracking methods used. A rough estimate for the range of CAPEX and OPEX is \$100.000 + \$100.000 annually for each tier. The costs of questioner forms will be negligible, while mobile tracking or the use of tracking bracelets will be increasingly more expensive, both in capital expenditures on providing the hardware and software, as well as the operational expenditures.

Screening

The costs related to the use of screening of passengers can also depend on the phase of the pandemic. A rough estimate for the OPEX is around \$50.000 annually for each tier, or \$500.000 over the 10 year life span.

Personal Protective Equipment

Personal Protective Equipment (PPE) for both passengers, but especially the crew involved with infection cases, will vary depending on the size of the cruise ship, the virus, the number of infected, the certain requirements by the cruise operator, the availability of PPE and the quality of the PPE used. The main cost for the cruise ship operator will be to have enough PPE available for even a large scale outbreak, as well as the day to day equipment, like masks. These factors makes a accurate approximation difficult. The average cost of PPE per patient was \$20.40 for US hospitals during Covid-19, and around \$7 before, therefore a rough estimation of enough PPE for half the passengers, with some change out over the years. A good estimation for the range of this operational expenditure is around \$200.000 annually per tier.

Capacity Restrictions

Typically this restriction of capacity wouldn't provide a cost for the cruise ship operator. However, due to the revenue being directly connected with the number of passengers, restricting the capacity will come at a cost. This loss of revenue, and thus loss of profit will for the simplicity of these calculations be regarded as an expense, so that this measure can be evaluated fairly against the others. The average revenue per passengers is dependent on the type of cruise ship, however, a good estimate is around \$1700 per passenger per cruise, with a average profit of \$290. This measure is however not applicable at all times, only during specific phases of a pandemic is this applicable. A exapmple calculation could be:

$$Tier * 3000 Passengers * \$290 ProfitLoss * 40 Trips * \frac{8 months}{10 years} = \$2.320.000 \tag{4.1}$$

A approximate "cost" of each tier of capacity restrictions is around \$2.320.000 per tier.

Distance Guide

The operational and capital expenditures related to distance guidelines will vary, some will have negligible costs, others will need to change the layout of the deck area greatly to accommodate these guidelines. This will therefore be very cruise line operator dependent for costs, but a approximation is around \$100.000 annually per tier.

Ventilation

Costs related to better ventilation systems will be based on the system already fitted, or the specifications of the layout. A total rework of the HVAC system, with HEPA filters will be very costly, however, most cruise liners are already equipped or designed with good ventilation systems, this would therefor not necessarily require a large upgrade, depending on the tier. An estimation for the CAPEX for each tier is around 4.000.000\$.

Medical Personnel

The need for medical personnel for the cruise liner is dependent on the phase of the relative pandemic. The cost of the medical personnel could be calculated from a typical cost pr crew of around \$150 pr day, with additional due to the qualifications. How often the medical personnel is in fact needed during the 10 year time span for this assessment is difficult to approximate, and therefore the OPEX of this measure is only a approximation. The estimated cost of Medical personnel is around $300.000 annually per tier. Or $2.500.000 over the time period of this evaluation.

Treatment Plan

The costs of a good and well trained protocol for treatment is difficult to asses, some costs can be covered by crew already on the pay role, however, some new qualified crew to deal with pandemic is most likely for each cruise liner. Training and practice can also be costly, so a approximation of the OPEX related to a treatment plan is around $150.000 annually per tier, or $1.500.000 over the 10 year time period.

Clinic Design

Cost of a medical clinic is dependent on the cruise ships layout, the size of the clinic, the equipment used. Related to viruses like Covid, the use of costly equipment like ventilators may be needed. A approximation for the CAPEX of this measure is around $3.000.000, with $200.000 in OPEX.

Debarking

The cost of debarking plans is based on the ports the cruise liners will have clearance for, the distances to these ports. How much these things will have in OPEX is diffcult to estimate, but it will be costly. During 2019, several cruise liners were not admitted into any ports, they were refused, having clearance ready,in case of larger outbreaks will therefor come at a premium, due to the necessities surrounding a debarking scenario with infection on board. OPEX is estimated at around $400.000 annually, or 4.000.000$ over the 10 year period.

Isolation

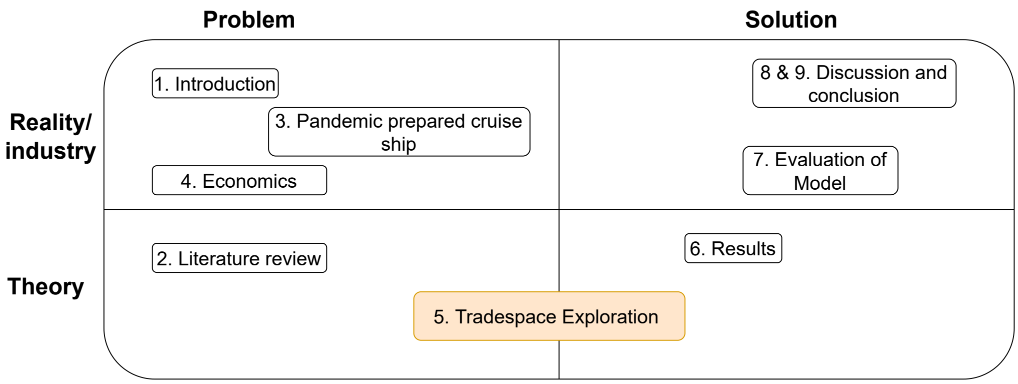
Isolation of passengers and crew requires increased operational costs. Some berths will have to be specified for isolation. Other instances the passengers cabins can work as isolation chambers. The amount of cabins available for isolation will also be different, and the outfitting of these isolation rooms. The ventilation might be a requirement as well. Having equipment and crew ready to deal with the infected will come at increased costs, and an estimated OPEX of $200.000 annually is set. Over the 10 year period this will come at the cost of $2.000.000.

Cohort

The ability of the cruise liner to divide the passengers into smaller cohorts will come at increased cost, increased spaces, increased crew, increased meal times, increased entertainment times. instead of doing things once, they will have to do it several times during the day, to let each cohort attend at different times. However, the ability to divide the passengers into cohorts, will not need to be used all the time, and therefor the real cost over a longer time period will be much lower. A estimated $2.000.000 is set for the cost over a 10 year period.

Chapter 5

Tradespace Exploration



This chapter will be about how the measures mentioned previously, can be adopted into tradespace exploration by using them as utilities. The chapter will also depict the weighting of these utility attributes, and the use of epoch era evaluation. Lastly, this chapter will touch on the feasibility of the solutions, and the relationship between combinations of measures.

The design variables can be shown in Figure 5.1. Overall there is 13 utilities. These are based on the measures mentioned in Section 3.5, as well in Section 3.6. To evaluate different utilities against each other, a stepped diagram is used, as shown in Figure 5.1. These tiers are from 0.0p to 0.2p for lowest tier, 0.2-0.5p for medium tier, and 0.5p to 0.8p for highest tier. To achieve a higher tier, there are certain requirements that need to be met. These requirements are found based on the relevant data for finding these measures [14] [36]. This thesis will not evaluate the effectiveness of these measures, and therefor this utility contribution will be used. The effectiveness of these measures are outside the scope of this thesis, and this will be further discussed in chapter 8. The criteria are detailed in Figure 5.1, and to advance a tier the requirements have to be met, while the measure would then receive a higher utility score.

Utility contribution

Utility	0.0-0.2p	0.2-0.5p	0.5-0.8p
Testing	Every month for crew	Every week for crew, and and in any case of symptoms	Every other day for crew, and in any case of symptoms
On board tracking and monitoring	Questionnaire forms	Mobile tracking	Bracelet tracking
Screening / covid-19 pass	Screening before embarking	Covid-19 pass, screening 1 week prior and while embarking	Covid pass required, screening 2 times before embarking, and while embarking
PPE usage	Recommended masks	Recommended masks for passengers, as well as staff members, mandatory in crowded areas. Gloves recommended for staff	Mandatory masks in all areas, gloves for staff
Capacity restrictions	0-19% reduction in passengers, compared to other ships	20-49% reduction in passengers, compared to other ships	50% reduction in passengers and above, compared to other ships
Distance guidelines	0-1m apart apart	1m apart for all activities, meals and coridors	2m apart for every passenger outside the household
Ventilation systems	Recirculation system or HEPA filter below grade 13	100% fresh air or HEPA filter grade13 and above filter	100% fresh air, through HEPA filter grade 13 and above
Medical personnel	0 doctors on board, nurse onboard	1 doctor onboard	Full medical team onboard
Treatment plan	Protocols for isolation and quarantine	Protocols for training crew, onboard isolation and quarantine, testing.	Protocols for training crew, onboard isolation and quarantine, testing, surveillance of symptoms, large outbreaks,
Clinic design and operations modifications	No designated medical clinic, with possibilities to appoint other available area	Medical clinic PPE, without hospital grade equipment like ventilators.	Hostpital grade equipment and clinic, (e.g., ventilators, PPE)
Debarking scenarios	No debarking plan in case of outbreak	Agreements with always closes port for debarking protocols	Good agreements with every authorities and closest ports, protocol for closest ports, never over 0.5 days sailing distance from a predetermined port, with capabilities for port quarantine or disembarking
Isolation/quarantine	Cabins work as isolation chambers	Designated isolation cabins for 10% of ship capacity	Designated isolation cabins, with negative pressure for 20% of ship capacity
Cohort possibilities	Can separate into cohort sizes of 50% of ship capacity	Can separate into cohort sizes of 33% of ship capacity	Can separate into cohort sizes of 10% of ship capacity

Figure 5.1: Utility Contribution for all measures proposed

As mentioned in Section 2.2, the perceived value a measure gives the stakeholders should be represented in the utility function. Figure 5.1 shows the available tiers that the measure can have, but they also need to be scaled according to the stakeholders preferences. From the initial market analysis, the deep understanding from function structure breakdown mentioned in Figure 3.8, and the stakeholder analysis, the weighted Table 5.1 can be generated. The main goal of this weighting is to distribute utility scores to match the perceived value from the stakeholders, as shown the utility of a tier 3 can range from 0.6p to 1p. Tier 1 would give all the measures 0.2p, to scale the weighting of all measures more correctly in the final assessment done later in Section 5.1. The way these will be scaled during the epoch era analysis, the lowest tier utility can't be 0, since 0.0 1.5 will not scale the score.

Table 5.1: Weighted utility for each measure

Measure	Tier 1 Utility	Tier 2 Utility	Tier 3 Utility
Testing	0.2	0.5	0.8
Monitoring	0.2	0.5	0.8
Screen	0.2	0.5	0.8
PPE	0.2	0.5	0.8
CapRes	0.2	0.6	1
DistanceGuide	0.2	0.6	1
Ventilation	0.2	0.6	1
MedicalPers	0.2	0.5	0.8
Treatment	0.2	0.4	0.6
Clinic	0.2	0.6	1
Debarking	0.2	0.5	0.8
Isolation	0.2	0.6	1
Cohort	0.2	0.6	1

5.1 Epoch era evaluation

To generate the tradespace exploration, MATLAB was used. The scripts will be presented in Section B.2. This script is based on a very basic provided script during the course TMR4135 - Design Methods 2: Special Vessels. It was made by Sigurd Solheim Pettersen, handed out during the course, for a ABD Design Project. The script have been modified by me to fit the thesis, however, the elements from the handout is clear.

In Section 2.3.2, epoch era analysis was presented. This is chosen as the method for this thesis, as it provides the best understanding of future scenarios, for the model of evaluation pandemic prepared cruise ships. The first step in epoch era analysis is to generate epoch variables. These will be the same as our measures, and will be assigned values based on the tier of measure. Tier 1 will have the value 0, Tier 2 the value 1, and Tier 3 the value 2. For this analysis the values for all these measures will be based on these tiers. We will also introduce another decision variable, Capacity, which is needed for some of the calculations done, however this variable will not be presented here. The next step in the process of a epoch era analysis is to generate the epochs. For this model a 3x3 method will be used. Three epochs in each of the three eras presented. These eras and epochs are presented in Table 5.2.

We will generate three eras. The main objective of these eras is to test the cruise ship in a possible future scenario, therefore these eras will depict different pandemic scenarios, with changes compared to the Covid-19 pandemic. Era 1 is Covid-19 equivalence, this scenario will be of the same characteristics of the Covid-19 pandemic, and should give a informative results regarding the best combinations during the pandemic. This will also give the model the possibility to be checked against how the cruise industry actually did react, and test if the best and most cost effective combinations where in fact chosen. Era 2 is higher lethality but lower spread. So the virus presented in this type of pandemic will be more deadly, but have a lower chance of spreading between the passengers. This era is interesting, as the main issue with cruise ships, in regards to decease prevention, is the close proximity of passengers and relatively small spaces.Lastly, Era 3 will have increased spread and increased lethality, it will be a worst case scenario for the cruise operators, and therefore interesting to investigate.

Table 5.2: Epoch era weighting for utility

Chance of happening		50%	30%	20%	70%	20%	10%	30%	30%	40%
Epoch era	*Outbreak type*	*No*	*Small*	*Large*	*No*	*Small*	*Large*	*No*	*Small*	*Large*
			ERA 1			**ERA 2**			**ERA 3**	
		Epoch 1	*Epoch 2*	*Epoch 3*	*Epoch 4*	*Epoch 5*	*Epoch 6*	*Epoch 7*	*Epoch 8*	*Epoch 9*
	Testing	Low	Med	Med	Low	Med	Med	Med	High	Med
	Monitoring	Low	Med	Low	Low	Low	Low	Med	Med	Low
	Screening	Low	Low	Low	Low	Low	Low	Med	Med	Low
	PPE	Low	Med	High	Low	Low	Med	Med	High	High
	CapacityRes	Low	High	High	Low	Med	Med	Med	High	High
	DistanceGuide	Low	High	High	Low	Med	Med	Med	High	High
	Ventilation	Low	Med	High	Low	Med	High	Med	High	High
	MedicalPers	Low	Low	Med	Low	Med	High	Med	High	Med
	TreatmentPlan	Low	Low	Low	Low	Med	High	Med	High	High
	ClinicDesign	Low	Low	Med	Low	Med	High	Med	High	High
	Debarking	Low	Low	Low	Low	Low	Low	Med	Med	High
	Isolation	Low	Med	Med	Low	Low	Med	Med	High	High
	Cohort	Low	Med	Med	Low	Low	Med	Med	High	High

For epochs, the main three scenario will be that the cruise ship will have no outbreak over a shorter period. The second epoch type is a small outbreak, and the last epoch type is that the cruise ship will face a large outbreak over a shorter period. Together the combinations of epochs and eras generate 9 possible future scenarios, and these will all be investigated. A table with these combinations is presented in Table 5.2. This table will also show the weighting for the nine different scenarios. The weighting system for the epochs are based on stakeholder needs. The value of a given measure, will increase compared to the standard provided in Table 5.1. This table will serve as a basis for the rest of the scaling in the epoch era analysis. From Table 5.2, a indication of Low means no increased perceived value by the stakeholders, and therefor the scaling factor will be 1. For measures marked with Med, a scaling factor of 1.5 will be used. For measures marked with High, a scaling factor of 2 will be used. This means that the stakeholders perceive twice more value for this specific measure, in that possible scenario. As an example let's focus on the measure ventilation. For Era 1, a Covid-19 equivalent pandemic, the value of having better ventilation will low during no outbreak, Med during a small outbreak, and High during a large outbreak. Having a better ventilation system gives twice as much value during a large outbreak on board, compared to while there is no outbreak occurring. The ventilation system will still give the stakeholders value while there is no outbreak, as it provides a less chance for contamination, better public image for the cruise liner, peace of mind for passengers etc. For the same measure, in Era 3, with higher spread and lethality compared to the Covid-19 pandemic, it will provide a Med increase in value during no outbreak, and High value for both small and large outbreak.

The given scenarios will also be scaled based on chance of happening. In Table 5.2, the chance of each scenario is presented at the top of the table. A large outbreak is less likely to occur than a small, and it even less likelier to occur if the scenario have a virus with lesser spread. Similarly, in Era 3, with higher spread and lethality, a larger outbreak is more increasingly more likely. These factors, will be how the three epochs in each era will be scaled. The values will be normalized for a range between 0-1, so that the utility will be scaled correctly, and be able to plot against each other, as shown in chapter 6.

5.2 Feasibility

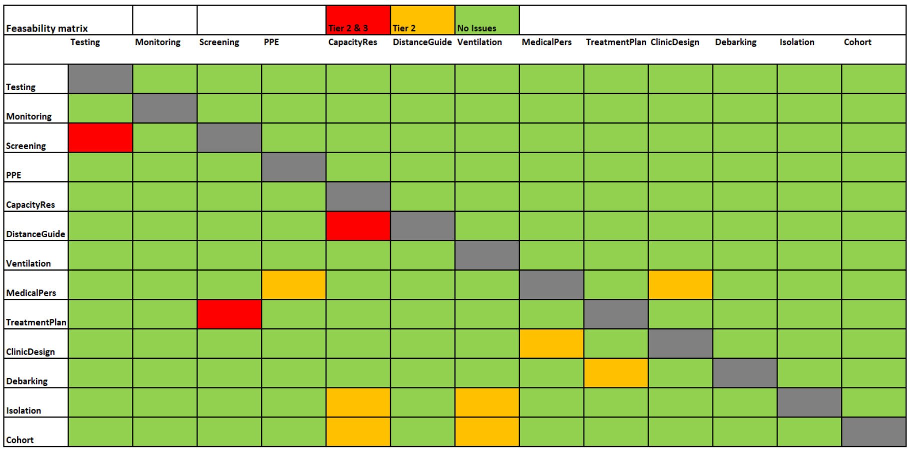
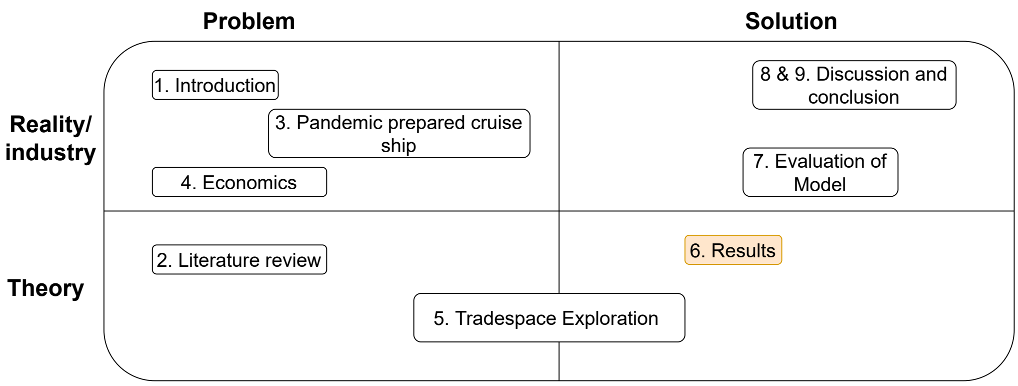


Figure 5.2: Feasibility matrix

Tradespace exploration will generate every combination of the measures presented earlier. However, some of these measures affect each other, there are some relationships. Some measures might require the other to be possible. Therefor the use of feasibility is applied. The feasibility is how feasible that specific design is, if it is not possible it is disregarded. This is done by sorting through the tradespace, and if a concept is not possible it is removed from the tradespace. For this specific model, the tradespace contained 1.594.323 concepts before the feasibility analysis was done. And was decreased to 320.796 concepts when completed. The feasibility analysis is done so that no infeasible solution gets evaluated. The relationship of the measures are shown in the feasibility matrix in Figure 5.2. It shows three different types of relationships. "No issues" in green, means that there is no issues regarding these combinations. "Tier1" in yellow means that the the measures on the left, will only be able to achieve at most tier 2, unless the measure at the top is used. "Tier23" in read, means that the measure on the left can not exist, if the measure on top does not exist in the concept. As an example, lets study the relationship between distance guideline and capacity restriction. From the matrix it is shown that this is categorised as "Tier23",red. This means that if there is no capacity restriction, there cant be distance guidelines. this would be due to the lack of space available on the cruise ship. However, the opposite is not true, there can be capacity restrictions, without having distance guidelines, shown by a green, "No issue" category.

Chapter 6

Results



In this chapter, the results found using tradespace exploration method, as well as the epoch era analysis, are presented. These results will be discussed briefly in this chapter, but a more thorough discussion is presented in chapter 8.

Before the results are presented it is needed to repeat the object of this master thesis.

"This master thesis aims to develop an evaluation model for cruise ship design and operation, with respect to pandemic preparedness"

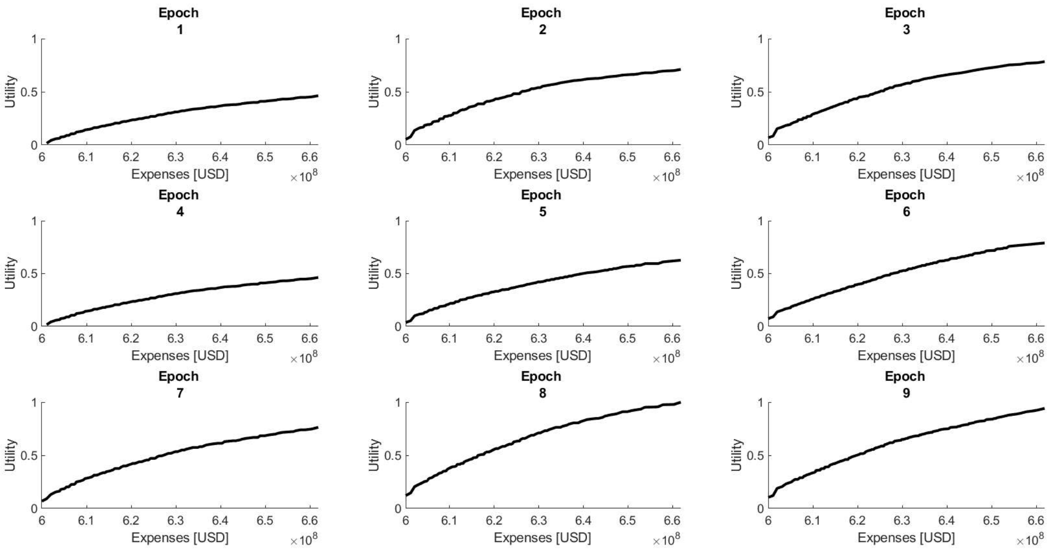


Figure 6.1: The epochs pareto front plotted

From all the feasible solutions, we end up with a design space consisting of 320.796 different combinations. These solutions are the different combinations of tiers of the measures, as long as they are feasible as mentioned in Section 5.2. These 320.796 are the once explored in the trade space exploration, as well as in the epoch era analysis. From Figure 6.1 the pareto front of all 9 epochs are shown. These epochs are labeled and are scaled based on the mentioned weighting in Section 5.1. The illustration shows that the first, fourth, and seventh epochs seem to show the lowest utility overall, despite being located in three different eras. These are contained in the bracket called no outbreak type, which gives them the lowest utility, due to giving the stakeholders low value compared to other scenarios. If there is a larger outbreak on board a ship, the utility of the measures will be larger, compared to a scenario where there is no outbreak.

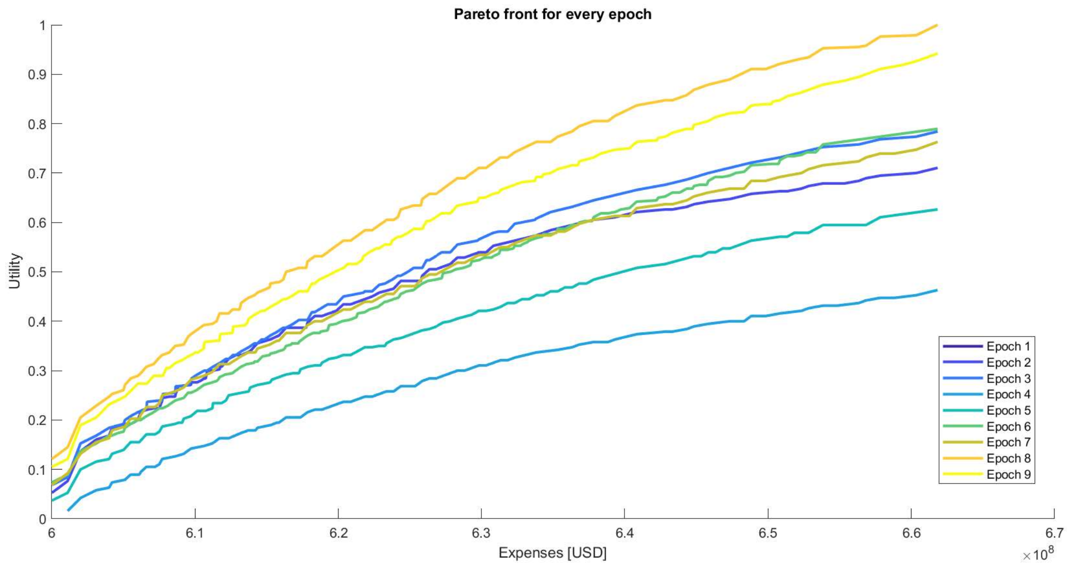


Figure 6.2: The pareto front of the epochs plotted in the same figure

To show a more explicit graphical demonstration of the nine epochs Figure 6.2 is shown. This plots the 9 epochs against each other, on the same figure. It should be noted that only 8 lines are drawn,that is due to the exact same line for epochs 1 and 4. Referring to Table 5.2 that is because both epoch 1 and 4 contains the same weighting on all measures, thus resulting in the exact same line. Regarding epoch 7, it is shown that the value is consistently lower than that of epoch 6 and sometimes lower than epochs 5 and 3. This presents that even tho the seventh epoch is in a era of a much worse pandemic, it is still more utility to have a ship that is in a kinder pandemic but having a large or small outbreak, compared to no outbreak in the worse era.

The costs of the presented solutions range from 600.000.000$ to 662.000.000$ for combined CAPEX and OPEX, over the 10 year time span. Era 1 is a scenario with similar characteristics to Covid-19, era 2 is a lower spread but higher lethality, and era 3 is a higher spread and lethality. Era 1 contains epochs 1-3, while era 2 contains epochs 4-6, and lastly, era 3 contains epochs 7-9. The expenses the ship owner would have to endure during a better era, era 1, compared to the worst era, era 3, is quite a large shift for the same utility. In a scenario of era 1, with a small outbreak, a utility of around 0.5 is achievable with about 645 million USD. For the same utility in era 3, with a small outbreak, the shipowner would only have expenses of around 617 million USD. This displays the importance of including multiple scenarios into consideration when evaluation the best overall pandemic prepared cruise ship.

An additional aspect illustrated by Figure 6.2, is that epoch 8 achieves higher utility compared to epoch 9. Referring back to Table 5.2, it unveils that the weighting of epoch 9 compared to epoch 8 is lower. Several measures are rated lower in a large outbreak, compared to a small outbreak. Measures such as testing, and monitoring. This is because the value perceived by the stakeholders, while undergoing a large outbreak compared to a small outbreak, is indeed lower. When a very large part of the ship is already infected, the usefulness of testing and monitoring decreases. The helpfulness of testing the crew and passengers decreases when such a large part of the ship is infected. The testing will less and less be effective, and will no longer be able to keep up with the number of infected. It will no longer be as beneficial.

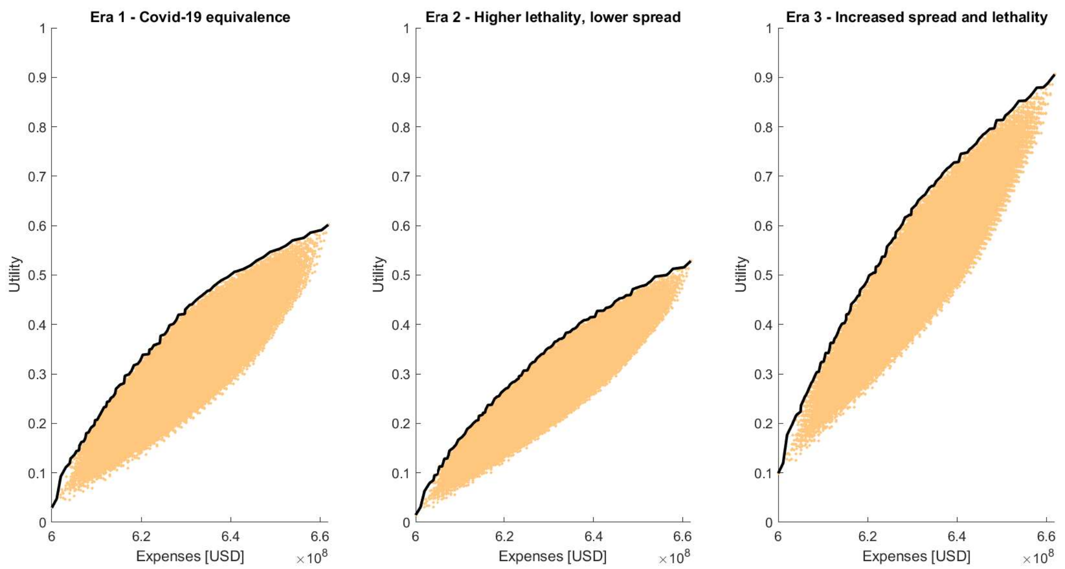


Figure 6.3: The three eras used in the model

To gain a better understanding of how the three different eras affect the utility Figure 6.3 is displayed. It depicts the average weighted utility for the three epochs included in that era. It also depicts the three different eras, on the same scales of utility against expenses. It is abundantly clear from Figure 6.3 that era 3 is valued the highest, with era 1 in second and where era 2 is the least valued. These three eras show different pandemic scenarios, where era 1 functions as a baseline, with the known characteristics of the pandemic from Covid-19. If a worse pandemic than Covid-19 hits, then the value for the cruise ship operator, and the stakeholders, of having a better-prepared pandemic cruise ship will increase. The stakeholders would rather own a better-equipped pandemic-prepared cruise ship if a worse pandemic shows up. Much like the stakeholders of a cargo ship would rather own a better weather-resistant ship, when the storm hits, than when it's clear.

For the second era, era 2, the results point to it being valued less by the stakeholders during a pandemic with those characteristics. For a cruise ship, the biggest problem in the past, regarding sickness and health, has been the relatively small spaces and distance between passengers. Therefore the utility decreases with the proposed measures, when the virus characteristics show a lower spread, as this is the main aspect that a cruise ship is inherently bad at handling. From Table 5.2 the value for the stakeholders of medical personnel and a good clinic to handle the more deadly virus is increased, but it does not outweigh the loss in utility from the distance and ventilation-focused measures. It is important to note that the expenses for each era do not change, that is because it is the exact same solution that is being evaluated in the three different eras.

From the findings above, a final result can be made. In Figure 6.4 below, every design possibility is plotted for its utility against the expenses. Each design is one of the feasible designs explored in the tradespace exploration, and then weighted to account for different epochs and eras. The pareto front can be shown marked in black, the designs along this line are the designs best suited, according to the criteria specified earlier, and the weighting of the utility function. These solutions are the ones recommended by the model. Some of the solutions on the pareto front will later be shown in Table 6.1.

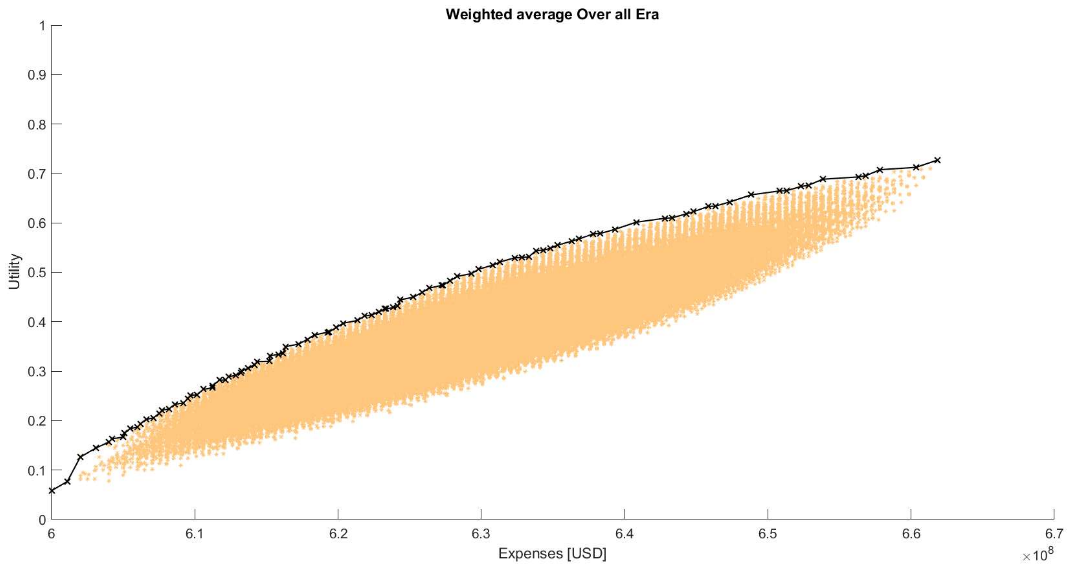


Figure 6.4: A weighted average of all eras, from tradespace exploration and epoch era analysis

The results of the weighted average show a large increase in utility vs the cost of the solution in the beginning. While approaching the middle of the designs, the increase gets linear, with a fall-off in the end. We can also see that there is no solution that reaches a utility of 1, the upper point for the weighted average is a utility of 0.7323. It is shown that several vessels get this exact utility, however, due to the cost difference, the one closer or on the pareto front is the better solution. The use of tradespace exploration as a design method is clear from Figure 6.4, it clearly shows the better solutions over the many millions of worse solutions. However, one main goal is to choose one solution, and this illustration does not show exactly one solution. It gives the decision-makers a graphical illustration of the solutions against each other, and the value for each of them. We can now remove the solutions that are not at the pareto front, to better investigate the findings.

Below in Figure 6.5is only the pareto front of the weighted averages shown, it also depicts eight example solutions, that is also shown in Table 6.1. The illustration in Figure 6.4 displays that the middle section of the pareto front is quite linear, and also shows the exact locations of eight of the chosen examples. These eight shows a steady decline in both expenses and utility.

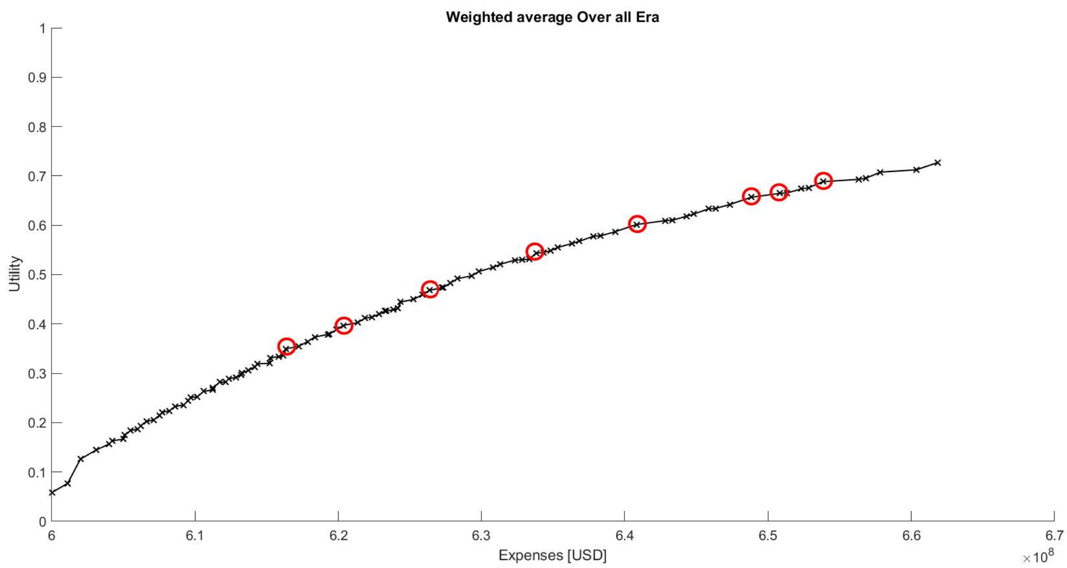


Figure 6.5: Weighted average pareto front for all eras

Evaluating these eight against each other based on the results in Figure 6.5 would be quite difficult. The decision maker would need to factor in if the increase in utility is worth it, compared to the added expenses. One of the advantages of tradespace exploration methodology is that it can reduce the possible solutions down to a few, and depending on the parameters defined, some clear best results might show up. On occasions like this however, with a pareto front that is quite linear, the decision maker would need to evaluate the specific designs against each other. This pareto front would be useful to evaluate other solutions that is not on the pareto front, or close to it, but this method might lack in finding a specific best solution, this will be discussed further in chapter 8.

Table 6.1: 8 examples of the parameters from the solutions on the pareto front of the weighted average of all eras

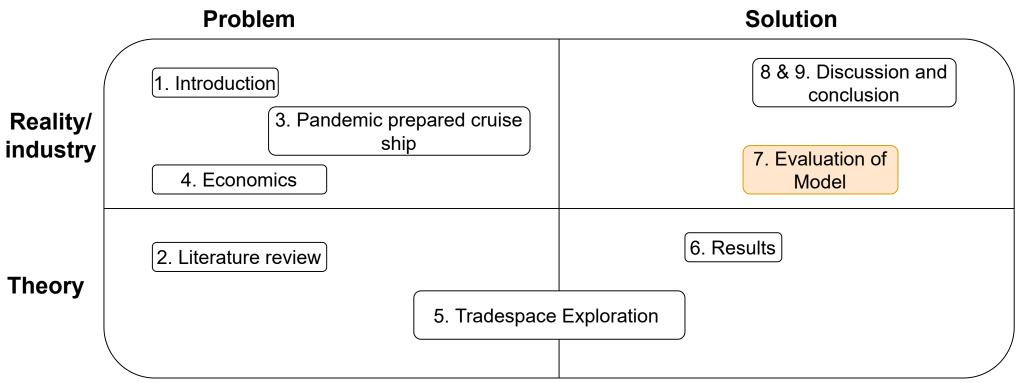
ID	Capacity	Testing	Monitoring	Screen	PPE	CapRest	DistanceGuide	Ventilation	Medicalpers	Treatment	Clinic	Debarking	Isolation	Cohort	Utility	Expenses
306166	3000	2	2	2	2	2	2	2	2	2	2	0	2	2	0.688	653.8
305886	3000	2	2	2	2	2	2	2	1	2	2	0	2	2	0.665	650.8
303716	3000	2	2	2	2	2	2	2	2	2	1	0	2	2	0.657	648.8
299796	3000	2	2	2	2	2	2	2	1	2	0	0	2	2	0.601	640.8
299166	3000	2	2	2	2	2	2	1	0	2	0	0	2	2	0.544	633.8
297149	3000	1	2	2	1	2	2	1	0	0	0	0	2	2	0.468	626.3
175202	3000	1	2	2	2	2	2	0	0	0	0	0	1	1	0.397	620.3
175160	3000	1	2	2	0	2	2	0	0	0	0	0	1	1	0.350	616.3

Studying the examples of chosen solutions on the pareto front of the weighted average of all eras, some trends emerges. Debarking seems to be under represented in the higher utility brackets, indicating that the value for the stakeholders of this measure, is not worth the cost, compared to the others. The same goes for a medical clinic, the high costs, and the quite low value for stakeholders during two of the three ears, means that this does not make the cut for most of the best solutions on the pareto front. Going along side the clinic is the use of medical personnel, the value of this measure does gain some value during the second and third era, where the lethality is increased, but with its high expenses it is only present in the most expensive solutions on the pareto front. Some of the cheaper alternatives that still bring good overall value to the stakeholders, seem to be, testing, monitoring, screening, PPE, capacity restrictions distance guidance and isolation. This result does in fact match how the cruise industry adopted in the later stages of the Covid-19 pandemic, pointing to a somewhat realistic model, at least in regards to a Covid-19 scenario.

One large drawback of the use of tradespace exploration is the fact that the influence of the utility attributes and weighting during the analysis, largely affect the outcome. It is therefor crucial that the analyst have a solid understanding of the stakeholders needs, as well as the system the analysis is applied to. This could also be one of its benefits, as the model made using the tradespace exploration methodology, can easily be modified to meet exact requirements from a shipowner. The more specific the data the better the analysis. The choice of tradespace exploration with epoch era analysis proved to be a very suitable methodology for developing a general model for evaluation cruise ship design and operation. The general nature of the task made for a good match with the method, where the model can later be adapted quite easily to a cruise liners specific data, while still giving some good insights based on the widespread data adopted in this model. This will be discussed further in chapter 8.

Chapter 7

Evaluation of Model



To validate that the general model also works for a specific set of parameters, the use of two ships with different measures will be used. The first ship presented will be how the "Diamond Princess" most likely was set up, prior to the incident described in Section 1.1. The parameters for this ship will be shown in Table 7.1, with the "Diamond Princess" being the lowest, with ID 8416. The capacity of "Diamond Princess" is 2670[37]. The ship would have Tier 2 testing, referring back to the tiers in Figure 5.1. Would not have the capabilities for monitoring. Screening is the highest tier, in the start of 2020, the screening was the most common tool for Covid-19 preventative measures. PPE was in high demand, so it is very likely that it either tier 1 or 2. There where not implemented any capacity restriction at the time of the incident, and neither any distance guide.

From research done after the incident, the "Diamond Princess" was well ventilated, and it it did not recirculate air [34], therefor we will study the case with ventilation tier of 3. The ship had one doctor on board, so it gets a tier 2 for medical personnel. It had zero treatment plan, so that will be the lowest tier, tier 1. It was equipped with a clinic, so that is a tier 2. And lastly, debarking, isolation and cohort was all given a tier 1, for lack of meeting the necessary requirements.

The second ship will illustrate a resurging cruise ship, while the cruise ship industry was trying to

Table 7.1: Parameters of "real life" examples during Covid-19

ID	Capacity	Testing	Monitoring	Screen	PPE	CapRest	DistanceGuide	Ventilation	Medicalpers	Treatment	Clinic	Debarking	Isolation	Cohort	Utility	Expenses
52773	2,670	2	2	2	1	2	1	2	1	0	0	0	1	0	0.4234	628.84
8416	2,670	1	0	2	1	0	0	2	1	0	1	0	0	0	0.2632	621.50

restart the cruises. The measures and its tiers represent such a vessel. This ship would have most of the operational aspects at the highest tier, while some would be lacking due to the limitations the ship would have, based on its design and its limited preparation time. The values are represented in Table 7.1, and the ship is classified as ID 52773.

From Table 7.1 the cost of the early stage resurging ship is not that much higher compared to "Diamond Princess". However, the utility would be much greater, at a utility score of 0.434 against "Diamond Princess" score of 0.2632. To gain a better understanding of these scores, Figure 7.1 is graphed. From this graph it is clear that the "Diamond Princess" was very far away from the pareto front. The early stage resurging Covid-19 cruise ship on the other hand is getting fairly close to the pareto front, indicating that the cruise ship operators used the best available measures when trying to restart the cruise ship industry. The cruise ship operators did not have the time, or the correctly designed cruise ship to be able to achieve a ship that was on or very close to the pareto front, but they did maximize the utility for the costs of the available measures.

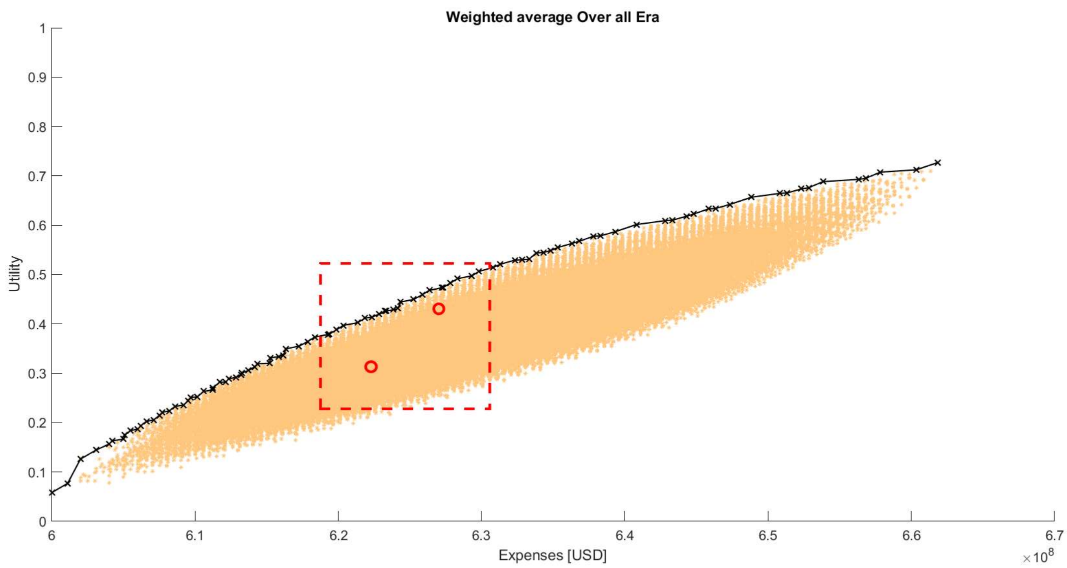


Figure 7.1: Area of interest on the weighted average graph, showing two real life examples

To explore how close each of the ships gets to the pareto front, Figure 7.2 shows a close up of the red rectangle depicted in Figure 7.1. From the illustration it can be showed that there is great improvements for both ships. The ship marked in red on the right upper side is the case of the resurging cruise ship, in the early stage of cruise industry restart. while the red circle on the bottom left is the "Diamond Princess" prior to the incident. These both have improvements that could have been done, for the "Diamond Princess", a better solution for almost the same cost, would be ID 175202, represented in Table 6.1 from the results in chapter 6. Comparing these to concepts against each other reveals some good indications, to be able to come close to the pareto front, the need for capacity restrictions, and distance guidance is necessary. The value of both cohort and isolation measures should also be considered. The resurging Covid-19 cruise ship, did much better, mostly due to having high capacity restriction, some distance guidance, and including some isolation measures. A comparable result from the pareto front would be ID 297149, from Table 6.1. It would increase the utility from 0.423 to 0.468, as well as reduce the expenses by 2.000.000$. The main differences in measures between the two being higher distance guidance, isolation and cohort.

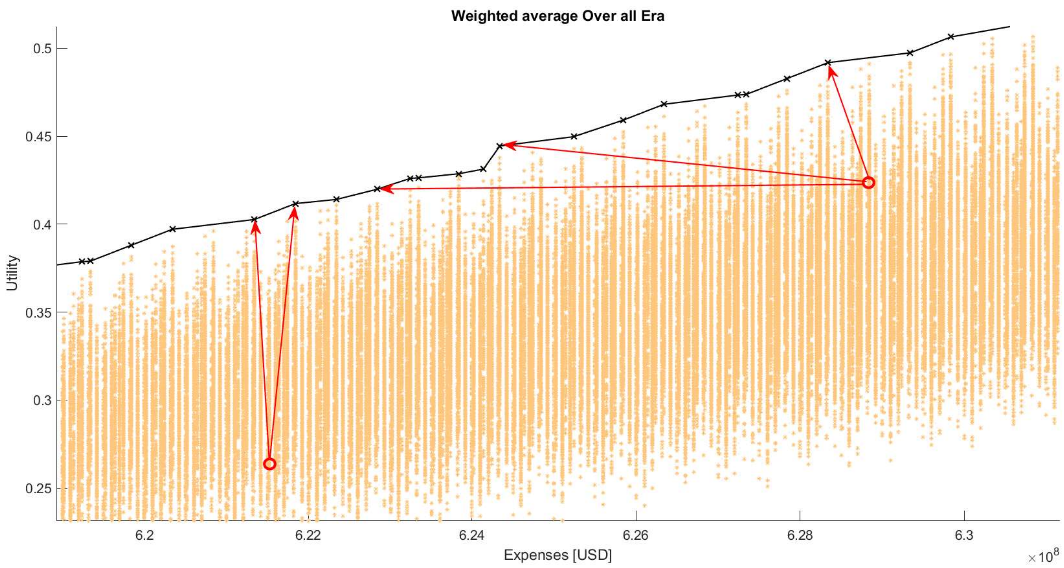
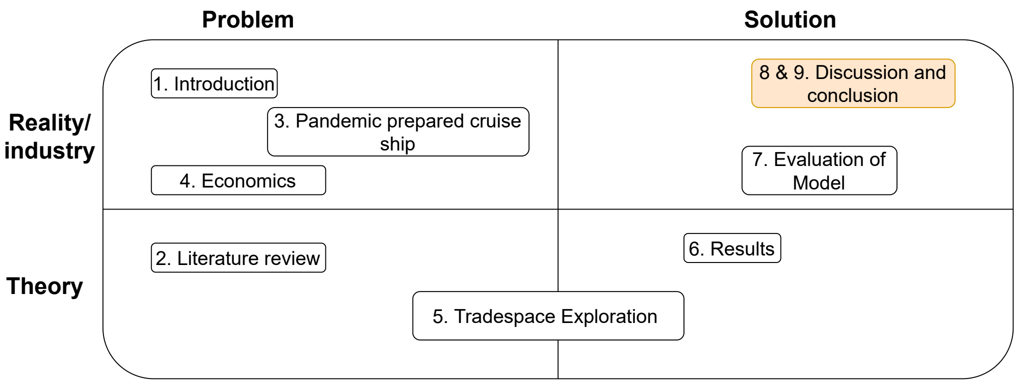


Figure 7.2: Zoomed in area of weighted average graph, showing better alternatives

The evaluation of real life cruise ship cases, shows that while the model is made to be very general, some aspects can still be applied to real life ships, with given parameters. The model is made so that it can be applied to a general cruise ship, and the model should also have the option to accommodate much more specific data sets, if provided by a cruise liner or a decision maker. The real life applications of the model will be further discussed in chapter 8.

Chapter 8

Discussion



The main objective of the thesis was to develop an evaluation model for cruise ship design and operation, with respect to pandemic preparedness. To achieve this model, the model started with understanding the background and trends in the cruise ship industry. Stakeholder needs was then found, and mapped to the function structure, as well as the changes in function structure due to Covid-19 Pandemic, this would lead to the form elements. To map the function structure to form, the use of KPIs was used. This methodology was not the best, as these KPIs would need to change to non typical KPIs to later be able to be applied in the trade space exploration as utility attributes. The use of KPIs was a initially a large part of the preliminary project, but the master's thesis underwent several changes in its aim from that preliminary project. It became clear in the later stages of the master's thesis that the use of KPIs was not a good approach. The main problem with KPIs is that they would have been a good methodology if KPIs were determined to be the way the cruise ships would eventually be evaluated in the end. Based on the findings in chapter 2, the use of tradespace exploration was deemed more suiting for the objective of this thesis. Thus the KPI approach changed from a end goal, to a means to an end, which it did not suit this thesis that well.

The design methodology used, based mainly on Kai Lavender's function structure and changes in them due to Covid-19, gave a very good understanding of the systems in a cruise ships. This was a very helpful approach that synergized well with the use of tradespace exploration. The system model was also based on stakeholder needs, a necessity to understand when doing a tradespace exploration. The details in functional structure gave a good foundation for finding possible measures to evaluate. This design process was also necessary to establish the weighting and utility attributes during the tradespace exploration. One large drawback with tradespace exploration is that the user have considerable control over the final outcome. Changes in weighting of these utility attributes, directly affects the end results. The good and structural design approach used in this thesis was therefor a good choice, to be able to apply tradespace exploration as the method for developing the model.

The use of tradespace exploration as an evaluation tool in this thesis, also gives a broader application into the industry. The weighting is based on stakeholders needs, and thus if the model was to be applied to a specific case, the cruise liner would be able to apply its data for these stakeholder needs, thus evaluation the utility attributes correctly for them, giving a more accurate result. The model took on a general approach. The main reason for this was the uncertainty revolving the affects of Covid-19 pandemic on the cruise industry. There is lacking research done on the subject still, and therefor developing a broad model was deemed necessary. To combat some of this uncertainty, the use of Epoch Era Analysis was implemented. It reduced the uncertainty by including possible scenarios different from Covid-19 pandemic. We already had Covid-19, what is the chance that the next pandemic will be like Covid-19? It gave the tradespace exploration a broader data set to base its evaluations on.

The use of tradespace exploration as a method for developing a model for evaluation cruise ship pandemic preparedness was an excellent approach. The results presented in chapter 6, show that the model works on a general level. It gives the decision maker better insight into the best combinations of measures, based on the attributes used. The model also shows some resemblance to real life, like the two examples shown in chapter 7. Tradespace exploration generates several concepts, as well as evaluates them against each other. It does not give the decision makers a final solution, but instead gives a pareto front consisting of the best concepts for each price points, this gives the decision maker the ability to choose the final solution based on the actual stakeholders value. This suits the broad approach, as it will also show trends in the value for the concepts, what is valued more compared to the cost. One approach that was not used was to consider the fuzzy pareto front, but due to the already very general approach to the model, including the use of fuzzy pareto front in the model would not give much greater insights.

The cost of the measures used is the main uncertainty with the results in this thesis. The costs are very broad approximations, as finding the real costs of the measures was impossible, especially when taking a general approach to the model. The costs are based on findings and assumptions made. This could have been done in a more systematical way. The expenses is a main contributor to the results. Changes in the approximations of the costs will change the results drastically. The use of evaluating the measures over a longer time period of 10 years was applied. This was done to measure the expenses of the OPEX heavy expenses on comparable terms to the CAPEX focused. The shorter time span compared to a typical cruise ships lifespan of 30 years, was also chosen. The thought process behind this was that due to the state the research related to Covid-19 is in. Too high a lifespan will give unrealistic results as they will not reflect the real world, where the measures from 2021, most likely will not be applicable in 2031. This decision was also supported by the fact that most cruise ships undergoes overhauling several times during its lifespan, allowing for a ample opportunity of applying different measures. The model does have the option to be applied to a specific case, as mentioned above. The model also facilitates for this in regards to the expenses. With very specific expenses from a specific cruise liner, the results would also be more precise.

The measures was found based on the function structure, stakeholder needs and the recommendations from two health related sources. The thesis is for a marine system design engineer, therefor, relying on credible health informational sources to base these measures on should be adequate. The effectiveness of the measures it self is outside the scope of the master's thesis. At the time of writing this thesis, the research done on the possible measures to combat pandemics in the wake of Covid-19, is still quite lacking. That is because the world is just now entering its post Covid-19 state.

Chapter 9

Conclusion

In this thesis, we have developed a general model for evaluating pandemic preparedness in cruise ships. To develop this model, tradespace exploration was applied based on a system design process. The system design process was completed, where stakeholders needs were analyzed, the functional structure of a cruise ship was found. The use of KPIs allowed the stakeholders needs and the functional structure to be mapped to specific proposed measures for pandemic preparedness. These measures were also based on recommendations from qualified health researchers. Based on these measures, utility attributes was constructed and used in the tradespace exploration. Furthermore, the use of Epoch Era Analysis allows the model to evaluate possible future pandemic scenarios, with basis in findings from Covid-19 pandemic.

The results from the tradespace exploration provides good insight to the best combination of measures. The pareto front was found, showing the best concepts at each price point, allowing the model to be a good tool in the decision making of future cruise ship designs, in regards to pandemic preparedness. The model was also tested on two specific "real world" ships, with realistic parameters. The results by applying these "real world" ships showed resemblances to how these ships functioned in the Covid-19 pandemic. The model was developed on a general level, allowing for insight, while working as a general model for evaluating pandemic prepared cruise ships. The model can also be applied to specific cruise liners, with more precise data the results of the model will also be more precise.

The results from this thesis shows that a valid model for evaluating cruise ships pandemic preparedness was developed, however, at this time, much further work is needed to adopt the model with more precise inputs, as the post Covid-19 era sets in.

9.1 Further work

Finishing this master's thesis, several aspects still need to be worked on. Due to the topic being very new, and very little research is done on the topic thus far, many of the possible future work would be to adopt to the increase of research.

The main aspect is how the model need to be tailed to more specific data, after more research on the topics of Covid-19 and cruise ships are published. This includes abandoning the approximations used for the expenses, when more data becomes available.

With more available expense data from the Covid-19 pandemic probably available in a few years, that would also allow for a proper Life Cycle Assessment to be done on the subject.

When facing cruise ship owners, the model should be tailored to their specific data sets of stakeholder needs, as well as their expense reports, or offers for equipment and services. This would greatly increase the accuracy of the model.

More future scenarios should also be included in the model, and the probability of these scenarios should be explored. Increasing the possible future scenarios included in the model, would increase the chance that the cruise ships the model would evaluate, actually are prepared for the next pandemic.

The mapping of stakeholder needs should also be done to a greater extent, these needs are so important to the tradespace exploration method, and should therefor be redone on a larger scale.

Lastly, when more data and research is available, a reevaluation of the measures used i is needed. To stay relevant, the model would need to be assesing the most effective measures, and ot do that it needs to b

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Appendix

A.1 Pareto front result, weighted averages over all Eras

ID	Capacity	Testing	Monitoring	Screen	PPE	CapRest	DistanceGuide	Ventilation	Medicalpers	Treatment	Clinic	Debarking	Isolation	cohort	Utility	Expenses
320796	3000	2	2	2	2	2	2	2	2	2	2	2	2	2	0.727	661.84
320096	3000	2	2	2	2	2	2	2	2	1	2	2	2	2	0.712	660.34
315476	3000	2	2	2	2	2	2	2	2	2	2	1	2	2	0.708	657.84
319396	3000	2	2	2	2	2	2	2	2	2	1	2	2	2	0.695	656.84
314776	3000	2	2	2	2	2	2	2	2	1	2	1	2	2	0.693	656.34
306166	3000	2	2	2	2	2	2	2	2	2	2	0	2	2	0.688	653.84
313026	3000	2	2	2	2	2	2	2	2	2	1	1	2	2	0.676	652.84
305466	3000	2	2	2	2	2	2	2	2	1	2	0	2	2	0.674	652.34
306165	3000	1	2	2	2	2	2	2	2	2	2	0	2	2	0.665	651.34
305886	3000	2	2	2	2	2	2	2	1	2	2	0	2	2	0.665	650.84
303716	3000	2	2	2	2	2	2	2	2	2	1	0	2	2	0.657	648.84
302596	3000	2	2	2	2	2	2	2	2	1	1	0	2	2	0.642	647.34
303715	3000	1	2	2	2	2	2	2	2	2	1	0	2	2	0.634	646.34
303436	3000	2	2	2	2	2	2	2	1	2	1	0	2	2	0.633	645.84
303576	3000	2	2	2	2	2	2	1	2	2	1	0	2	2	0.623	644.84
302316	3000	2	2	2	2	2	2	2	1	1	1	0	2	2	0.618	644.34
303435	3000	1	2	2	2	2	2	2	1	2	1	0	2	2	0.610	643.34
303016	3000	2	2	2	2	2	2	2	0	2	1	0	2	2	0.609	642.84
299796	3000	2	2	2	2	2	2	2	1	2	0	0	2	2	0.601	640.84
298956	3000	2	2	2	2	2	2	2	1	1	0	0	2	2	0.587	639.34
299795	3000	1	2	2	2	2	2	2	1	2	0	0	2	2	0.579	638.34
299376	3000	2	2	2	2	2	2	2	0	2	0	0	2	2	0.578	637.84
299586	3000	2	2	2	2	2	2	1	1	2	0	0	2	2	0.568	636.84
298536	3000	2	2	2	2	2	2	2	0	1	0	0	2	2	0.563	636.34
299375	3000	1	2	2	2	2	2	2	0	2	0	0	2	2	0.555	635.34
297486	3000	2	2	2	2	2	2	2	0	0	0	0	2	2	0.549	634.84
299585	3000	1	2	2	2	2	2	1	1	2	0	0	2	2	0.545	634.34
299166	3000	2	2	2	2	2	2	1	0	2	0	0	2	2	0.544	633.84
299361	3000	1	2	2	1	2	2	2	0	2	0	0	2	2	0.531	633.34
298745	3000	1	2	2	2	2	2	1	1	1	0	0	2	2	0.530	632.84
298326	3000	2	2	2	2	2	2	1	0	1	0	0	2	2	0.529	632.34
299165	3000	1	2	2	2	2	2	1	0	2	0	0	2	2	0.521	631.34
297171	3000	2	2	2	2	2	2	1	0	0	0	0	2	2	0.515	630.84
298325	3000	1	2	2	2	2	2	1	0	1	0	0	2	2	0.506	629.84
299151	3000	1	2	2	1	2	2	1	0	2	0	0	2	2	0.497	629.34
297170	3000	1	2	2	2	2	2	1	0	0	0	0	2	2	0.492	628.34
298311	3000	1	2	2	1	2	2	1	0	1	0	0	2	2	0.483	627.84
299137	3000	1	2	2	0	2	2	1	0	2	0	0	2	2	0.474	627.34
297168	3000	1	1	2	2	2	2	1	0	0	0	0	2	2	0.473	627.24
297149	3000	1	2	2	1	2	2	1	0	0	0	0	2	2	0.468	626.34
298297	3000	1	2	2	0	2	2	1	0	1	0	0	2	2	0.459	625.84
297147	3000	1	1	2	1	2	2	1	0	0	0	0	2	2	0.450	625.24
297128	3000	1	2	2	0	2	2	1	0	0	0	0	2	2	0.444	624.34
297145	3000	1	0	2	1	2	2	1	0	0	0	0	2	2	0.431	624.14
226477	3000	1	2	2	0	2	2	1	0	1	0	0	2	1	0.429	623.84
179465	3000	1	2	2	2	2	2	0	0	2	0	0	1	1	0.426	623.34
297126	3000	1	1	2	0	2	2	1	0	0	0	0	2	2	0.426	623.24
175203	3000	2	2	2	2	2	2	0	0	0	0	0	1	1	0.420	622.84
225308	3000	1	2	2	0	2	2	1	0	0	0	0	2	1	0.414	622.34
177701	3000	1	2	2	2	2	2	0	0	1	0	0	1	1	0.412	621.84
179451	3000	1	2	2	1	2	2	0	0	2	0	0	1	1	0.403	621.34
175202	3000	1	2	2	2	2	2	0	0	0	0	0	1	1	0.397	620.34
177687	3000	1	2	2	1	2	2	0	0	1	0	0	1	1	0.388	619.84
179437	3000	1	2	2	0	2	2	0	0	2	0	0	1	1	0.379	619.34

175200	3000	1	1	2	2	2	2	0	0	0	0	0	1	1	0.379	619.24
175181	3000	1	2	2	1	2	2	0	0	0	0	0	1	1	0.373	618.34
177673	3000	1	2	2	0	2	2	0	0	1	0	0	1	1	0.364	617.84
175179	3000	1	1	2	1	2	2	0	0	0	0	0	1	1	0.355	617.24
175160	3000	1	2	2	0	2	2	0	0	0	0	0	1	1	0.350	616.34
175177	3000	1	0	2	1	2	2	0	0	0	0	0	1	1	0.337	616.14
53185	3000	1	2	2	0	2	2	0	0	1	0	0	1	0	0.334	615.84
175158	3000	1	1	2	0	2	2	0	0	0	0	0	1	1	0.331	615.24
177645	3000	1	2	2	1	0	2	0	0	1	0	0	1	1	0.320	615.20
50672	3000	1	2	2	0	2	2	0	0	0	0	0	1	0	0.319	614.34
175156	3000	1	0	2	0	2	2	0	0	0	0	0	1	1	0.313	614.14
175118	3000	1	2	2	1	0	2	0	0	0	0	0	1	1	0.306	613.70
50670	3000	1	1	2	0	2	2	0	0	0	0	0	1	0	0.301	613.24
177631	3000	1	2	2	0	0	2	0	0	1	0	0	1	1	0.296	613.20
175147	3000	0	2	0	0	2	2	0	0	0	0	0	1	1	0.292	612.84
398	3000	1	2	2	0	2	2	0	0	0	0	0	0	0	0.289	612.34
50668	3000	1	0	2	0	2	2	0	0	0	0	0	1	0	0.282	612.14
175097	3000	1	2	2	0	0	2	0	0	0	0	0	1	1	0.282	611.70
396	3000	1	1	2	0	2	2	0	0	0	0	0	0	0	0.270	611.24
53143	3000	1	2	2	0	0	2	0	0	1	0	0	1	0	0.266	611.20
175095	3000	1	1	2	0	0	2	0	0	0	0	0	1	1	0.263	610.60
394	3000	1	0	2	0	2	2	0	0	0	0	0	0	0	0.252	610.14
50609	3000	1	2	2	0	0	2	0	0	0	0	0	1	0	0.251	609.70
175093	3000	1	0	2	0	0	2	0	0	0	0	0	1	1	0.245	609.50
2869	3000	1	2	2	0	0	2	0	0	1	0	0	0	0	0.236	609.20
50607	3000	1	1	2	0	0	2	0	0	0	0	0	1	0	0.233	608.60
175084	3000	0	2	0	0	0	2	0	0	0	0	0	1	1	0.224	608.20
335	3000	1	2	2	0	0	2	0	0	0	0	0	0	0	0.221	607.70
50605	3000	1	0	2	0	0	2	0	0	0	0	0	1	0	0.215	607.50
175081	3000	0	1	0	0	0	2	0	0	0	0	0	1	1	0.206	607.10
333	3000	1	1	2	0	0	2	0	0	0	0	0	0	0	0.203	606.60
124810	3000	0	2	0	0	0	2	0	0	0	0	0	0	1	0.194	606.20
175078	3000	0	0	0	0	0	2	0	0	0	0	0	1	1	0.187	606.00
331	3000	1	0	2	0	0	2	0	0	0	0	0	0	0	0.184	605.50
50593	3000	0	1	0	0	0	2	0	0	0	0	0	1	0	0.175	605.10
325	3000	1	0	1	0	0	2	0	0	0	0	0	0	0	0.167	605.00
322	3000	0	2	0	0	0	2	0	0	0	0	0	0	0	0.163	604.20
50590	3000	0	0	0	0	0	2	0	0	0	0	0	1	0	0.157	604.00
319	3000	0	1	0	0	0	2	0	0	0	0	0	0	0	0.145	603.10
316	3000	0	0	0	0	0	2	0	0	0	0	0	0	0	0.126	602.00
4	3000	0	1	0	0	0	0	0	0	0	0	0	0	0	0.077	601.10
1	3000	0	0	0	0	0	0	0	0	0	0	0	0	0	0.058	600.00

B.2 MATLAB-Script:Tradespace Exploration

A DesignSpace.m

```
function [Design_Space_Fin] = Design_Space(Design_Space_inf)



tic
des_num = length(Design_Space_inf);
%[des_num, des_var] = size(Design_Space); %Store size of design space
feasible = zeros(des_num, 1);

fprintf('Size of total design space: %f\n', des_num);



%C_range, Testing, Monitoring, ScreeningCovid, PPE, CapacityRestrictions,...
    %DistanceGuidelines, Ventilation, MedicalPersonnel, TreatmentPlan, ClinicDesign, ...
    %Debarking, Isolation, Cohort

for i = 1:des_num
    if (Design_Space_inf(i,2) == 0) && (Design_Space_inf(i,4) == 1)...          % if there is no
    ↪ testing there cant be screening
        || (Design_Space_inf(i,2) == 0) && (Design_Space_inf(i,4) == 2)...       % if there is no
        ↪ testing there cant be screening
        || ((Design_Space_inf(i,3) == 0 && Design_Space_inf(i,10) == 1 )) ...   % if there is no
        ↪ monitoring there cant a good treatment plan
        || ((Design_Space_inf(i,3) == 0 && Design_Space_inf(i,10) == 2 )) ...   % if there is no
        ↪ monitoring there cant a good treatment plan
        || ((Design_Space_inf(i,5) == 0 && Design_Space_inf(i,9) == 2 )) ...    % if there is no ppe
        ↪ there cant a good medical staff
        || ((Design_Space_inf(i,9) == 0 && Design_Space_inf(i,11) == 2 )) ...   % if there is no
        ↪ medical staff there cant a good clinic
        || ((Design_Space_inf(i,11) == 0 && Design_Space_inf(i,9) == 2 )) ...   % if there is no
        ↪ clinic, the medical staff cant be perfect
        || ((Design_Space_inf(i,6) == 0 && Design_Space_inf(i,13) == 2 )) ...   % if there is no
        ↪ capacity restriction, there cant be a top notch isolation syste
        || ((Design_Space_inf(i,6) == 0 && Design_Space_inf(i,14) == 2 )) ...   % if there is no
        ↪ capacity restriction, there cant be a top notch cohort system
        || ((Design_Space_inf(i,6) == 0 && Design_Space_inf(i,7) == 1 )) ...    % if there is no
        ↪ capacity restriction, there cant be distance guidelines
        || ((Design_Space_inf(i,6) == 1 && Design_Space_inf(i,7) == 2 )) ...    % if there is no
        ↪ capacity restriction, there cant be distance guidelines
        || ((Design_Space_inf(i,10) == 0 && Design_Space_inf(i,12) == 2 )) ... % if there is no
        ↪ treatmentplan, there cant be fulls core for debarking
        || ((Design_Space_inf(i,8) == 0 && Design_Space_inf(i,13) == 2 )) ...   % if there is no
        ↪ ventilation, there cant be full score for isolation
        || ((Design_Space_inf(i,8) == 0 && Design_Space_inf(i,14) == 2 ))    % if there is no
        ↪ ventilation, there cant be fulls core for cohorts
```

```
    else
        %If constraints are satisfied
        feasible(i) = i;                %Save the location of that feasible vessle.
    end

end
feasible(find(feasible == 0)) = [];     %Locates all the zeroes and deletes it.
Design_Space_Fin = Design_Space_inf(feasible, :);   %Locates all the stored feasible vessles based
↪   on index,
                                                    %and puts it into the finished matrix.
                                                    ↪   %finished materix
toc;
%[des_num1, des_var1] = size(Design_Space_Fin);

%des_num1 = length(Design_Space_Fin);
[des_num1, des_var1] = size(Design_Space_Fin);
fprintf('Size of feasable design space: %f\n', des_num1);



end
```

B DesignSpaceGen.m

```
clear, clc, close all
set(gcf,'color','w');
%Generating the first designspace, This will include the infeasable designs

tic
%Capacity Passsengers
C_min = 3000; C_max = 3000;
C_range = linspace(C_min, C_max, 1);

Testing = [0,1,2];                      %Testing of crew and passengers
Monitoring = [0,1,2];                   %Monitoring of passengers and crew
ScreeningCovid = [0,1,2];               %Monitoring of passengers and crew
PPE = [0,1,2];                          %Monitoring of passengers and crew
CapacityRestrictions = [0,1,2];         %Monitoring of passengers and crew
DistanceGuidelines = [0,1,2];           %Monitoring of passengers and crew
Ventilation = [0,1,2];                  %Monitoring of passengers and crew
MedicalPersonnel = [0,1,2];             %Monitoring of passengers and crew
TreatmentPlan = [0,1,2];                %Monitoring of passengers and crew
ClinicDesign = [0,1,2];                 %Monitoring of passengers and crew
Debarking = [0,1,2];                    %Monitoring of passengers and crew
Isolation = [0,1,2];                    %Monitoring of passengers and crew
Cohort = [0,1,2];                       %Monitoring of passengers and crew


%Generating the design space (also infeasible):

DesVariables = {C_range, Testing, Monitoring, ScreeningCovid, PPE, CapacityRestrictions,...
    DistanceGuidelines, Ventilation, MedicalPersonnel, TreatmentPlan, ClinicDesign, ...
    Debarking, Isolation, Cohort};

%Enumerating all possible (including infeasible) designs:
[a b c d e f g h i j k l m n] = ndgrid(DesVariables{:});
Design_Space_inf = [a(:) b(:) c(:) d(:) ...
    e(:) f(:) g(:) h(:) i(:) j(:) k(:) l(:) m(:) n(:)];

%Here, we create arrays that refer to the specific variable value for each ship.

[des_num, des_var] = size(Design_Space_inf);            %Store size of design space
fprintf('Size of total design space: %f\n', des_num);   %Displayes size of the designspace, usefull
↪  for testing.
toc

tic
Design_Space_Fin = Design_Space(Design_Space_inf);
%Design_Space_Fin = Design_Space_inf;
%solving utility for each epoch.
utility = Utility_Function(Design_Space_Fin); %0, C_max
```

```
%Total utility, per epoch
tic
%Era 1
tot_utility(1,:) = totalUtility(utility,1,1,1,1,1,1,1,1,1,1,1,1,1);
tot_utility(2,:) = totalUtility(utility,1.5,1.5,1,1.5,2.0,2.0,1.5,1,1,1,1,1.5,1.5); %
tot_utility(3,:) = totalUtility(utility,1.5,1,1,2.0,2.0,2.0,2.0,1.5,1,1.5,1,1.5,1.5); %

%Era 2
tot_utility(4,:) = totalUtility(utility,1,1,1,1,1,1,1,1,1,1,1,1,1);
tot_utility(5,:) = totalUtility(utility,1.5,1,1,1,1.5,1.5,1.5,1.5,1.5,1.5,1,1,1);
tot_utility(6,:) = totalUtility(utility,1.5,1,1,1.5,1.5,1.5,2,2,2,2,1,1.5,1.5);

%Era 3
tot_utility(7,:) = totalUtility(utility,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5);
tot_utility(8,:) = totalUtility(utility,2,1.5,1.5,2,2,2,2,2,2,2,1.5,2,2);
tot_utility(9,:) = totalUtility(utility,1.5,1,1,2,2,2,2,2,1.5,2,2,2,2);

%Normalizing the utility from 0 - 1
range = max(tot_utility(:)) - min(tot_utility(:));
tot_utility_norm = (tot_utility - min(tot_utility(:))) / range;

avg_utility = mean(tot_utility_norm);

toc

%Capex is static for all epochs and eras
capex = capexfunc(Design_Space_Fin);
toc

%utility over all eras
p = Pareto(tot_utility_norm,capex);
p_avg = Pareto(avg_utility,capex);

%for i = 1:length(p_avg)
%Tabel(i,:) = [p_avg,Design_Space_Fin(p_avg(i),:)];
%end

color = [1, 0.7804, 0.4941];

  for i = 1:9
      subplot(3,3,i)
      s = p(i,:);
      s = s(s~=0);
      txt = {'Epoch ',i};
      title(txt);
      %scatter(capex,tot_utility_norm(i,:),5,color,'*');
      hold on
      plot(capex(s),tot_utility_norm(i,s),'k','LineWidth',2);
```

```
    ylim([0,1])
    xlabel('Expenses [USD]');
    ylabel('Utility');
end

figure
%colorLine = ['blue','#D95319','yellow','blue','green','cyan','red','magenta','black'];
cmap = colormap(parula(9));
title('Pareto front for every epoch');
for i = 1:9
    s = p(i,:);
    s = s(s~=0);
    %scatter(capex,tot_utility_norm(i,:),5,color,'*');
    hold on
    plot(capex(s),tot_utility_norm(i,s),'LineWidth',2,'Color',cmap(i,:));
    ylim([0,1])
    xlabel('Expenses [USD]');
    ylabel('Utility');
    legend('Epoch 1','Epoch 2','Epoch 3','Epoch 4','Epoch 5','Epoch 6','Epoch 7','Epoch 8','Epoch
    ↪  9')
end




paretoFront = Design_Space_Fin(p_avg,:);
paretoFront(:,15) = avg_utility(p_avg);


%Calculating average utility for each era, based on probability for a
%epoch to happen
tot_utility_norm = 3*tot_utility_norm;
%Era 1
tot_utility_norm(1,:) = 0.5*tot_utility_norm(1,:);  %Calculating total utility for epoch 1, with 50%
↪  weight
tot_utility_norm(2,:) = 0.3*tot_utility_norm(2,:);  %Calculating total utility for epoch 2, with 30%
↪  weight
tot_utility_norm(3,:) = 0.2*tot_utility_norm(3,:);  %Calculating total utility for epoch 3, with 20%
↪  weight

%Era 2
tot_utility_norm(4,:) = 0.7*tot_utility_norm(4,:);  %Calculating total utility for epoch 4, with 70%
↪  weight
tot_utility_norm(5,:) = 0.2*tot_utility_norm(5,:);  %Calculating total utility for epoch 5, with 20%
↪  weight
tot_utility_norm(6,:) = 0.1*tot_utility_norm(6,:);  %Calculating total utility for epoch 6, with 10%
↪  weight

%Era 3
```

```
tot_utility_norm(7,:) = 0.3*tot_utility_norm(7,:);  %Calculating total utility for epoch 7, with 30%
↪  weight
tot_utility_norm(8,:) = 0.3*tot_utility_norm(8,:);  %Calculating total utility for epoch 8, with 30%
↪  weight
tot_utility_norm(9,:) = 0.4*tot_utility_norm(9,:);  %Calculating total utility for epoch 9, with 40%
↪  weight

%Plotting just the pareto front
set(gcf,'color','w');
figure
%scatter(capex,avg_utility,10,color,'*');
hold on
plot(capex(p_avg),avg_utility(p_avg),'k-x','LineWidth',1);
title('Weighted average Over all Era')
xlabel('Expenses [USD]');
ylabel('Utility');
ylim([0,1]);


%with every vessel
set(gcf,'color','w');
figure
scatter(capex,avg_utility,10,color,'*');
hold on
plot(capex(p_avg),avg_utility(p_avg),'k-x','LineWidth',1);
title('Weighted average Over all Era')
xlabel('Expenses [USD]');
ylabel('Utility');
ylim([0,1]);




%utility per era
era1_utility = mean(tot_utility_norm(1:3,:));
p_era1 = Pareto(era1_utility,capex);
era2_utility = mean(tot_utility_norm(4:6,:));
p_era2 = Pareto(era2_utility,capex);
era3_utility = mean(tot_utility_norm(7:9,:));
p_era3 = Pareto(era3_utility,capex);

figure
subplot(1,3,1)
scatter(capex,era1_utility,5,color,'*');

hold on
plot(capex(p_era1),era1_utility(p_era1),'k', 'LineWidth',2)
ylim([0 1])
```

```
xlabel('Expenses [USD]');
ylabel('Utility');
title('Era 1 - Covid-19 equivalence')
subplot(1,3,2)
scatter(capex,era2_utility,5,color,'*');
hold on
plot(capex(p_era2),era2_utility(p_era2), 'k','LineWidth',2)
ylim([0 1])
xlabel('Expenses [USD]');
ylabel('Utility');
title('Era 2 - Higher lethality, lower spread')
subplot(1,3,3)
scatter(capex,era3_utility,5,color,'*');
hold on
plot(capex(p_era3),era3_utility(p_era3),'k', 'LineWidth', 2)
ylim([0 1])
xlabel('Expenses [USD]');
ylabel('Utility');
title('Era 3 - Increased spread and lethality')
```

C CAPEXFunc.m

```
function [capex] = capexfunc(space)
    capex = zeros(1,length(space));
    for i = 1:length(space)
%         C_range, Testing, Monitoring, ScreeningCovid, PPE, CapacityRestrictions,...
%     DistanceGuidelines, Ventilation, MedicalPersonnel, TreatmentPlan, ClinicDesign, ...
%     Debarking, Isolation, cohort

        capex(i) = capex(i) + 300000000;                              %Starting cost
        capex(i) = capex(i) + space(i,1)*100000;                      %Aditional costs
        ↪  contributed to higher capacity
        capex(i) = capex(i) + space(i,2)*2500000;                     %Testing
        capex(i) = capex(i) + space(i,3)*1100000;                     %Monitoring
        capex(i) = capex(i) + space(i,4)*500000;                      %ScreeningCovid
        capex(i) = capex(i) + space(i,5)*2000000;                     %PPE
        capex(i) = capex(i) + (space(i,1)*(space(i,6)*773.3));    %CapacityRestrictions
        capex(i) = capex(i) + space(i,7)*1000000;                    %DistanceGuidelines
        ↪  Deckareal/passasjerer
        capex(i) = capex(i) + space(i,8)*4000000;                    %Ventilation
        capex(i) = capex(i) + space(i,9)*3000000;                    %MedicalPersonnel
        capex(i) = capex(i) + space(i,10)*1500000;                   %TreatmentPlan
        capex(i) = capex(i) + space(i,11)*5000000;                   %ClinicDesign
        capex(i) = capex(i) + space(i,12)*4000000;                   %Debarking
        capex(i) = capex(i) + space(i,13)*2000000;                   %Isolation
        capex(i) = capex(i) + space(i,14)*2000000;                   %Cohort


%         Testing = [0,1,2];                      %Testing of crew and passengers
%         Monitoring = [0,1,2];                   %Monitoring of passengers and crew
%         ScreeningCovid = [0,1,2];               %Monitoring of passengers and crew
%         PPE = [0,1,2];                          %Monitoring of passengers and crew
%         CapacityRestrictions = [0,1,2];         %Monitoring of passengers and crew
%         DistanceGuidelines = [0,1,2];           %Monitoring of passengers and crew
%         Ventilation = [0,1,2];                  %Monitoring of passengers and crew
%         MedicalPersonnel = [0,1,2];             %Monitoring of passengers and crew
%         TreatmentPlan= [0,1,2];                 %Monitoring of passengers and crew
%         ClinicDesign = [0,1,2];                 %Monitoring of passengers and crew
%         Debarking = [0,1,2];                    %Monitoring of passengers and crew
%         Isolation = [0,1,2];                    %Monitoring of passengers and crew
%         Cohort = [0,1,2];
%



    end
```

D Pareto.m

```
function [Pareto_Set] = Pareto(Utility,CAPEX_Total)
%This function identifies the Pareto frontier for the tradespaces of each
%epoch.
%Initializing:

tic
[num_epochs,num_designs] = size(Utility);
%For each epoch:
for e = 1:num_epochs
 %Condition for while loop:
 i = 0;
 %The first element in the Pareto array:
 k = 1;
 while i == 0
 %Finding the maximum utility element.
 [a,b] = max(Utility(e,:));
 %Adding point design to Pareto array.
 Pareto_Set(e,k) = b;
 %Setting current max utility to -1 to avoid rechecking.
 Utility(e,b) = -1;
 %Setting utility of all elements with a larger cost to -1.
 for j = 1:num_designs
 if CAPEX_Total(j) >= CAPEX_Total(b)
 Utility(e,j) = -1;
 end
 end
 %Exiting while loop when the lowest cost is reached or the max
 %utility is 0.
 if (CAPEX_Total(b) == min(CAPEX_Total(:))) || (max(Utility(e,:)) == 0)
 i = 1;
 end
 %For finding next element in Pareto array.
 k = k + 1;
 end
 toc

end
```

E TotalUtility.m

```
function res = totalUtility(utility, Test, Mon, Screen, Ppe, Capres, Dist, Vent, Med, Treat, Clinic,
↪  Debark, Isol, Cohort)
    %Input = the weighting of utilities

        tot_utility = Test * utility(:,1) + ...
        Mon * utility(:,2) + ...
        Screen * utility(:,3) + ...
        Ppe * utility(:,4) + ...
        Capres * utility(:,5) + ...
        Dist * utility(:,6) + ...
        Vent * utility(:,7) + ...
        Med * utility(:,8) + ...
        Treat * utility(:,9) + ...
        Clinic * utility(:,10)+...
        Debark * utility(:,11)+...
        Isol * utility(:,12)+...
        Cohort * utility(:,13);

    %Utileties:



    res = tot_utility;
end
```

F UtilityFunction.m

```
    function [Utility] = Utility_Function(space)


vessel = zeros(length(space), 14);
Utility = zeros(length(space), 13);     %

tic
for i = 1:length(space)


    %Capacity = space(i,1);
    Test     = space(i,2);
    Mon      = space(i,3);
    Screen   = space(i,4);
    Ppe      = space(i,5);
    Capres   = space(i,6);
    Dist     = space(i,7);
    Vent     =  space(i,8);
    Med      = space(i,9);
    Treat    = space(i,10);
    Clinic   = space(i,11);
    Debark   = space(i,12);
    Isol     = space(i,13);
    Cohort   = space(i,14);

    %utility

    Utility(i,1) = 0.2 + Test * 0.3 ;                    %
    Utility(i,2) = 0.2 + Mon * 0.3 ;                     %
    Utility(i,3) = 0.2 + Screen * 0.3 ;                  %
    Utility(i,4) = 0.2 + Ppe * 0.3 ;                     %
    Utility(i,5) = 0.2 + Capres * 0.4 ;                  %
    Utility(i,6) = 0.2 + Dist * 0.4 ;                    %
    Utility(i,7) = 0.2 + Vent * 0.4 ;                    %
    Utility(i,8) = 0.2 + Med * 0.3 ;                     %
    Utility(i,9) = 0.2 + Treat * 0.2 ;                   %
    Utility(i,10) = 0.2 + Clinic * 0.4 ;                 %
    Utility(i,11) = 0.2 + Debark * 0.3 ;                 %
    Utility(i,12) = 0.2 + Isol * 0.4 ;                   %
    Utility(i,13) = 0.2 + Cohort * 0.4 ;                 %




end
toc
```

```
end
```

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