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Evaluation of new design concept of submerged fish farm

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Preface

This master thesis is a part of the Master of Science degree in Marine technology with specialization in Marine System Design at the Norwegian University of Science and Technology. The thesis has been written during spring 2019, and the workload is equivalent to 30 ETCS. The thesis focus on the concept of an air-dome supplying oxygen to a submerged fish farm within the Norwegian aquaculture.

I would like to thank my Supervisor, Pål Lader, for support and guidance during the semester. I would also like to thank my Co-Supervisor Sigurd Solheim Pettersen for continuous support and for providing relevant information and valuable guidance along the way.

Ingrid Elisabeth Glestad,
Trondheim, June 12, 2019

Abstract

The aquaculture is experiencing a rapid development towards developing new designs of fish farms that can withstand a harsher climate in more exposed waters. The new designs for the aquaculture aim to solve the problems concerning the sea lice as well as several of the environmental challenges that the aquaculture has faced in recent years while still be profitable and satisfying the fish welfare standards. This thesis can be seen as a first step in conducting a concept study on the new concept of an air-dome supplying oxygen to a submerged fish farm. The air-dome investigated is still under development by the respective company which has made available information limited.

The main focus of this thesis was to improve the knowledge and understanding of the air-dome in a submerged condition. This leads to the first research question: *What is the connection between a force from current and the tilt-angle of the air-dome?*. Secondly, the focus was on finding a good design for the air-dome which lead to the second research question: *Which methodologies exist for decision making that can provide decision support for a new concept as the air-dome for a submerged fish farm?*

To answer the two research questions, a thorough description of the air-dome and the submerged system as well as a comprehensive investigation concerning the hydrodynamic aspect of the air-dome, has been conducted. In addition, the design theory concerning multi-objective decision making and tradespace exploration gave the foundation of the case study, where a functional breakdown of the system was developed. The aim of the case study was to achieve an understanding of what a good design is, for an air-dome in a submerged condition, by using the design theory and understanding the hydrodynamic aspect of the air-dome.

Due to limited information and the early phase of development of designing the air-dome system, the results are based on some assumptions and may differ somewhat from the real air-dome developed. This thesis concluded on the first research question that the height and the draft play an important role for the tilt-angle, given an incoming force. The first research question relieved interesting information on how the different parameters of the air-dome system are connected together. And that changing one of these parameters has a severe effect on the tilt-angle of the air-dome.

The choice of design method - tradespace exploration, however, proved to not be a good choice for this new concept concerning the air-dome. The main reason for this is the utility function of the tradespace analysis. The utility function reduces the insights of the

analysis due to the weighting of attributes that are done beforehand. This means that the decision maker sits with all the influence over which design will end up on the pareto front before the actual analysis is performed. For further work, it would have been desirable to explore new design methods to find the most beneficial design of the air-dome as well as run experiments which can indicate how the air-dome actually behaves in a submerged state when it is affected by forces from the current.

Sammendrag

Akvakulturen opplever en rask utvikling mot nye design av oppdrettsanlegg som kan plasseres i mer eksponerte farvann og tåle et tøffere klima. De nye designene for akvakulturen tar sikte på å løse problemene rundt lakselusen, samt flere av de miljømessige utfordringene som akvakultur i fjordene har møtt i løpet av de siste årene samtidig som de skal være lønnsomme og ivareta fiskens velfersstandard. Denne oppgaven kan anses som et første steg på en konsept-utredelse av et helt nytt konsept av en luftkuppel som skal forsyne et nedsenket anlegg med oksygen. Luftkuppelen som har blitt undersøkt og analysert er fremdeles under utvikling av det respektive selskapet, som har gjort at tilgjengelig informasjon har vært begrenset på grunn av konkurransemessige årsaker.

Målet med denne masteroppgaven var å forbedre kunnskapen og forståelsen av luftkuppelen i en nedsenket tilstand. Dette førte til det første forskningsspørsmålet: *"Hva er forbindelsen mellom en innkommende kraft fra strømningen og tilt-vinkelen til luftkuppelen ?"*. For det andre, for å finne et godt design for luftkuppelen prøver denne oppgaven å svare på følgende forskningsspørsmål: *"Hvilke metoder eksisterer for beslutningstaking som kan gi beslutningsstøtte til et nytt konsept som luftkuppelen til et nedsenket oppdrettsanlegg?"*

For å besvare de to forskningsspørsmålene ble det gjennomført en grundig beskrivelse av luftkuppelen og det nedsenkede systemet, i tillegg til en omfattende undersøkelse vedrørende det hydrodynamisk aspekt av luftkuppelen, for å forstå oppførelsen av kuppelen i en nedsenket tilstand. Bruk av designteorien om multi-objektiv beslutningstaking og tradespace exploration ga grunnlaget for case-studiet, hvor en funksjonell nedbrytning av systemet ble etablert. Målet med case-studiet var å oppnå en forståelse av hva et godt design er for en luftkuppel i en nedsenket tilstand ved å bruke design teori og forstå det hydrodynamiske aspektet av luftkuppelen.

På grunn av begrenset informasjon og den tidlige utviklingsfasen av luftkuppelen er resultatene basert på en del antagelser og kan avvike noe fra den virkelige luftkuppelen som er utviklet. Denne oppgaven konkluderte på det første forskningsspørsmålet med at høyden og dypgangen av luftkuppelen spiller en viktig rolle for tilt-vinkelen gitt av en innkommende kraft. Det første forskningsspørsmålet ga i tillegg en del interessante opplysninger om hvordan de forskjellige parameterne til luftkuppelsystemet er koblet sammen, og hvordan endringer av disse parameterne har stor effekt på tilt-vinkelen til luftkuppelen.

Valget av design metode - tradespace exploration, viste seg å ikke være et ideelt valg av metode for å designe luftkuppelen. Hovedgrunnen til dette er utility funksjonen som inngår i tradespace analysen. Den gjør at en del av innsikten i analysen blir borte på grunn av vektingen av attributter som blir gjort før selve analysen kjøres. Det gjør at beslutningstakeren sitter med all makt over hvilke design som skal score høyest og havne på pareto fronten før selve analysen er blitt gjort. For videre arbeid ville det vært ønskelig å utforske nye design metoder for å finne frem til det mest gunstig designet for luftkuppelen i tillegg til å kjøre eksperiment som kan viste til hvordan luftkuppelen faktisk oppfører seg i en nedsenket tilstand når den blir påvirket av krefter fra strømning.

Nomenclature

Abbreviations

HDPE High-density polyethylene

PP Polypropylene

Greek Letters

α Tilt-angle of air-dome

$\beta_{1,2}$ Angle of net roof angle in tilted state

$\gamma_{1,2}$ Angle between air-dome and net roof mooring line in tilted condition

μ Net roof rope angle

ρ_f Density of fresh water

ρ_s Density of sea water

Roman Letters

a Length of net roof mooring line

B Boyancy force

C_{cage} Circumference cage

C_D Drag coefficient

D_{cage} Diameter cage

D_{FS} Diameter of free surface

F_D Drag force

F_L Lift force

F_N Normal force

H_1 Depth net wall

H_2 Depth coned wall

h_{air} Height of air pocket

L Diameter of floating collar

m_{max} Max dry weight of air-dome

R Radius of air-dome

Re Reynolds number

$S_{1,2}$ Force in mooring line between air-dome and floating collar in tilted state

S_n Netting solidity

U_c Current velocity

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Chapter 1

Introduction

1.1 Background

The world population is increasing every year and the proportion of the population of the world that is dependent on marine resources is constantly increasing. Products from fish cover at least 20% of the animal protein content of 1.5 billion people and are an important support for the livelihood of about 540 million people in the world [13]. In 2017, Norway exported up to 1 million tons of salmon and a growth to 5 million tons is assumed by 2050. If the goal from the Norwegian government of producing 5 million tonnes by 2050 is to be a success the aquaculture needs to expand, and the environmental factors must be taken care of. Since 2012 no new commercial licenses have been issued in Norway, because of the environmental impacts that have been discovered from the fish farming so far [14]. The most important environmental challenge for Norwegian aquaculture is the salmon lice. This parasite costs the aquaculture several million NOK every year, here both treatments for the lice and the preventive measures are taken into account. The salmon lice have a large impact on the behavior of the salmon, both directly and from the treatments that the salmon need to go through to prevent the lice to infect [15].

Restrictions on the area inshore and the lice problem force the aquaculture to be moved to more offshore locations. The impact of the aquaculture industry on the environment is a growing concern and has become important as new designs for the aquaculture are being developed. In order to create new and innovative solutions for aquaculture, the Norwegian government opened in 2015 for the opportunity to apply for development licenses. This process was completed in 2017 when the respective projects were then selected [16]. The goal behind the development licenses was to facilitate new technology to solve the area and environmental problems for the aquaculture [17]. By focusing on new solutions that can be used offshore, the investment can pay off by reducing mortality on the fish, increasing growth rate, reducing disease and spreading disease, reducing pollution and befouling on the cages. The conditions offshore will present new challenges for the design and the fish farms must withstand harder weather conditions. New designs for offshore conditions are still in the start-up phase, and it is a race to find the cheapest and best design that can withstand the new challenges [2].

1.2 Research Question

The goal of this master thesis is to investigate the new concept concerning an air-dome to supply oxygen to the fish in a submerged open fish cage. The upbringing of this new concept is to solve the sea lice problem of Norwegian aquaculture, and still be profitable. The basis of the problem is the inspection of the air-dome and the system around this concept. For the air-dome to be operational it needs to be stable and to not lose buoyancy in a submerged state. This leads to the first research question:

What is the connection between a force from current and the tilt-angle of the air-dome?

The idea of a submerged fish farm has existed for some time, but this solution has not been used in the Norwegian Aquaculture so far. One reason for this may be that the knowledge to design the type of geometry for the air-dome in a submerged state is limited within the Norwegian aquaculture. Due to the problems with limited space and sea lice, it is important that new methods are created to develop fish farm systems, as well as analyze how existing knowledge can be included in the development of future submerged fish farms. This leads to the second research question:

Which methodologies exist for decision making that can provide decision support for a new concept as the air-dome of a submerged fish farm?

1.3 Simplifications and Assumptions

The main limitation of this thesis is that the air-dome investigated is still in an early stage of development and that the information of the research so far is classified information. This limits the knowledge about the air-dome in a submerged state. In the absence of tested and validated data from the air-dome, some simplifications have been made. The assumptions regarding the air-dome have been made based on the information given from AKVA Group during the project thesis, autumn 2018, together with the current knowledge about the aquaculture in Norway.

Assumptions regarding the hydrodynamic aspect of the air-dome:

– The effect of waves on the water surface will not be taken into consideration in this thesis. Waves will induce water flow, which might affect the cage through fluctuating movements from the buoys floating on the water surface which can provide forces to both the cage and the air-dome in a submerged condition. However, as a simplification, this will not be considered further in this thesis.

– The current is assumed uniform. Varying the current for different depths and widths will probably influence the fish farm different than a uniform flow. However, through all analysis in this thesis, the current will be assumed uniform.

1.4 Structure of the Report

The structure of this thesis is laid out in the following way:

- **Literature review**
  Chapter 2 presents a literature review on the theory for system design methods and presents work done by the use of design methods on design tasks in the aquaculture. In addition, presenting a few examples of new designs for the exposed aquaculture.

- **Description of a submerged fish farm & the air-dome**
  Chapter 3 presents a thorough description of a submerged fish farm and all the components that are important for this concept. In addition, the air-dome is presented with all the important parameters and possible geometries that are of interest.

- **Economic aspect of the air-dome**
  Chapter 4 presents the economy for a submerged fish farm, both the expenditure and revenue. As well as how all the components that might impact the economic feasibility are connected together. The main focus for this chapter concerns the economy around the air-dome and delousing expenditure.

- **Case study**
  Chapter 5 presents a generic case study addressing the air-dome of the submerged fish farm using tradespace exploration and investigate the hydrodynamic restrictions for the system.

- **Results & Discussion**
  Chapter 6 and 7provides the results from the case study and discuss the value of these results in addition to sources of errors.

- **Conclusion & Further Work**
  Chapter 8 provides the conclusion of the thesis and provides ideas for further work.

Chapter 2

Literature Review on System Design Methods

In this thesis, emphasis will be placed on the design of aquaculture facilities and how different design methods can be used to solve the upcoming challenges that will encounter this industry. The following chapter will give a brief review of the design process with the most important aspects. In addition, design theory used in the Norwegian aquaculture and some examples of new designs will be presented.

2.1 Design Process

The design process is "a systematic problem solving strategy, with criteria and constraints, used to develop many possible solutions to solve a problem or satisfy human needs and wants and to narrow down the possible solutions" [18].

A thorough description of the design process is presented by Shainee, together with Ellingsen, Leira and Fredheim,[2]. In the description, they go through the importance of defining the problem at an early stage and identifying the stakeholders needs and finding the functional requirements that need to be satisfied by the final design. N. P. Suh, [1], highlights how the design problem should be as abstract as possible in the initial phase. The more abstract, the greater is the freedom for the designer to develop an innovative solution. Suh summarizes the design process in three stages, illustrated in Figure 2.1.1.

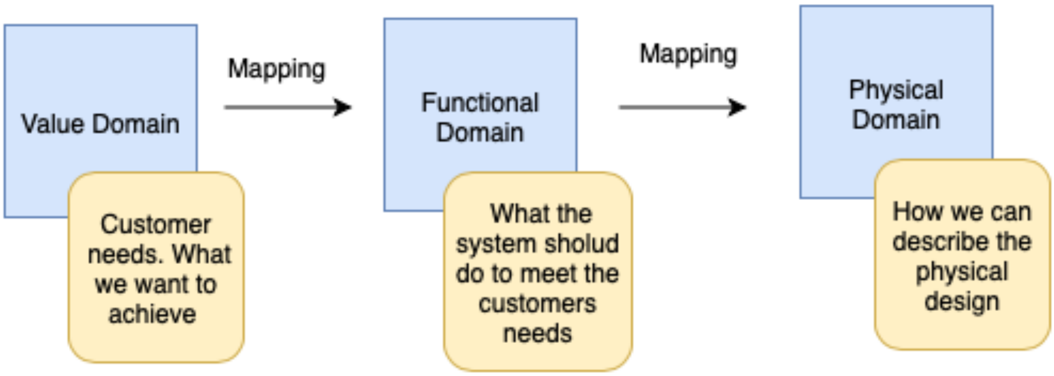


Figure 2.1.1: Illustration of the design process. The value domain represents the stakeholder or customer needs, the functional domain consists of the functional requirements and the physical domain are design parameters and the actual design [1].

Whereas the objective of the design is presented in the functional domain, while the physical solution of the design is presented in the physical domain. The objective of the design is built up by the functional requirements and the physical solution is built up by design parameters, set to satisfied the functional requirements. Suh points out that the design process is a continuous mapping between these two domains, where the questions that should be asked for the design are *"What we want to achieve"* and *"How we want to achieve it"*[1]. Ross, [19], has the same perception as Suh on how to divide the design process into the three domains. In addition, he described the mapping between the functional domain to the physical domain as analogous with the form-to-function mapping. The value domain is mainly introduced to make sure that the value of the design cannot only be described by a set of capabilities.

2.2 Design Theory in Norwegian Aquaculture

Norway is the worlds largest exporter of Atlantic salmon, in addition to being the leading country when it comes to new technology and competence within the aquaculture industry. The Norwegian aquaculture started in the fjords along the coastline with sheltered waters. However, over the years the industry has been pushed further out to more exposed sites due to lack of area and the increasing problem of sea lice. By pushing the aquaculture to more exposed areas the industry is dependent on finding new innovative solutions to encounter the challenges that meet the industry when moving the industry offshore.

Shainee, together with Haskins, Ellingsen, and Leira, [20], inspected how system engineering principles can be used when designing offshore fish farm systems. The design process for designing a fish cage, according to shainee, is summarized in Figure 2.2.1. For the aquaculture, the primary stakeholders would be the fish and the fish farmers, the environment and the consumers.

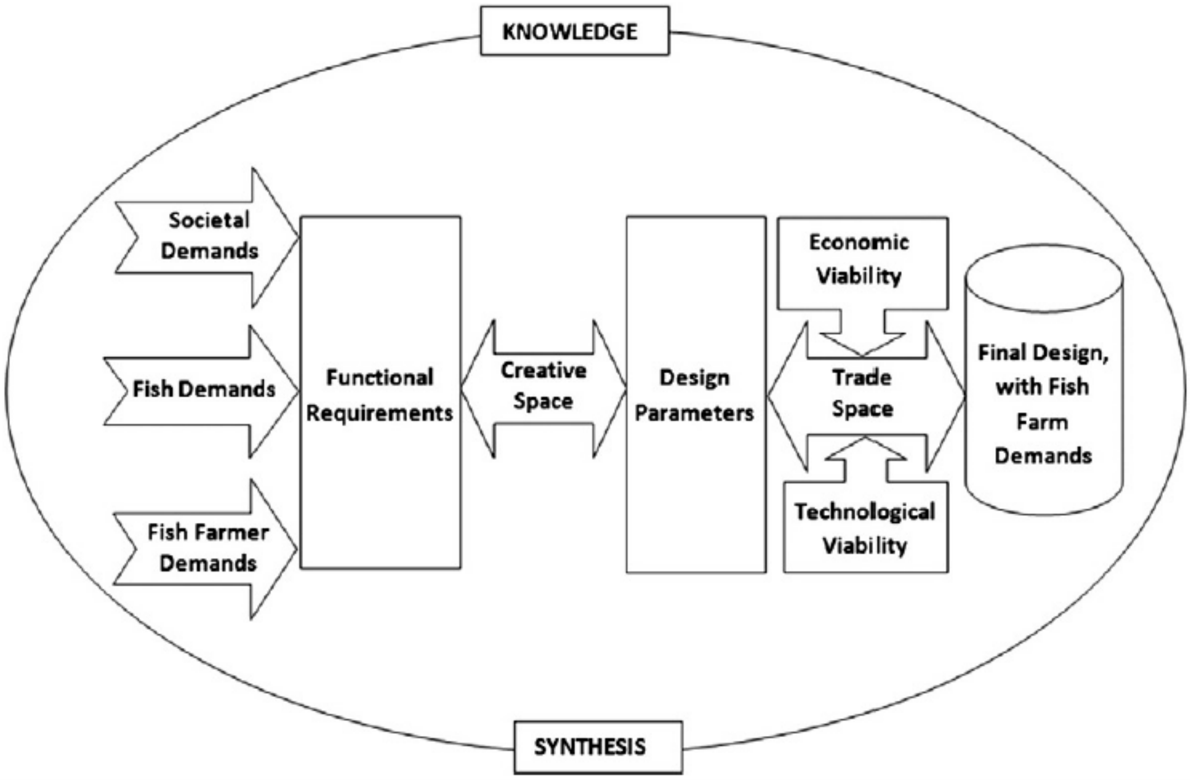


Figure 2.2.1: Illustration of the design process when designing a fish cage [2]

Shainee, [2] [20], summarizes the main functional requirements from the primary stakeholders as:

- Fish farmer demands - The fish farm should be sustainable, both economic and technical. There should be safe and easy access to the cage for management activities such as feeding and maintenance.
- Fish demands - Good water quality, small waves, and currents in the water. And an optimal density of fish in the cage.
- Environmental demands - Minimal impact on the surrounding environment and minimal environmental impact in the plant from the surrounding factors (e.g. factories)
- Consumer demands - High-quality meat. Not too high a price, and it is bred without too much impact on the environment - a green product.

Shainee, incorporation with Ellingsen, Leira and Fredheim [20] points out the importance of the environmental factors as well as the biological factors that need to be taken into consideration when designing an offshore fish cage. Not only are the cage to withstand harsher conditions, but the fish welfare needs to be maintained and the environmental impact must be held to a minimum. Shainee, together with Ellingsen, Leira and Fredheim,[2], discuss how different methods can be used to approach the design task of designing an offshore fish cage system. System engineering is a well known methodical approach of design, where the result can be recognized among fellow designers. Keeping in mind that there seldom is only one solution to a design problem, system engineering takes in different aspects regarding the environment, technical and budget constraints. This makes system engineering a good recommendation when designing a new offshore fish cage system.

2.3 Multi-objective Decision Making in Design

Design is a time consuming and expensive process. It is estimated that 60-80% of all project costs come from the concepts design phase. Accordingly, it is important that the design process is to be as efficient and precise as possible. Engineering design is a systematic process, which carries out a concept development, an analysis and ultimately provides a prototype design. When a new product is designed from scratch, there can be unlimited possibilities of design alternatives and how to interpret the solution of a problem. In order to limit the number of design alternatives, multi-objective decision making is a good approach. This methodology consists of several criteria and enables conceptual alternatives to be optimized. [21]. Shapira points out the importance of the decision makers role in the design process. The decision maker needs to choose between several of the design alternatives and weight the positive and negative aspects of these alternatives. In order to achieve an effective decision-making process, the decision maker must be able to predict which of the design alternatives that "best" will meet future expectations. [22].

Gaspar, [23], describes how the aim in a multi-objective decision-making process is to first be able to establish a set of key constraints for the design and determine who the main stakeholders are, as well as what gives the most value for the design. The use of the word "value" for a design has increased in recent years. The focus has shifted over to understanding what gives value for the design and what gives value for the stakeholders involved. Success in engineering design has previously been associated with requirements and/or cost-related properties, which meant that the systems often came short of delivering their full potential because it was either too expensive or that they performed worse than expected. [24] [25]. O.C. Brown and Eremenko discuss how the focus of system engineering has changed in recent years, the focus is now on achieving high system capacity through harsh system requirements and minimizing cost. O.C Brown and Eremenko believe that the challenges of the complex system come from a demand-focused mindset, also referred to as the "death spiral". In order to move away from this "death spiral", the decision-maker should have a value-focused mindset instead. A value-focused mindset in design allows for evaluation of both system design development and cost advantages in a more integrated manner, whereby application of strict capacity constraints at an early stage will be avoided [26] [10]. The meaning of the word "value" has no consensual definition. Value creation in design can, therefore, be difficult to understand and formulate, especially when several stakeholders with different opinions are involved. An attribute that is considered to give great value to one stakeholder can seem irrelevant to another. Value creation of the system to be designed therefore requires a good understanding of all the main stakeholders needs and expectations [11]. This value creation of a system can be achieved through various methods that allow the decision maker to measure utility since the value is often reflected through utility measures. [25]. A. M. Ross and O'Neill, [10], discuss that there is no method that completely captures the whole definition of value. To capture the expected understanding of the value the decision maker needs to adjust and choose the right methods depending on the stakeholders for the respective project.

2.3.1 Methodologies for Multi-objective Decision Making

Multi-objective decision making takes into account decision issues given by a number of criteria, from which the decision maker must choose the option that best meets the requirements set for the problem [27]. Multi-objective decision making is considered a subset of operations research, where openness research is a discipline that addresses the use of advanced analytically methods to help decision makers make better decisions [27] [28]. Multi-objective decision making is a tool to help the decision maker to rank and prioritize different design alternatives based on a set of criteria and attributes. Instead of searching for the "best" or most correct solution, the multi-objective decision method is based on describing how well a system meets a set of needs by translating criteria or attributes into utility measures [29]. The multi-objective decision-making methods that will be discussed further in this chapter are illustrated in Figure 2.3.1.

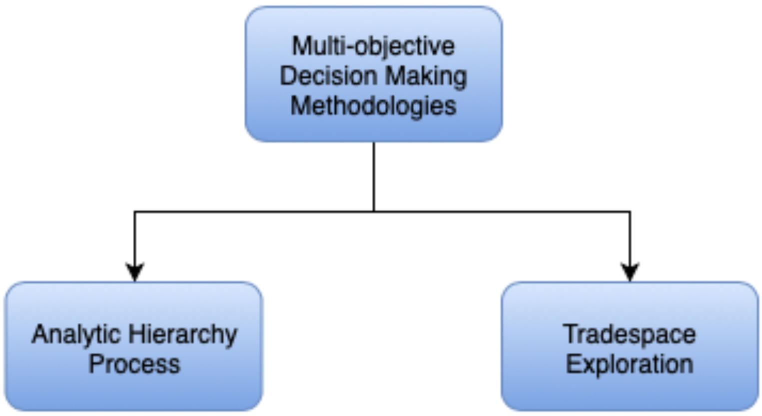


Figure 2.3.1: Exampels of multi-objective decision making methods

Before discussing some of the methodologies a few terms should be defined for further use. The most relevant system engineering terms used in this chapter are listed in Table 2.3.1 below.

Table 2.3.1: Definition of terms in multi-attribute tradespace exploration [5][10][11]

Term	Definition
Attribute	A metric which reflects how well a decision maker-defined objective is met.
Design variable	A set of variables that describe the functional requirements set to describe the aspect of the design.
Tradespace	A space spanning over the complete set of design parameters, representing possible design options
Utility	A dimensionless parameter that reflects the value of an attribute
Value	A measure of how "good" something is perceived by the stakeholders.

2.3.2 Analytical Hierarchy Process, AHP

The Analytical Hierarchy Process, AHP, is an effective tool for managing complex decision-making issues and can help decision-makers set priorities and determine the best decision. By reducing complex decisions to pairwise comparison, then synthesizing the results. AHP is a tool that helps capture both the subjective and objective aspects of a decision. [30].

The AHP process begins with a description of the problem, which then is divided into a hierarchy of sub-problems that can be investigated independently [3]. Figure 2.3.2 illustrates an example of a problem breakdown of how to choose the best house to buy, using an AHP hierarchy.

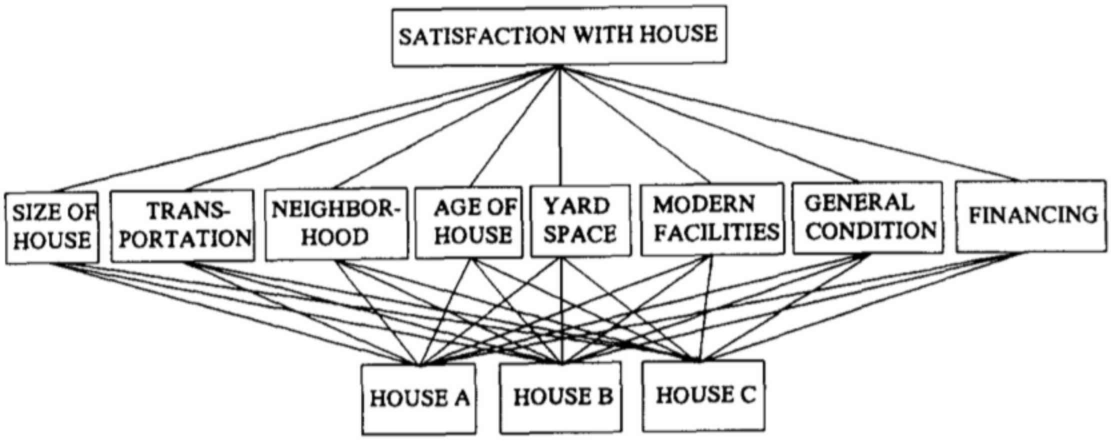


Figure 2.3.2: Problem breakdown of chosing the best house, using the AHP method [3]

As can be seen in the Figure above the top box illustrates the overall objective of the decision problem, and the second level presents the criteria that are important to the problem analyzed. A weight is generated for each criterion on the second level, according to the decision-makers pair-wise comparison of the criteria. The more important the criterion is, the higher the weighting it is given [3]. Then, for a fixed criterion, AHP gives a score of each option according to the decision maker's comparisons of the options based on that criterion. Finally, the AHP combines the weights of the criteria and the score of the alternatives and thereby determines the global score for each option as well as a ranking. The global score that comes out is a weighted sum of the points achieved relative to the criteria. [30].

The AHP method can become very complex when the criteria and alternatives become numerous. This is because the decision maker has to compare all the criteria in pairs based on their own knowledge and experience. This makes the AHP method potentially very time-consuming [10]. Using the AHP method to evaluate complex systems can, therefore, become difficult, as it results in many levels within the AHP hierarchy that must be evaluated. AHP is a very good tool when the criteria to be compared are kept to a minimum.

2.3.3 Tradespace Exploration

Tradespace exploration is a decision analysis that compares a large number of different system designs. The analysis is an approach that enables the decision maker to evaluate the performance of multiple designs at the same time. Ross and Hastings, [4], present a process that uncovers cost effects between a number of system designs rather than focusing on finding the optimal or best solution. Ross and Hasting's tradespace analysis is illustrated in Figure 2.3.3. The Tradespace analysis begins by identifying the needs of the stakeholders. Once these needs are met, attribute levels, design variables, and stakeholder preferences will be chosen to evaluate and compare possible solutions using utility and cost methods. Tradespace exploration also includes a mapping between different design parameters that represent the physical design and how well they perform, where attributes represent the value that is perceived as the decision maker.

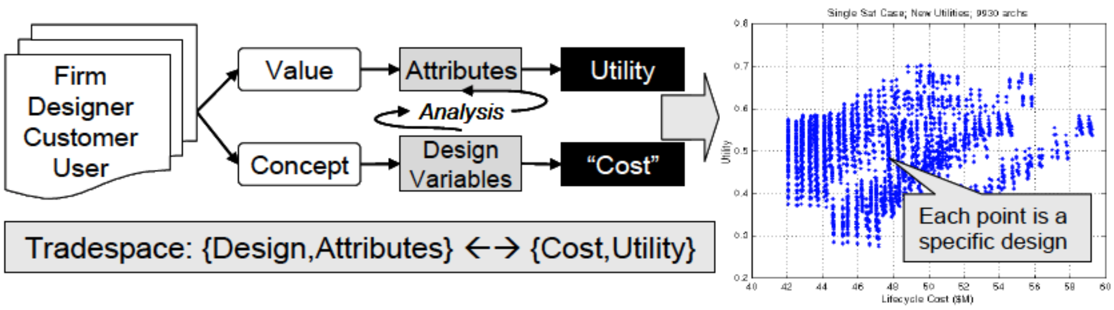


Figure 2.3.3: Illustration of a tradespace analysis which includes the design parameters and the stakeholder parameters evaluated in terms of utility and cost. [4]

Every single point in the tradespace plot represents a possible design option, see the blue dots in Figure 2.3.3. The points that are highest along the entire plot form the Pareto front. These designs are characterized by having the highest utility for a given cost. When the decision maker chooses between these designs, a cost-utility trade-off is made, which means that the decision maker must consider how much extra utility is worth in terms of how much it will cost. The design options that are not on the Parteo front are called dominated designs.

The preferences of the stakeholders may change due to future uncertainties. An example of such a change and how a tradespace analysis can capture this change is illustrated in Figure 2.3.4. The purple, green and red dot represents three different design solutions. As can be seen, the three design solutions do not change in the same direction or in the same size, although the change in preference is the same. This shows that some design solutions are more sensitive than others for a change. [5]. One way to capture these changes is to perform an Epoch-Era analysis, however, this will not be done in this thesis.

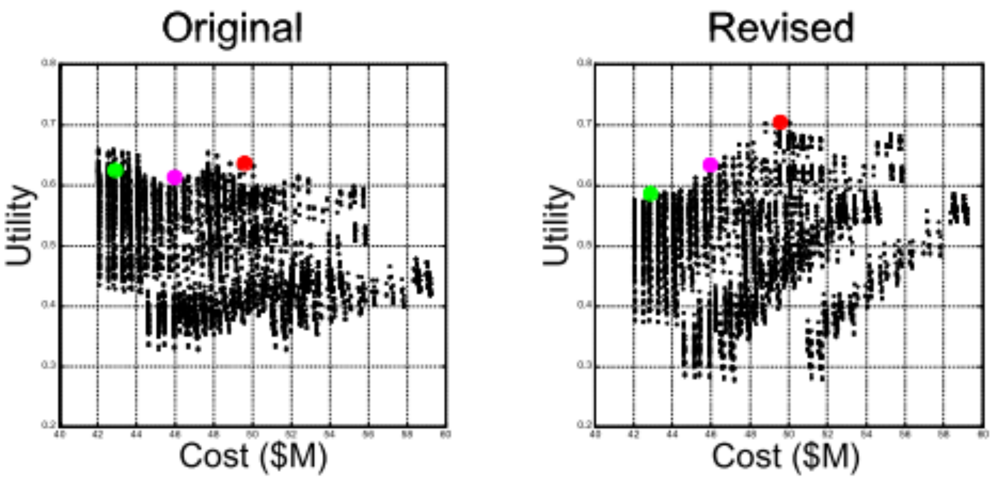


Figure 2.3.4: Illustration how the tradespace results may change when changing the preferences of the stakeholders.[5]

Each design is considered a potential start and end change state, this framework proposes a mechanism for assessing the ability to change. Change specification requires a start and end state and a transition path between these states, a traditional tradespace can become an action network, illustrated in Figure 2.3.5. An action network consists of nodes and arcs. Each node represents a state and each arc represents a path connecting specific nodes. The transition paths represent potential changes that are available to the particular design.

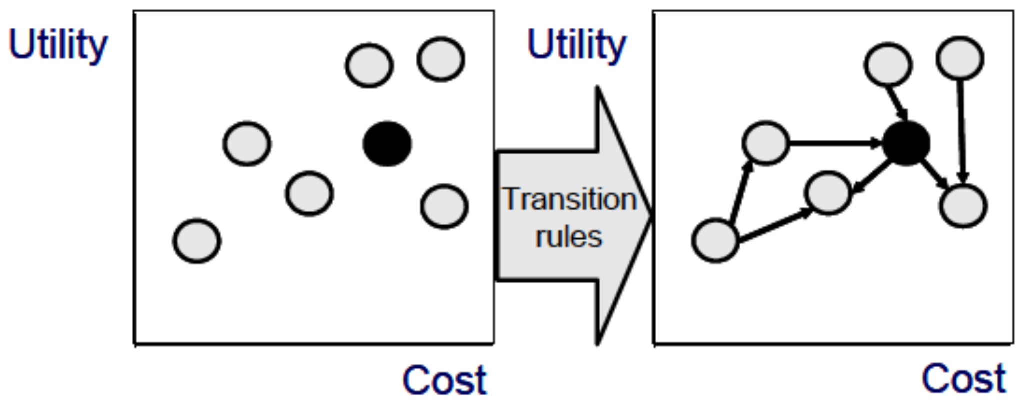


Figure 2.3.5: Illustration of a tradespace into a tradespace network via transitions rules to assess changeability [4]

The results from the tradespace exploration are investigated by the decision-maker together with the stakeholder, by comparing the solutions against each other. Through this process design, alternatives that have a high trade-off relative to the stakeholders need can be identified and potentially give a solution not yet discovered.

2.4 Designs for Exposed Locations

J.E. Huguenin, [31], presented in 1996 an article about the design of fish cages and focused on the development of design towards offshore fish cages. As mentioned, the conventional cages in sheltered waters have reached its maximum regarding the area and environmental impact. This drives the expansion of aquaculture to more exposed sites and to derive new designs of the fish cage to withstand the new climate offshore. According to J. E. Huguenin there are three ways to approach the exposed climate. Submerged fish farms, placing the fish farms on the sea bottom or to build a robust floating structure that can withstand the hostile environment on the water surface. Placing the fish cage at the sea bottom complicates the access for divers, maintenance and support if the water dept is too deep. Too little water depth, however, would not give the effect of protecting the cage form the wind and waves at the surface. Usable sites for the placing the fish cages at the sea bottom is therefore limited. Norway has in the past years designed and tested several floating structures for offshore sites. Two examples are Havfarm and Ocean Farm 1. Ocean Farm 1, see Figure 2.4.1, is design by Salmar's daughter company Ocean Farming AS. Ocean Farm 1 is a round cage with a diameter of 110m. With a height of 68m, it has a volume of 250 000 m^3 Ocean Farm 1 is a rigid steel structure and it enables a reduction in the service needed on site [6].

Figure 2.4.1: Ocean Farm 1, design by Ocean Farming [6]

Havfarm is developed by NSK Ship Design on behalf of Nordlaks, see figure 2.4.2. Two ocean farms were developed; one dynamic positioned and one stationary. The ocean farm looks like a ship and has a length of 430m and a breadth of 54 meters. This is a robust construction made of steel with six separate cages [32].

Figure 2.4.2: Nordlaks' Ocean Farm designed by Havfarm

Havfarm contributes to reducing the service needed by cleaning the net with a fixed unit on board, and all of loading and unloading can be done without a service vessel. In addition, Havfarm has a longitudinal maintenance rail on both sides, which makes the ocean farm more self-sufficient for the maintenance needed [32].

The approach of a submerged fish farm will be investigated further in this thesis and a thorough description of this concept is presented in Chapter 2.

Chapter 3

Submerged Fish Farm

This section will describe the concept of a submerged fish farm and describe the need and use of the air-dome. The information in this section is developed further from the work done in the project thesis of autumn 2018.

3.1 Framework Conditions

The system of the submerged fish farm is a standard model for a floating fish farm, and the components discussed in this thesis are based on Polarcircle HDPE, which is distributed by AKVA group, Sinkaberg Hansen and Egersund net, and are called Atlantis. An illustration of the fish farm is shown in the figure below.

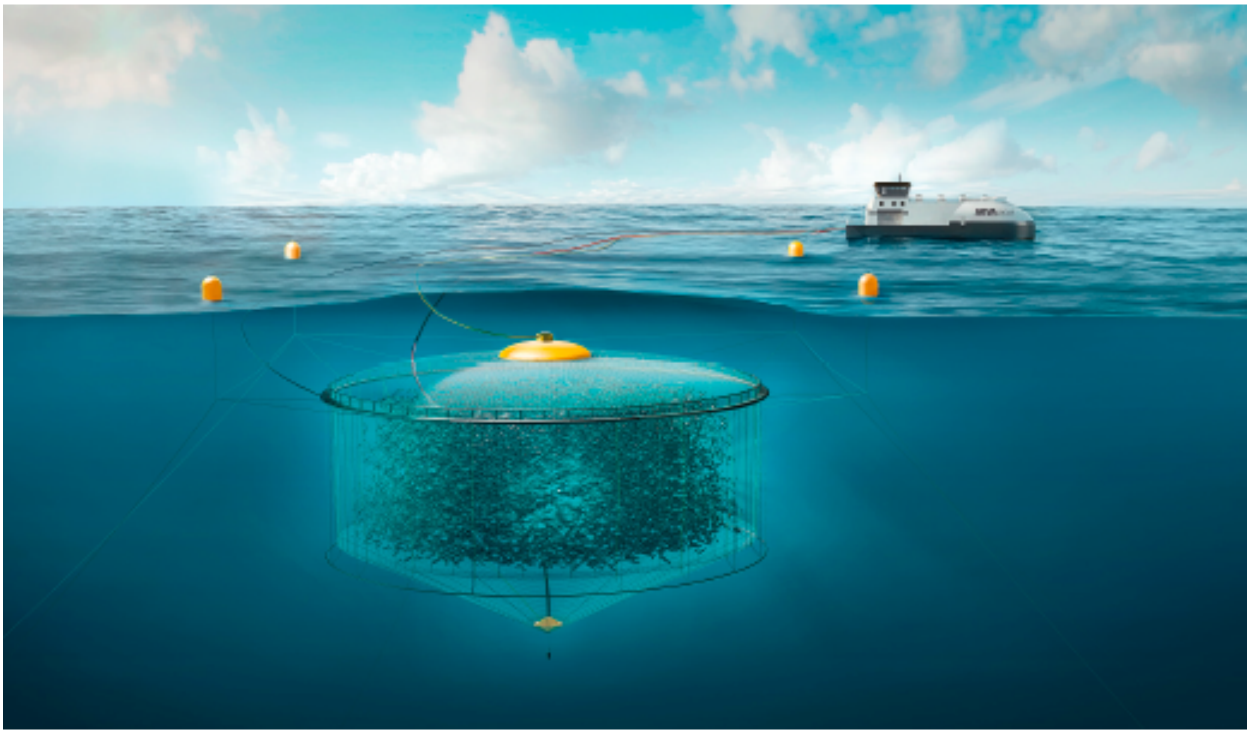


Figure 3.1.1: Illustration of the fish farm Polarcircle HDPE developed by Akavar Group, Egersund Net and Sinkaberg Hansen. [7]

The goal for the submerged fish farm concept is that it should be submerged 90% of the time and only be raised to the surface when performing absolutely necessary operations, such as dispensing and collecting salmon. The idea behind Atlantis is that by lowering the entire plant down to 10-15m below the surface, the salmon lice problem can be solved. At the same time, the stress from waves and currents will be less on this depth than on the sea surface. A detailed description from the Atlantis concept is not available since this concept is still under development, but part of the information has been sent by AKVA Group ASA. This information, along with knowledge of the aquaculture industry, sets the framework condition for the system to be analyzed in this thesis. Table 3.1.1 shows a summary of the most important variables for the submerged plant, as well as the most important factors for the air-dome.

Table 3.1.1: Framework parameters for the submerged fish farm

Variables	Notation	Value	Unit
Cage			
Circumference	C	160	m
Diameter cage	D	50	m
Depth net wall	H_1	15	m
Depth coned wall	H_2	10	m
Air-dome			
Max current velocity	U_c	1	m/s
Min height of air pocket	h_{min}	10	cm
Max dry wight	m_{max}	5000	kg
Diameter of free surface	D_{FS}	5	m

3.2 Components in the Submerged Fish Farm System

The way other components in a submerged aquaculture net cage moves due to current is not of paramount importance in this report. However, they are assumed to have a significant impact on the movement of the air-dome in a submerged condition.

3.2.1 Floating Collar

The floating collar, or floater, are circular tubes with a circumference of 160 m and are made of HDPE high-density polyethylene. For standard fish farms, the purpose of the floating collar is to give the cage enough buoyancy to keep floating in the water surface.

In many cases, they are filled with polystyrene in order to provide buoyancy in damage conditions [33]. Doing so in the case of a submerged net cage would lead to an unnecessary net buoyancy force. Based on the dimensions presented in Table 3.1.1 the buoyancy force would be approximately 350kN (assuming polystyrene has the same density as air), and 135kN when it is filled with water in a submerged state. For a submerged fish farm the floating collar is filled with water or air depending on if the cage is supposed to be lowered or lifted through the water. The floating collar can be thought about as the framework for the total system, and it is, therefore, important to understand the movement of this floating collar in a submerged state to understand the impact the movement of the floating collar has on the air-dome. The floating collar is connected directly to the ropes that hold the air-dome and are as a consequence absorbing the buoyancy force from the air-dome. In addition, the floating collar is connected to the mooring lines and the floaters through the connector plate, which is both affecting the floating collar with forces. The whole system can be thought of as a hydro-elastic system since more than one deformation is acting at the same time [34].

3.2.2 Net Cage

The cage consists of three nets; the net wall that goes around the cage, the conical net bottom and the net-roof that goes covers the entire surface of the cage. Due to the flow in the water, all three parts of the net will be affected by both the drag and lift force. It is assumed that when the rope in the top-net attached to the air dome has a steep angle, this will be advantageous for the stability of the air dome. This will be discussed in more detail in chapter 3.3.3. As the angle of the net-roof increases, the entire area of the net-roof will be larger, which in turn will give a larger drag and lift forces to the total system from the current. An analysis made for different areas of the net-roof due to different angles can be seen in Appendix A. Figure 3.2.1 shows two different scenarios for the net that may occur due to the forces from the current.

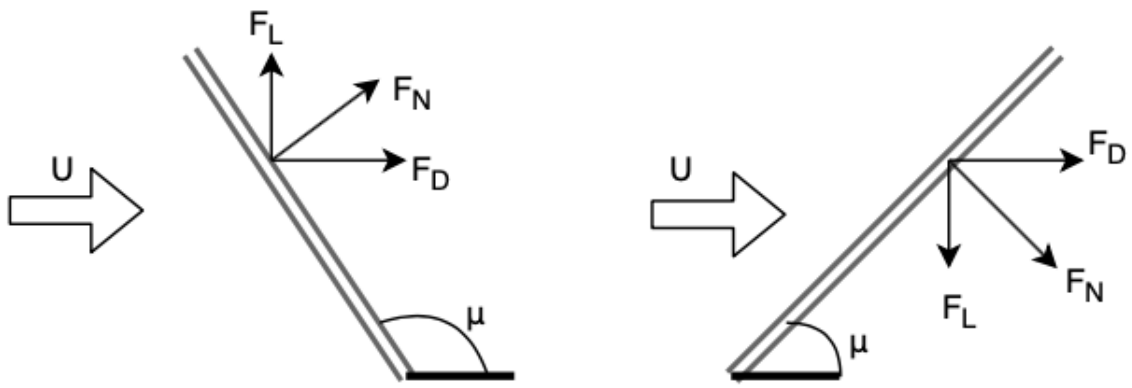


Figure 3.2.1: Illustration of how ropes and net roof deforming due to combination of lift and drag forces from currents.

Where F_D is the drag force, F_L is the lift force and F_N is the normal force. In the illustration to the left, the angle, μ, which is the angle between the floating collar and the net-roof, is large. This gives a larger drag force and the lifting force will be pointed upwards, as indicated in the figure. In the illustration to the right, the angle is smaller, which will result in a smaller drag force and the lifting force points upwards. How much drag and lift forces the net roof experiences is also dependant on the solidity of the net, which is discussed below.

Solidity and Mesh Size

Standardized plants change the net at least once during the cycle due to the ratio of the size to the fish and mesh size. If the mesh size is too large when the fish is still at smolt-stage, the fish can easily escape. Mesh size is the size of the mesh opening in the net, see Figure 3.2.2 for an illustration.

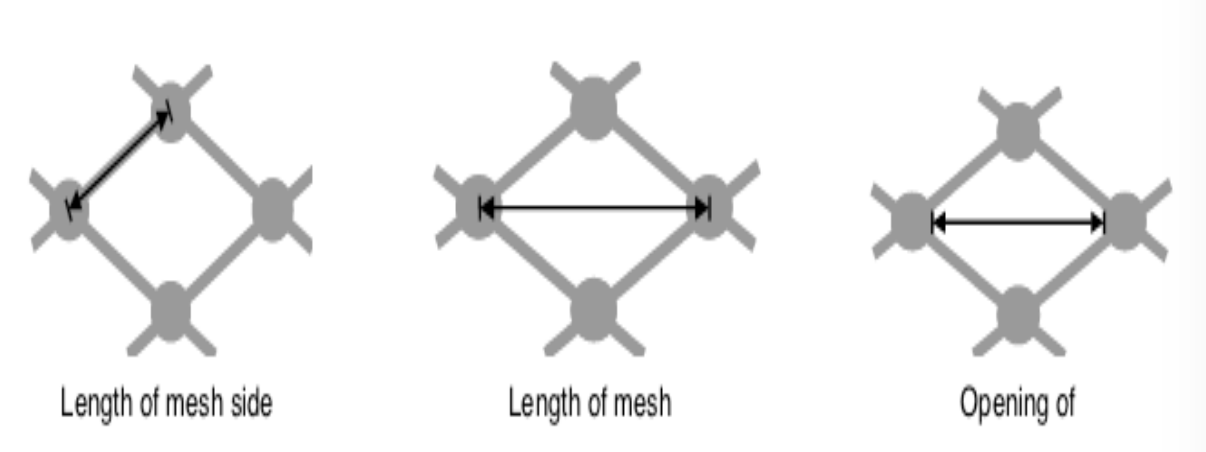


Figure 3.2.2: Illustration of mesh size for a net used in aquaculture [8]

It is an advantage to have a large mesh size as possible with regard to drag force since the total drag force will be lower for a net with a large mesh size than with a small mesh size. This can be explained by the fact that it will be a "denser wall" when there is small mesh size than with a large mesh size since the water can run more freely through the wall when the mesh size is large [35].

An additional factor that should be taken into account is the shielding effect from the net. The net panels that lay upstream to the current will reduce the current velocity on the components lying downstream [36]. The reduction factor will have an even bigger effect if there are several cages lying in the same area. The size of the drag and lift forces will determine how much deformation the grid will be exposed to. The deformation of the grid will again have an impact on air-dome, which is the main focus of this thesis. If the size of the grid ceiling is large enough, it can create a situation where the air-dome capsizes and lose air. One possible solution to prevent this scenario is to make the system stiffer so that these deformations will not be possible. For example, the system can be made stiffer by using stiffer ropes in the grid ceiling. Rigid ropes, on the other hand, can cause other problems.

3.2.3 Floater, Buoys and Mooring System

The only part of the submerged system above the surface is the top buoys. Through information provided by Atlantis, it was pointed out that each corner of the system consisted of three buoys that corresponded to 12 tons. In addition, one buoy are placed between the three top buoys and the connector plate. These buoys are filled with water or air, depending on if the plant is to be lowered or raised in the water. As well as providing an opportunity to regulate the overall buoyancy of the plant. In each corner of the plant is a connector plate, where both the mooring line and the rope that goes to the buoys are attached together with the cage. The frame of the mooring system is 100m long. The Mooring system used is a standardized system that is also used for the fish farms that float on the surface [37].

3.3 Design of Air Dome

The salmon has an open swim bladder that needs to be filled with air for the fish to maintain the buoyancy in the water. If the salmon does not get access to air, it has to swim faster to compensate for the lost buoyancy. This can lead to unacceptable welfare for the salmon, like poor appetite and low growth-rate [38], [39]. As can be seen in Figure 3.3.1 both air and feed are pumped through hoses at the top of the air-dome. The air-dome is open in the bottom down to cage so the salmon can swallow air, and are attached directly to the roof-net. The roof-net keeps the air dome in place and all the forces from the dome are taken up through the roof-net. The roof net acts like an anchoring point for the air-dome as well as preventing fish from escaping.

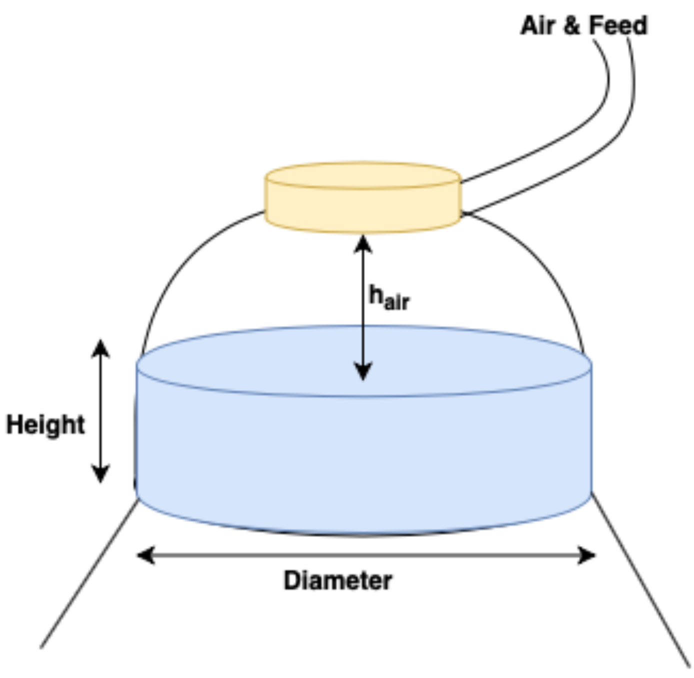


Figure 3.3.1: Illustration of a possible design of the air-dome

Figure 3.3.1 illustrates one example of a design of the air-dome with some of the most important parameters. From Akva Group, it was informed that the air dome must have a minimum air pocket height of 10 cm, illustrated as h_{air} in Figure 3.3.1. It is assumed that this is the minimum height requirement of the free surface since the free surface can be much larger than the surface having a clearance of 10cm depending on the curvature of the dome. The height will also have a large impact on the behavior of the dome, especially the vertical height, indicated as height in Figure 3.3.1, before it begins to curve. Determination of these parameters; height, curvature and diameter of the dome will affect both weight, strength, buoyancy and stability of the air-dome.

3.3.1 Weight

As can be seen from the framework conditions in Table 3.1.1 is the maximum total allowed weight for the air-dome 5 tonnes. This is the dry weight of the air-dome, meaning before it is placed into the water. This restriction is given based on operational activities, e.g lifting operations by service vessel. The main parameters that affect the weight of the air-dome are the choice of material as well as the thickness of the wall and the shape of the air-dome. The thickness is to be thick enough to withstand the forces from the current when it is submerged, but not too heavy so the air-dome will sink in a situation of capsizing. If this is the case the air-dome can sink and rip a hole in the roof net and as a consequence let the fish escape. In 2015 a bachelor thesis was conducted to try to find the optimal material for the air-dome. The thesis concluded with polypropylene (PP) as the best material choice [40]. The choice was based on four criteria; cost, CO_2 - footprint, ability to recycle and deformation.

3.3.2 Buoyancy

The volume of the air pocket inside the air-dome is the main factor that affects the amount of buoyancy for the air-dome. From Table 3.1.1 it was conducted that the minimum air-height inside the dome is to 10cm. As a simplification, it is assumed that the air-dome has a cylindrical bottom. This gives the following equation for the buoyancy;

$$\pi R^2 \cdot h_{min} \cdot g \cdot \rho sw = \pi(2.5m)^2 \cdot 9.81 \cdot 0.1m\frac{m}{s^2} \cdot 1025\frac{kg}{m^3} = 20kN \tag{3.3.1}$$

This indicates that the minimum buoyancy force is 20 kN, assuming a cylindrical shape and a material with a density similar to or lower than sea water. The buoyancy force of the air-dome can be described by holding a cup upside down in the water. The more air the cup is filled with, the more force must be applied to keep the cup in place. This gives a feeling of how much the air inside the air-dome influences on the whole system. The total weight of the air dome should not exceed the weight of the water it displaces since it is not desirable for the dome to sink in a damaged situation i.e total loss of the air pocket. Then again, an air dome that is not held in place by weight could move more freely than a heavier dome. This can cause problems such as snap loads on the ropes in the roof net attached to the dome. The three different scenarios, where the air-dome is held in place by buoyancy, weight or free to move, are illustrated in Figure 3.3.2.

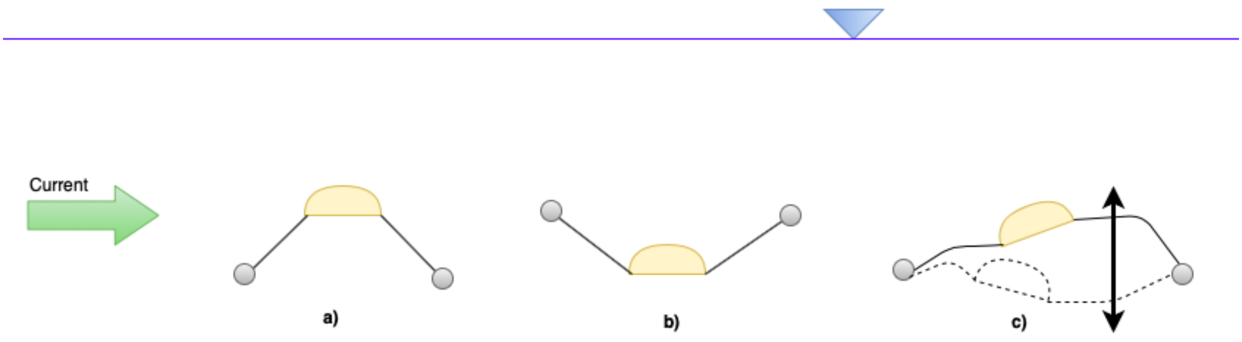


Figure 3.3.2: a): Dome held in place by buoyancy (no damage), b): Dome held in place by its own weight ($\rho_{dome} > \rho_{SW}$), c): Dome free to move due to current and waves ($\rho_{dome} < \rho_{SW}$).

3.3.3 Stability

The main concern of the air-dome is the stability when it is submerged, because of the forces acting on it. As a simplification, the air-dome is assumed to be the same problem as a ship floating upside down. Figure 3.3.3 are showing the simplification made.

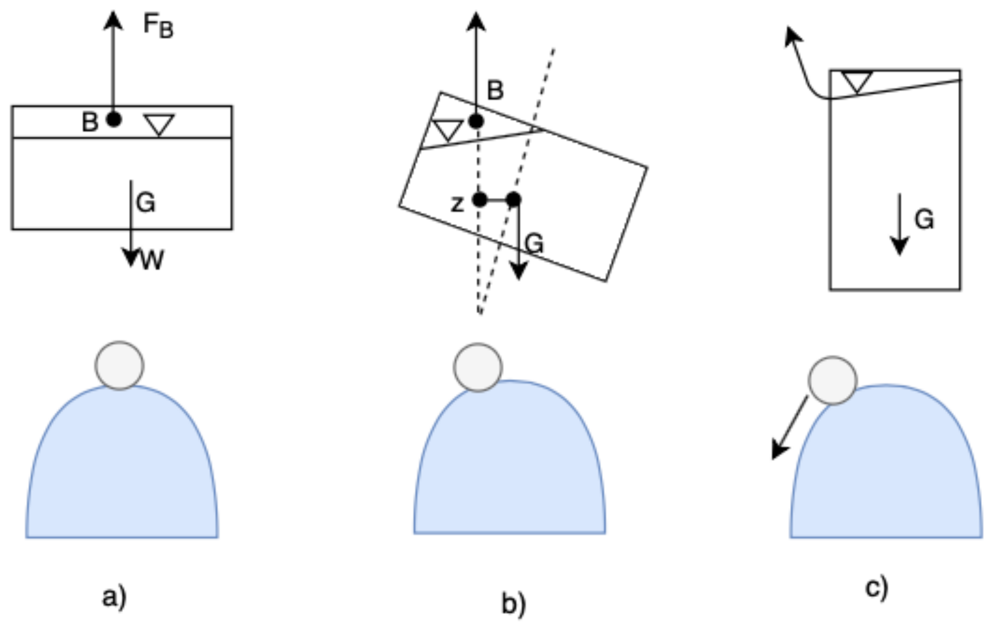


Figure 3.3.3: Illustration of possible states of the stability of the air-dome

Assuming the weight of the dome is exactly equal to the buoyancy, i.e. neutral buoyancy, the dome would float freely in the water column. The dome's center of mass (G) would be situated below its center of buoyancy (B). In situation a) the dome is floating upright with its buoyancy center situated above its gravitational center. As soon as the dome tilts, due to some external force, the buoyancy force initially works against the motion due to a righting moment. However the air is not contained within a watertight compartment, often the case of a ship, and is, therefore, free to move along the inner surface of the dome, causing a rotating motion (seen in b)). At some point, the air will escape from the dome and float to the surface. In reality, the dome is anchored to the net roof and it will have a positive buoyancy due to the air pocket. The connection between the net roof, dome and net wall was discussed in Section 3.2.2. For now, the focus will be on how the angle θ, of the ropes going from the floating collar to the dome impacts the overall stability.

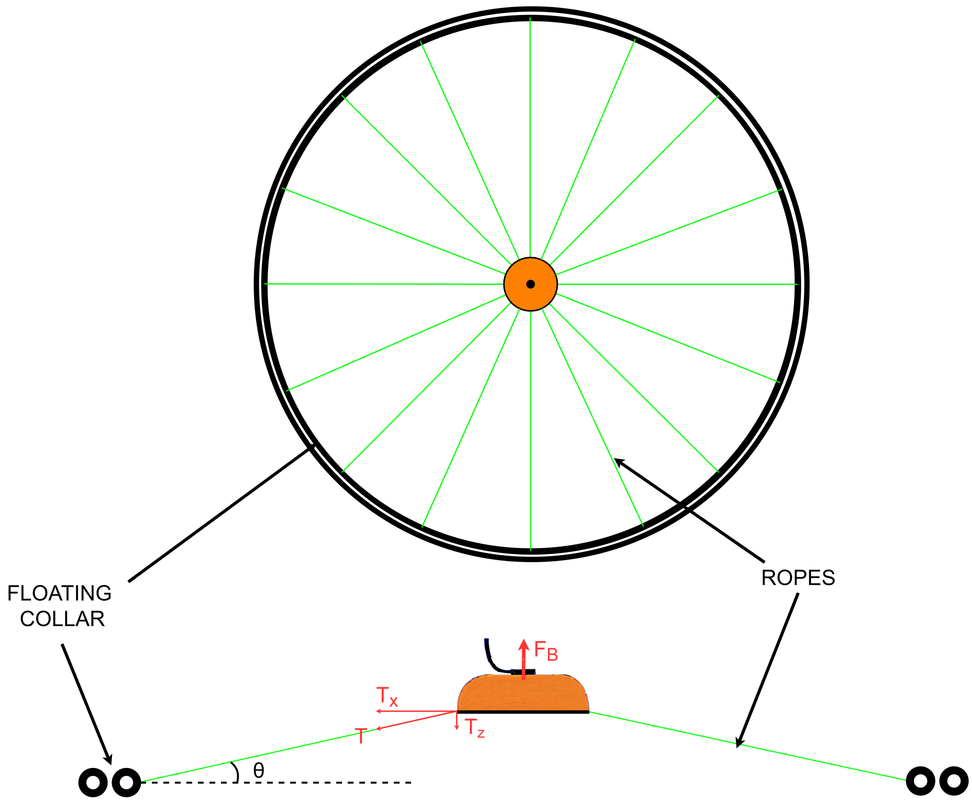


Figure 3.3.4: View of floating collar, dome and attachment ropes from top view (top) and side view (bottom). Side view shows the angle θ, buoyancy force F_B and tension force of the ropes T.

In a stationary situation, the tension force of the ropes is proportionate to the net buoyancy force of the dome as well as the number of ropes, $T_i = F_B/n$. Here i represents the rope number and n total number of ropes. The tensile force of the ropes can be decomposed in a vertical and a horizontal force, T_z and T_x respectively. Large angles will lead to better stability since $T_z = T \cdot sin(\theta)$ and therefore a larger righting moment once the dome is tilting. In Figure 3.3.5 a case of equilibrium between the buoyancy force and the total vertical tension forces, $T_{z,tot}$, can be seen in the top left part of the figure (in this case the weight of the dome and the horizontal tension forces are neglected).

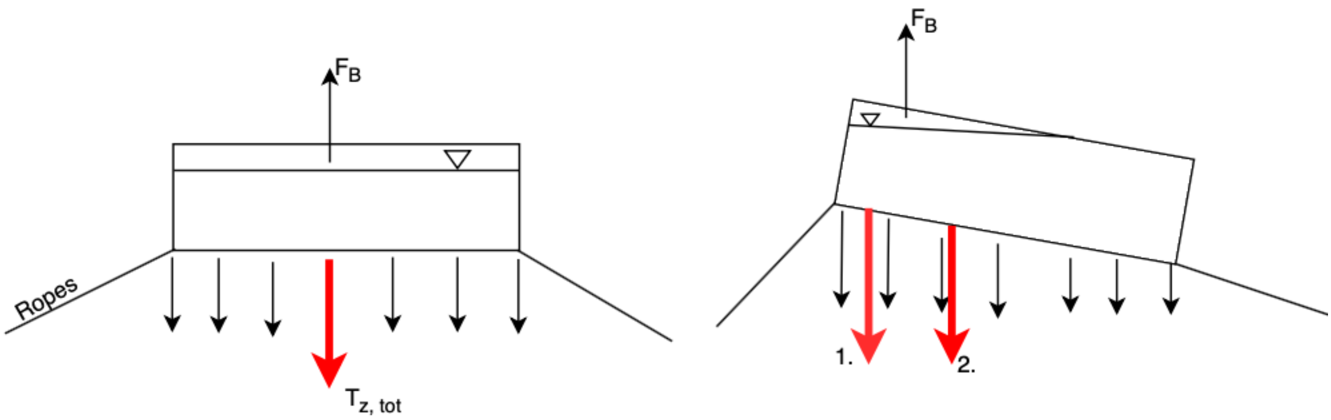


Figure 3.3.5: Stability criteria of dome. Illustrating how the righting moment may act when the air-dome begins to tilt.

In the top right part, the dome has tilted causing the acting buoyancy force to move to the left of the dome's center. If the total vertical tension force stays to the left of the buoyancy force a righting moment will move the dome back towards equilibrium (indicated as 1. in the figure). If the buoyancy force moves to the left of $T_{z,tot}$ (indicated by 2.) the righting moment has become negative, working to overturn the dome as in Figure 3.3.3. The ropes would keep the dome from capsizing, but air may escape and unless an external force moves the dome out of the area of vanishing stability the dome stays in this capsized position. Smaller angles on the ropes may have other advantages though. The problem discussed in Section 3.3.1 relating to a dome in damage condition moving freely in the water column would be mitigated. The oscillating radius would be shorter due to shorter ropes. If the dome is anchored via direct connections to ropes in the net roof, tensile forces in the ropes may cause the dome to deform [40]. A more rigid bottom part or ring could, however, mitigate this. Either way, ropes in the net roof will, in addition, to keep the dome in place, have an effect on the stability of the dome. Or rather, the angle of the ropes, their stiffness and the tensile force acting on the dome. The angle θ, seen in Figure 3.3.4, depends on the length of the ropes and their stiffness. Stiffer ropes will be less stretched due to the buoyancy force of the dome and movement of the floating collar.

3.3.4 Utilization

The function of the air-dome is to provide oxygen to the salmon in a submerged state. For the air-dome to serve a purpose, the salmon must use it to such an extent that the system can stay submerged. If only subgroups of the salmon use it or if they use it seldom the system will have to be raised to the surface at relatively frequent intervals. This may not be possible due to weather, and it may be disadvantageous due to potential salmon louse infestation and cost/risk associated with lifting operations. The angle of the roof net connected to the air-dome is assumed to have an impact on how often the salmon utilizes the air-dome. If the angle of the net roof is too steep salmon may not travel along with it upwards to the air pocket. In addition, the interface between the air-dome and the net roof seems to be important regarding salmon utilization. If the base of the air-dome is situated below the net roof, it forms a wall that the salmon will not swim under. These assumptions are rather uncertain and little other than anecdotal and some empiric evidence supports this. According to the head researcher on the study *Atlantic salmon (Salmo salar L.) in a submerged sea-cage adapt rapidly to re-fill their swimbladders in an underwater air filled dome*, there is a reason to believe that the shape of the dome itself and the draft inside the dome will have an impact on salmon utilization. It is an extension of the assumptions related to the angle of the net roof and the placement of the base of the dome; A large draft might cause salmon to not utilize it as it has to swim up and inside the dome before reaching the air pocket. Studies, where submerged net cages with a "snorkel" have been used, have, however, shown that salmon will go through the tube of the snorkel and up to the surface [41].

3.4 Air-Dome Shapes of Interest

In the following sections, a few different geometrical shapes of interest of the air dome is presented. Based on criteria that have been discussed in this section some advantages and disadvantages of the air dome shapes are discussed.

3.4.1 Square Box

A square box, shown in Figure 3.4.1, is not optimal regarding any criteria. In figure 3.3.3 a square box was used to illustrate the stability of the dome freely floating in the water column. The corners of the box allow air to travel further out from the center of the box, consequently shifting the buoyancy force line of attack further out from the center. As seen in Section 3.3.3 this has a negative impact on the air-dome stability. How it behaves in current depends on the line of action of these forces.

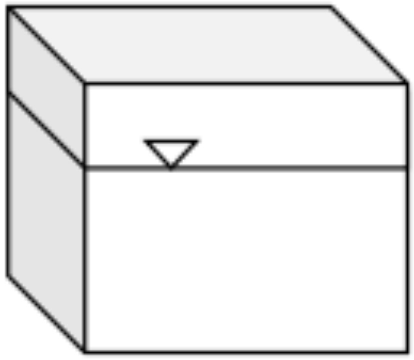


Figure 3.4.1: Possible design of air-dome: square shaped air-dome.

3.4.2 Hemisphere

A hemisphere will have better stability than a box, or a cylinder since the volume center of the air will stay closer to the center of the air-dome. The shape may also be somewhat more advantageous, from the perspective of salmon utilization, than a dome with vertical inner walls (as discussed at the end in Section 3.3.4.) A hemispherical dome with a base diameter of 5 m and the free surface at the base would contain 32.7 m^3 of air. This would mean a buoyancy force of approximately 33.5 kN. The draft in the dome could, of course, be increased, and consequently lower h_{air}, as seen in Figure 3.4.2. This would, however, mean increasing the base diameter, in order to meet requirements of D_{FS}. This would increase the weight and overall size of the dome, making it unwieldy. A fully hemispherical dome is for these reason presumed to be unfavorable.

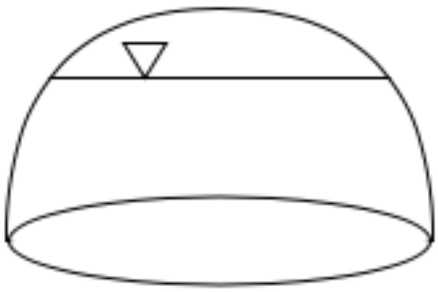


Figure 3.4.2: Possible design of air-dome: hemispherical air dome.

3.4.3 Frustum with Cylindrical Top

This dome has a cylindrical cap and a frustum-shaped "skirt" attached to it as seen in Figure 3.4.3. The cap allows for a minimal amount of air as it can meet the requirements regarding D_{FS} and h_{min}, without wasting space. The angle of the skirt could be set equal to the angle of the ropes attached to it. This could be advantageous relative to salmon utilization. Compared to a hemisphere the stability would be worse in situations where the dome is tilted. Depending on the angle of the skirt and the draft air may also be prone to escape. Also depending on the choice of material and the size of the skirt, the dome could potentially be quite heavy.

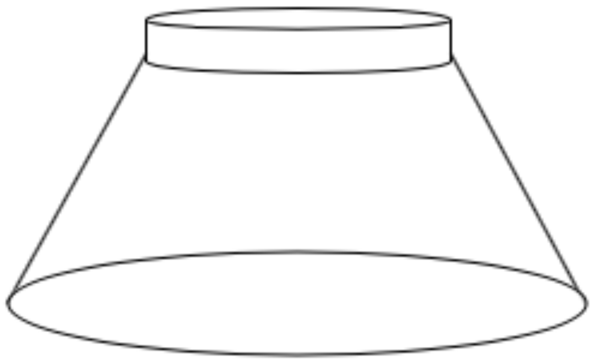


Figure 3.4.3: Possible design of air-dome: frustum shaped air dome.

3.4.4 Cylinder with a Curved Top

In Figure 3.4.4 an air-dome with a curved top and a cylindrical bottom can be seen. The total free surface has to be somewhat larger than D_{FS}. The base diameter can be equal to the free surface due to the vertical sides, but this is, however, dependant on the curvature at the top. As is stability, but any curvature will make it more stable than a fully cylindrical shape. Loss of air depends on the stability and the draft of the air-dome. The weight and overall size will also vary according to the choice of draft and curvature at the top.

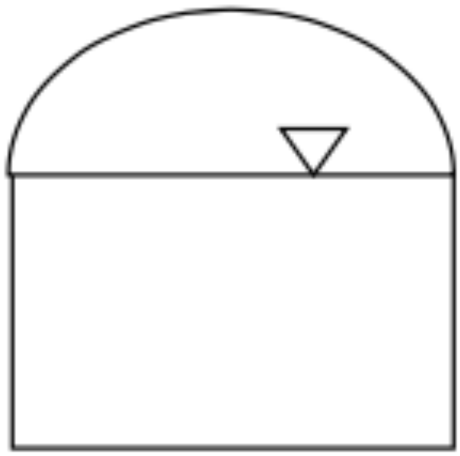


Figure 3.4.4: Possible design of air-dome: cylindrical shaped air dome with a round top.

Chapter 4

Initial Economic Feasibility

The aim of this chapter is to investigate the economic difference between a submerged fish farm and a standardized floating fish farm, regarding the costs concerning delousing procedures that will not be an issue if the fish farm is submerged. And to investigate if the air-dome together with the rest of the submerged fish farm has some unforeseen costs that will indicate that this type of fish farm is not profitable.

An initial economic feasibility study is decisive at an early stage for any developmental process. The purpose of this study is to discover if the project is viable and discover the benefits and yield of the project before the financial resources are allocated. The result of disabling such a feasibility study can help determine if the project is financially feasible and whether the project should continue. Figure 4.0.1 illustrates all costs for the submerged fish farm and how they are connected together. It is assumed in this thesis that the submerged fish farm uses the same equipment as a standardized floating fish farm. The analysis in this section will focus on the cost around the air-dome with all its equipment and the cost for delousing treatments.

Figure 4.0.1: Illustration of the components that effect the total cost of the submerged fish farm

4.1 Capital Expenditure (CAPEX)

Capital Cost, also called investment cost, is a one-time cost that usually occurs at the beginning of the operation. A normal investment cost for a standardized fish farmer is the investment for a license. For this project, the cost for the license is free until it is converted into a regular license since this project is granted with a development license. The development license will be discussed further down. Most of the capital expenditures are connected to the physical facilities, shown in blue in Figure 4.0.1. These components are excepted to have the same cost for the submerged fish farm as for a standardized floating fish farm and will not be investigated further in this thesis, except the cost regarding the air-dome.

4.1.1 Development Licenses

The goal of the Government is to quintuple the aquaculture by 2050, and a measure initiated by the authorities to increase interest in creating innovative solutions was to issue development licenses. The development licenses are a temporary arrangement with special permits to begin production, that can be awarded to projects that involve significant innovation and significant investments. The purpose is to facilitate the development of technology that can help solve one or several of the environmental and area problems that the aquaculture industry is facing today. In addition, to perhaps the main problem concerning the sea lice.

The development license is granted free of charge for up to 15 years and permits to produce 780 tonnes of fish per license. It is possible for the same company to apply and receive more than one licenses per project. If the projects are carried out according to the ambition that has been set, the license can after a given time be converted into a commercial license for a sum of NOK 10 million. 10 mNOK for a commercial license is considered a good price, compared to the price on the open market where a commercial license can be sold for as much as 75-90 mNOK [42]. After putting a stop to issuing new licenses, the prices for the available licenses increased drastically. As a result of the expensive licences in the open market, the development licences serves as a motivation for both parties, as companies will most likely benefit from investing in new solutions in the long run, even if the new solution is not going to be a success, since the company can buy the development license after a given time. One disadvantage of this arrangement is that the companies may not invest all they can in the new ideas to find the solution, as they know that they will still be able to buy a commercial license in a few years that will yield huge values for the company in the future.

4.1.2 Air-dome Cost

The cost for the air-dome depends on the shape and size of the geometry of the air-dome chosen, as well as the choice of material. The material was as mentioned in section 3.3.1 investigated through a bachelor thesis and the best material was concluded to be polypropylene (PP). This will be the choice of material for further calculations in this thesis as well. In addition to the material cost for the geometry of the air-dome several types of equipment are needed. The main equipment needed for the air-dome and the investigation of the cost will be analyzed further in the case study in Section 5.6.

4.2 Operational Cost (OPEX)

OPEX includes fixed expenses for a product, system or company. It can also include expenses in connection with employees and construction expenses, such as delousing procedures. The biggest operational cost in aquaculture is the feed, which approximately accounts for 50% of the production cost [43]. This section will mainly focus on the expenditure around the sea lice as an operational cost.

4.2.1 Sea Lice Expenditure

Sea lice, *Lepeophtheirus Salmonis*, lives on the salmon where it feeds on the skin and blood. A large density of sea lice on the salmon can lead to enormous injuries and wounds. In the worst cases, the salmon may die. The sea lice are not dangerous for humans but contribute to large costs for the aquaculture industry [44]. The expenditure from the sea lice can be categories into three groups; biological, economic and social. The three categories have sliding transitions, but the essence of each group are discussed below.

Biological expenditure
The biological consequence of sea lice is the effect it has on the quality off the fish. When the sea lice start to feed off the skin and blood the salmon reduces growth and has lower feed conversion. In addition, the sea lice weaken the immune system and can trigger higher mortality of the salmon in the cage [45]. When the growth rate of the fish is slower, the length of time in the sea will expand as well as the operational costs. The quality of the meat can also be reduced due to sea lice, which will then affect the final market value of the fish.

Economical expenditure
The main economical expenditure is the treatments for sea lice. covering both the treatments done to prevent the sea lice and after the sea lice have started harvesting on the fish. Some examples of treatments are mechanical treatment, cleaning fish, thermal delousing, fresh water treatment in addition to others. The economic cost is also a consequence of the decrease in market value if the meat is not optimal as well as the reputation for the farmers that can give severe consequences [46].

Social expenditure
The social costs mostly concern the reputation that the industry has, both national and global. Aquaculture is one of the biggest industries in Norway and an important part of the national economy. A poor reputation of the quality of the Norwegian fish can, therefore, be fatal for the economy of Norwegian aquaculture.

All expenditures regarding sea lice costs are illustrated in Figure 4.2.1. The most common delousing methods, thermal, freshwater delousing and cleaner fish, are investigated further. The cost for the delousing is based on numbers from a report issued by ilaks.no [12]. The numbers in this report are estimated based on interviews with breeders in addition to other actors in the industry. The article classifies that the numbers presented are based on assumptions from both subjective expectations and experience-based statistics.

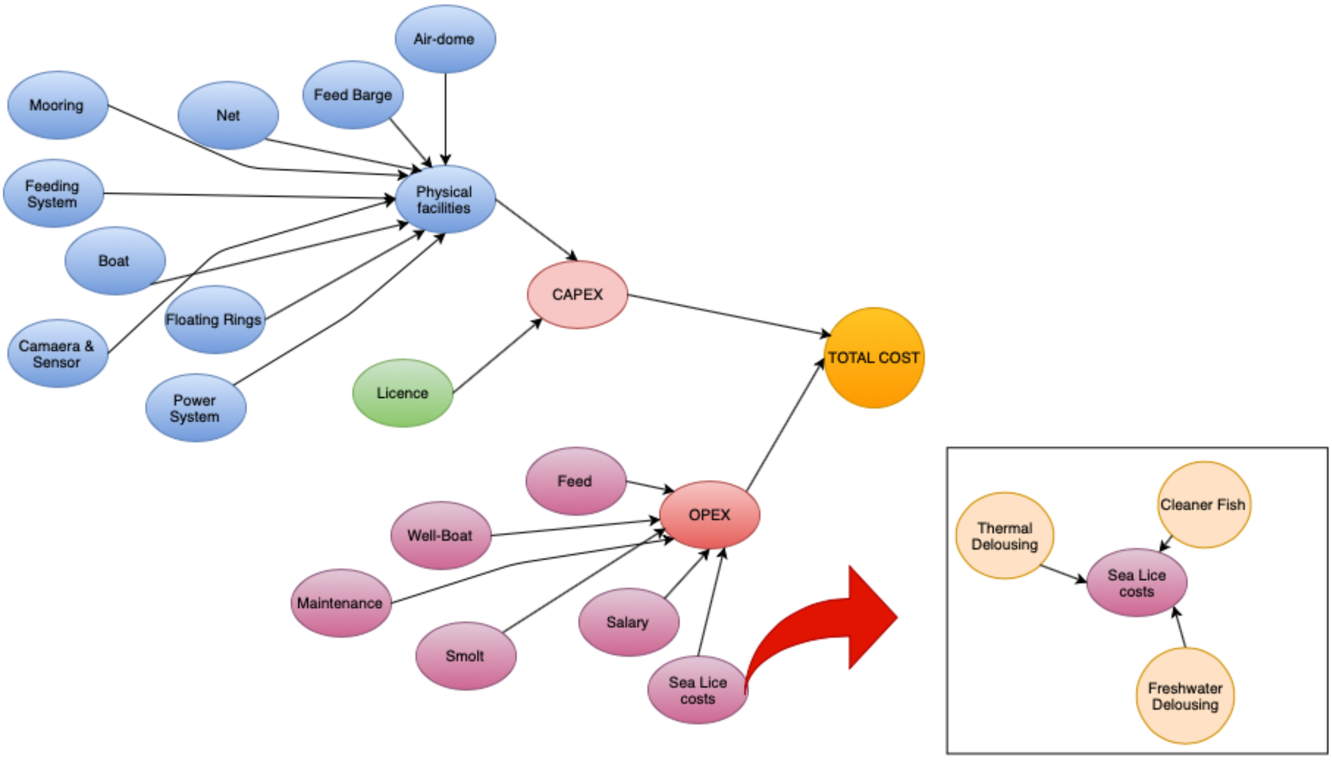


Figure 4.2.1: Illustration of expenditure regarding sea lice

Thermal Delousing

There are currently two commercial methods categorized under thermal delousing, Optilice and Thermolicer. The cost estimates for thermal delousing are based on interviews with seven different actors. The expenditure covers the cost for maintenance, service vessel, fuel, mortality, labor and other costs. The estimated price is 0.57 NOK/Kg [12]. A full site treatment for a standardized Norwegian site is estimated to approximately 4000 tonnes, resulting in a price of almost 2.3 mNOK.

Freshwater Delousing

For freshwater delousing fish are treated in well-boats where fish are exposed to fresh water, usually for 4-8 hours, before it is discarded and returned back to the cages. The direct costs associated with the treatment are primarily related to the use of well-boats, fresh water, service vessels and growth losses. The prices used for freshwater delousing are based on a research interview with only two actors - therefore some uncertainty regarding the cost must be taken into account. The estimated price for freshwater delousing is 1.36 NOK/Kg [12]. A full site treatment for a standardized Norwegian site is estimated to approximately 4000 tonnes, resulting in a price of almost 5.5 mNOK.

Cleaner Fish

Cleaner fish is a type of fish that feed lice of the skin of the salmon. The cleaner fish is released directly into the cage and has proven to be a good method to keep the number of lice per salmon down. One of the great advantages of using cleaner fish is that the salmon is not exposed to any handling. It is also seen as an efficient, environmentally friendly and sustainable delousing procedure. The largest expenditure regarding cleaner fish is purchases and transport of the cleaning fish. In addition, the cleaner fish will need feeding as well, which will increase the feed expenditure. The cost for cleaner fish is based on interviews with three breeders and the estimated price for cleaner fish is 1.12 NOK/Kg [12]. A full site treatment for a standardized Norwegian site is estimated to approximately 4000 tonnes, resulting in a price of almost 4.5 mNOK.

Table 5.6.1 shows the costs for the three different treatment methods per kilo of biomass and the estimated price for a whole site and for one license.

Table 4.2.1: Initial estimation of cost for sea lice [12]

	NOK/Kg	Expenditure per site (4000 tonnes)	Expenditure per licence (780 tonnes)
Thermal Delousing	0.57	2.3 mNOK	500 000 NOK
Freshwater Delousing	1.36	5.5 mNOK	1 mNOK
Cleaner Fish	1.12	4.5 mNOK	900 000 NOK

4.3 Revenue

In 2017 it was sold salmon for over 61 million NOK from the Norwegian aquaculture. This is twice as much as five years ago and 2% more than in 2016. The amount of sold salmon is 1% less than in 2016, but the value has had an increase of 2%. The development of the price of salmon compared to the number of tonnes produced can be seen in the graph in Figure 4.3.1[9].

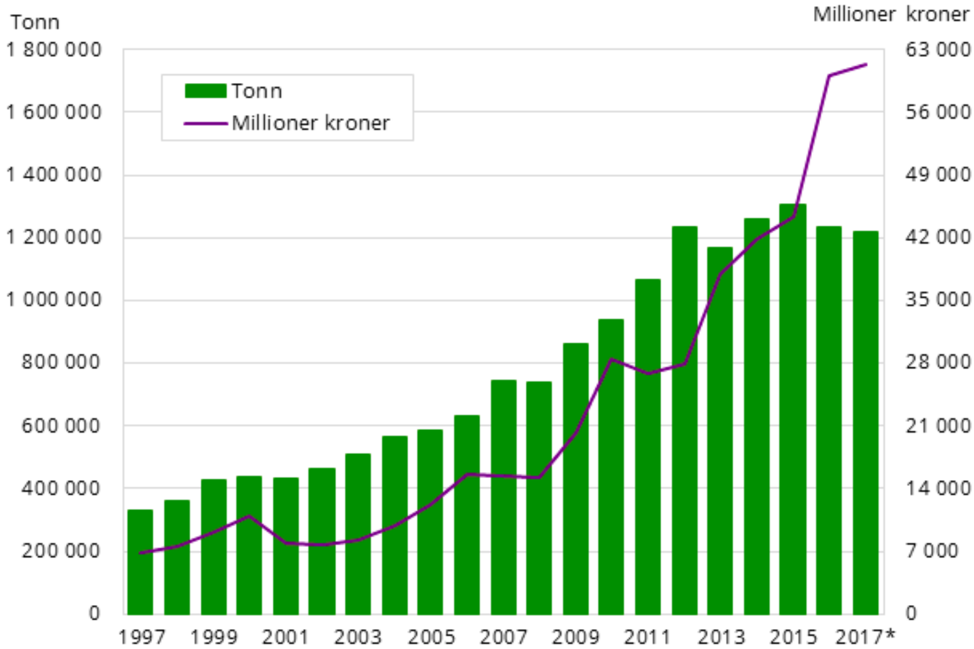


Figure 4.3.1: Illustration of the produced amount of salmon[tones](green) and the price for salmon[mNOK](purple)[9]

The revenue of salmon follows the export price in the market. The export price varies every week and fisk.no [47] documents the export price for fresh and frozen salmon every week throughout the year. Figure 4.3.2 illustrates the fluctuation of the export price over the last years. The volume of the Norwegian salmon industry has expanded up until 2012. Since 2012 the volume of produced salmon has stabilized, a consequence in the price for salmon being record high in 2016 - 80NOK/Kg [48]. The prognoses for the last years are a little lower as can be seen in the graph below.

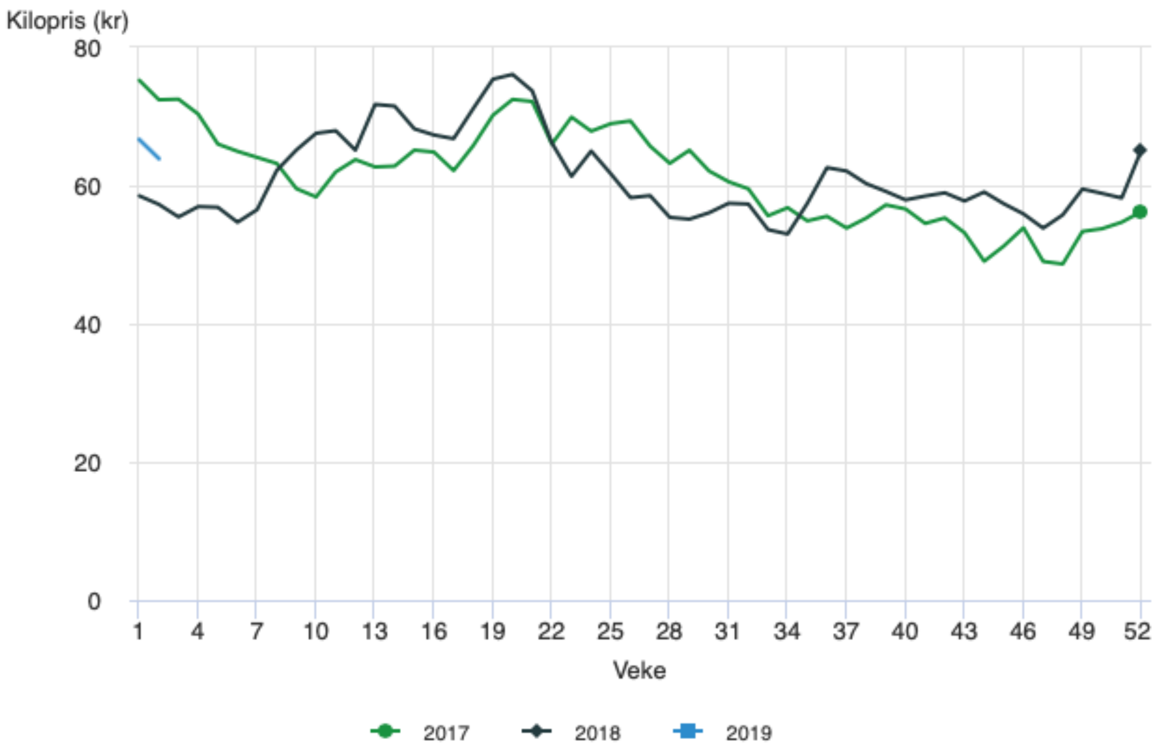


Figure 4.3.2: Illustration of the export price on salmon [9]

The numbers of the economical feasibility are based on the cost for one license, corresponding to 780 tonnes. The expected revenue is often based on the gutted weight equivalent, corresponding to 84% of the total weight [49].

Table 4.3.1: Initial estimation of yearly revenue.

Export Price	67.33	NOK/kg
Average biomass	780	tonnes/year
Average GWE	655,2	tonnes/year
Average yearly revenue per license	44 114 616	NOK

The export price is based on the export price from week 15 2019 [47].

4.4 Discussion

An interesting issue is to compare the expenditure for delousing with the expenditure for a submerged fish farm, where the goal is to have zero delousing cost. However, the cost for the whole submerged fish farm will not be conducted in this thesis. Comparing the cost for delousing and the costs for the air-dome may give the wrong idea since there are additional costs that come with the use of the air-dome. Anyhow, bearing in mind that there is more to the total cost of the submerged fish farm than the cost for the air-dome. investigating the total cost of delousing gives a clue of how expensive the air-dome with all equipment can become and still be profitable. As presented earlier in this section, the delousing procedures become very expensive. Solving the delousing problem would save the aquaculture industry for multiple millions every year. In 2010 the cost for salmon lice, as an average, was estimated to 1.5 NOK/Kg, by 2016 the price increased to 6 NOK/Kg [48]. The price probably increased even more in the last two years. The increasing price for sea lice indicates that new solutions, like the air-dome and the submerged fish farm, can avoid the sea lice are very applicable. The quality of the meat will also be better if there are no sea lice, which will give a better market value and better profit. The expand in technology might give future costs that are not considered here. Possible future cost groups are; environmental costs, cost of CO_2 emission and nutrient discharge. Licenses to farm, area/production fee, license fee, and other taxes [48]. However, this investigation shows that the air-dome and the submerged fish farm can become quite expensive and still be profitable, given that zero delousing expenditure is obtained.

Chapter 5

Case Study

This chapter will present the most important attributes that will give value for the air-dome, discuss the hydrodynamic restrictions and investigate expenditure for the air-dome. Then, by the use of design theory, try to find a suitable design for the air-dome in a submerged condition. The main objective of this case study is to analyze how different values of the design variables of the air-dome will affect the cost and utility of the air-dome.

5.1 Case Description

A new solution to avoid the growing sea lice problem for Norwegian aquaculture is to use submerged fish farms. The fish cage is lowered down to a depth of 10-15m, where it is assumed that there will be a significantly lower density of sea lice due to a lower temperature and less light. For the salmon to survive at this depth it needs access to fresh air, this is solved by the use of an air-dome, which is connected directly to the roof-net of the fish cage. Through the analysis in this case study, it is desirable to see how the design parameters of the air-dome will affect the performance attributes and the hydrodynamic behavior of the air-dome. In addition, to find the most suitable design for the air-dome, based on the analysis done in this case study.

5.2 Selecting Design Methodology

In the literature review, presented in Chapter 2, several methodologies for solving a design problem were introduced. In this case study, tradespace exploration is chosen as the main design methodology. This design methodology gives a good understanding of what defines a good design in terms of utility versus cost. A brief summary of the tradespace exploration method is presented below:

Multi-objective decision making has the ability to take in a number of criteria, from which the decision maker must choose the option that best meets the requirements set for the problem. Multi-objective decision making is used as a tool to help the decision maker to rank and prioritize different design alternatives. Instead of finding the "best" or most correct solution, multi-objective decision making is based upon describing how well a system meets a set of needs. Choosing tradespace exploration as the multi-objective decision maker method gives a good overview of the "goodness" of the different design alternatives. Tradespace exploration is a decision analysis that compares a large number of different system designs, and the results from the analysis enable the decision maker to evaluate the performance of multiple designs at the same time. Tradespace exploration also includes a mapping between different design parameters that represents a physical design and how well they perform compared to each other. Figure 5.2.1 describes the main steps of the tradespace exploration with all the elements included and in what order they should be conducted.

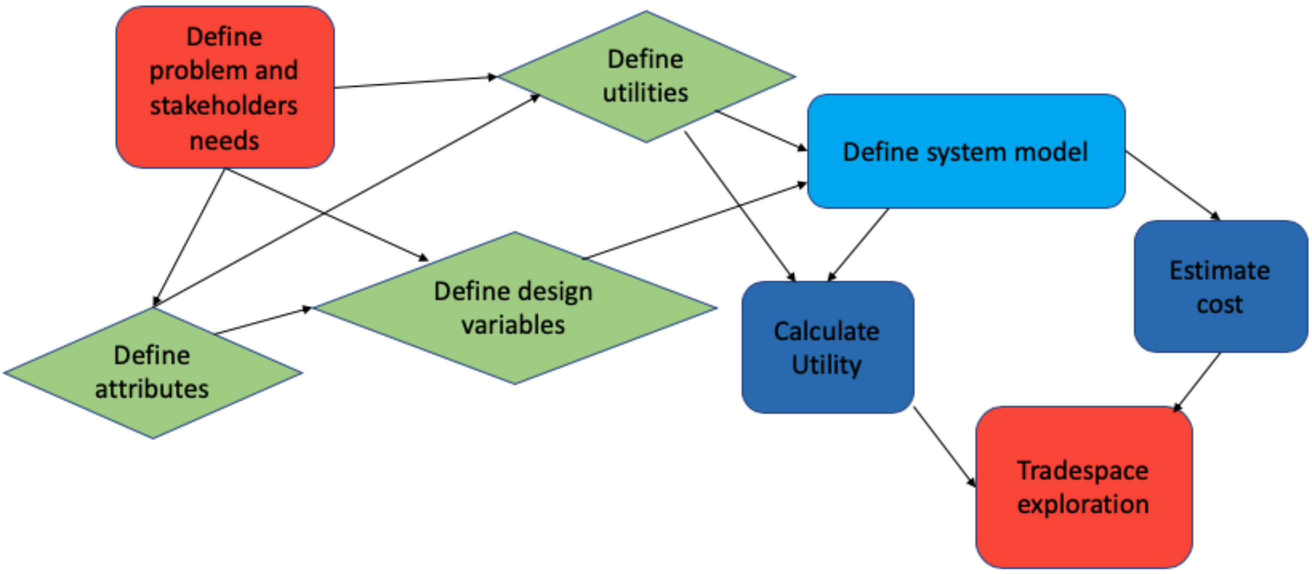


Figure 5.2.1: Illustration of the main point and the procedure of the tradespace exploration.

5.3 Hydrodynamic Aspect of Air-dome

This section will present the important hydrodynamic aspects of the air-dome. Regarding the hydrodynamic calculations, only response from current has been taken into account and it is assumed uniform. The aim of this investigation is to better understand the connection between the force applied to the air-dome from the current and the tilt-angle that will occur when the force becomes large enough. The results from this analysis will set the basis for the hydrodynamic restrictions for the tradespace exploration performed later in this case study.

The force acting on the air-dome and how large the angle can get before the air-dome will begin to lose air is a critical state. Even small angles will be undesirable since this probably will affect the usability for the salmon, due to the fact that the effective diameter of the water surface inside the air-dome may become smaller. Figure 5.3.1 shows a possible state stat might occur due to forces from the current.

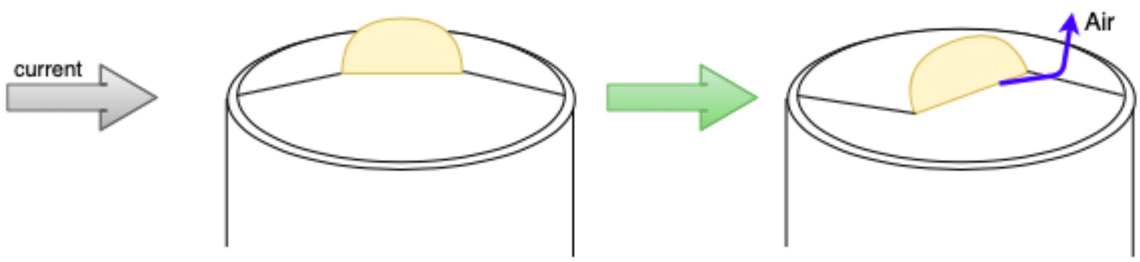


Figure 5.3.1: Illustration of air-dome tilting due to force from current

The behavior of the air-dome is hard to predict without doing actual experiments. However, by breaking down the system of the air-dome to a 2D problem and adding some assumptions, simplified calculations can be established to estimate the tilt-angle due to an incoming force. It is desirable that the air-dome is as stable as possible so no air will escape. There is no information available on how the air-dome will behave if some of the air is lost, or if this is a condition that is operable at all. Based on this, the requirement for the maximum allowable tilt-angle will be set to when the air-dome first begins to lose air.

5.3.1 Air-dome System as a 2D-problem

The air-dome system is a complex system with an abnormal geometry. No research is previously published on forces on a "dome-shaped", a cylinder with spherical top, in a submerged condition. As a simplification, the air-dome is broken down to a 2D problem to investigate the connection between the force acting on the air-dome and the tilt-angle. The challenges with simplifying a 3D problem to a 2D problem will be discussed later in Chapter 7. Even when breaking down the problem to a static 2D problem the calculations appeared to be quite complex, due to the number of unknown parameters. An illustration of the breakdown of the 2D problem of the air-dome is illustrated in Figure 5.3.2.

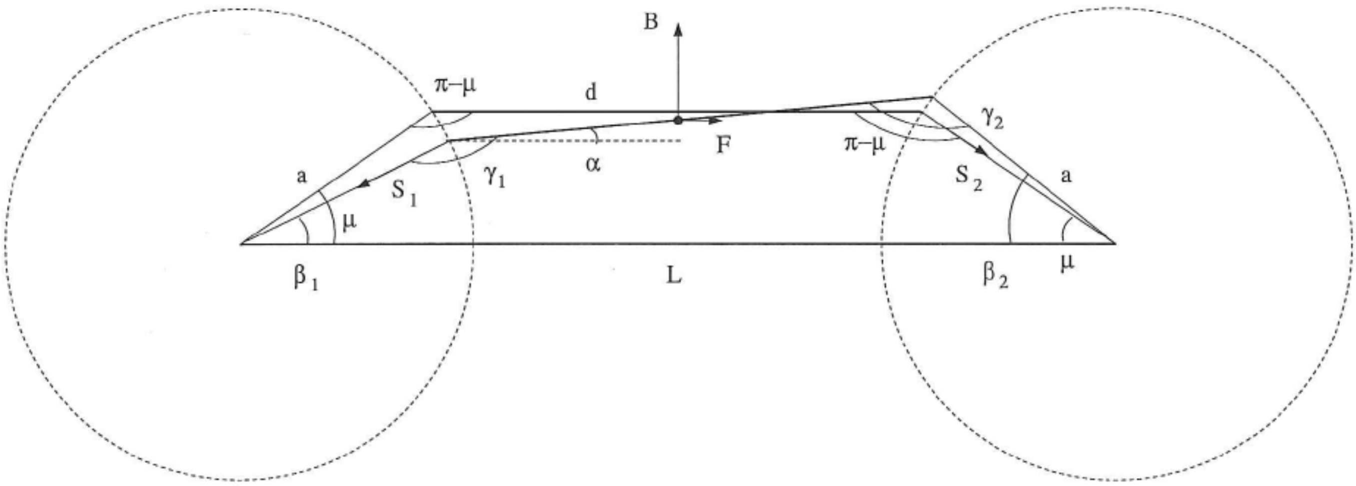


Figure 5.3.2: Illustration of the breakdown of the air-dome as a 2D-problem

Here L represents the diameter of the floating collar, d the diameter of the air-dome and the length of the mooring lines between the air-dome and the floating collar. From the figure, it noticeable that the mooring lines, S_1 and S_2, has to lie on a circle where the radius is the length of the mooring line, no matter how the air-dome moves. μ is the angle of the mooring line in the original state before the air-dome begins to tilt. This angle is the same on both sides of the air-dome, see Figure 5.3.2. It is assumed that the air-dome will begin to tilt when the force, F, becomes large enough. This will cause a tilting angle α, of the air-dome, between the original state and the tilted state. As can be seen from Figure 5.3.2 the angle to the left, β_1, will then become smaller while the angle to the right, β_2 becomes larger when the air-dome begins to tilt. This will again affect the tilting angle of the air-dome, as observed from the figure. The aim of this 2D problem is to establish the connection between the applied force, F, and the tilting angle α numerical.

The illustration above presents a static 2D problem which indicated that there has to be the same number of independent equations as there are unknown parameters. The following relations can be conducted from Figure 5.3.2:

$$
\begin{aligned}
F &= S_1 cos\beta_1 - S_2 cos\beta_2 \ (1) \ (\Sigma F_x = 0) \\
B &= S_1 sin\beta_1 + S_2 sin\beta_2 \ (2) \ (\Sigma F_z = 0) \\
S_1 sin\gamma_1 &= S_2 sin\gamma_2 \ (3) \ (\Sigma M_{CM} = 0) \\
\beta_1 + \beta_2 + \gamma_1 + \gamma_2 &= 2\pi \ (4) \\
\pi + \alpha &= \beta_1 + \gamma_1 \ (5a) \\
\pi - \alpha &= \beta_2 + \gamma_2 \ (5b) \\
L &= acos\beta_1 + dcos\alpha + acos\beta_2 \ (6) \ (\Sigma \Delta x = L) \\
0 &= asin\beta_1 + dsin\alpha - asin\beta_2 \ (7) \ (\Sigma \Delta z = 0)
\end{aligned}
\tag{5.3.1}
$$

where L, F, μ, d, a and B are know variables and S_1, S_2, α, β_1, β_2, γ_1 and γ_2 are unknown variables. 7 unknown variables and 7 equations. It is desirable to reduce these seven equations before implementing them into a numerical MATLAB script.

Equation (5a) and (5b) can be combined and written as:

$$\beta_1 - \beta_2 + \gamma_1 - \gamma_2 = 2\alpha \tag{5.3.2}$$

Now γ_1 and γ_2 can be eliminated:

$$
\begin{aligned}
\gamma_1 &= \pi + \alpha - \beta_1 \\
\gamma_2 &= \pi - \alpha - \beta_2
\end{aligned}
\tag{5.3.3}
$$

By using the well-known relations of cosine and sinus

$$
\begin{aligned}
cos(a \pm b) &= cos(a)cos(b) \pm sin(a)sin(b) \\
sin(a \pm b) &= sin(a)cos(b) \pm cos(a)sin(b)
\end{aligned}
$$

and keeping in mind that $Sin(\pi) = 0$ and $cos(\pi) = -1$ the following relations can be established:

$$
\begin{aligned}
sin(\gamma_1) &= sin(\pi + \alpha)cos(\beta_1) - cos(\pi + \alpha)sin(\beta_1) \\
&= [sin(\pi)cos(\alpha) + cos(\pi)sin(\alpha)]cos(\beta_1) - [cos(\pi)cos(\alpha) - sin(\pi)sin(\alpha)]sin(\beta_1) \\
&= -sin(\alpha)cos(\beta_1) + cos(\alpha)sin(\beta_1) \\
sin(\gamma_2) &= sin(\pi - \alpha)cos(\beta_2) - cos(\pi - \alpha)sin(\beta_2) \\
&= [sin(\pi)cos(\alpha) - cos(\pi)sin(\alpha)]cos(\beta_2) - [cos(\pi)cos(\alpha) + sin(\pi)sin(\alpha)]sin(\beta_2) \\
&= sin(\alpha)cos(\beta_2) + cos(\alpha)sin(\beta_2)
\end{aligned}
\tag{5.3.4}
$$

To give a better overview of the equations, all cosine and sinus elements are replaced by a variable as follows:

$$x_1 = sin(\beta_1)$$
$$x_2 = sin(\beta_2)$$
$$y = sin(\alpha)$$

which according to the context between cosine and sinus gives:

$$cos(\beta_1) = -\sqrt{1 - x_1^2}$$
$$cos(\beta_2) = -\sqrt{1 - x_2^2}$$
$$cos(\alpha) = \sqrt{1 - y^2}$$

By implementing these variables the equations from 5.3.4 can be simplified to:

$$\begin{aligned} sin(\gamma_1) &= y\sqrt{1 - x_1^2} + \sqrt{1 - y^2}x_1 \\ sin(\gamma_2) &= -y\sqrt{1 - x_2^2} + \sqrt{1 - y^2}x_2 \end{aligned} \tag{5.3.5}$$

The moment equilibrium of CM, represented through equation (3), can by implementing new variables for $sin(\gamma_1)$ and $sin(\gamma_2)$, now be written as:

$$S_1[-y\sqrt{1 - x_1^2} + x_1\sqrt{1 - y^2}] = S_2[y\sqrt{1 - x_2^2} + x_2\sqrt{1 - y^2}] \tag{5.3.6}$$

This equation, together with equation (1), (2), (6) and (7) now represents 5 independent equations, presented below.

$$F = S_1 cos\beta_1 - S_2 cos\beta_2$$
$$\Rightarrow F = -S_1\sqrt{1 - x_1^2} + S_2\sqrt{1 - x_2^2}$$

$$B = S_1 sin\beta_1 + S_2 sin\beta_2$$
$$\Rightarrow B = S_1 x_1 + S_2 x_2$$

$$L = acos\beta_1 + dcos\alpha + acos\beta_2$$
$$\Rightarrow L = d\sqrt{1 - y^2} + a(\sqrt{1 - x_1^2} + \sqrt{1 - x_2^2})$$

$$0 = asin\beta_1 + dsin\alpha - asin\beta_2$$
$$\Rightarrow 0 = ax_1 + dy - ax_1$$

The five independent equations with five unknown parameters, S_1, S_2, x_1, x_2 and y:

$$\begin{aligned} F &= -S_1\sqrt{1-x_1^2} + S_2\sqrt{1-x_2^2} \ (1) \\ B &= S_1x_1 + S_2x_2 \ (2) \\ L &= d\sqrt{1-y^2} + a(\sqrt{1-x_1^2} + \sqrt{1-x_2^2}) \ (3) \\ 0 &= ax_1 + dy - ax_2 \ (4) \\ S_1[-y\sqrt{1-x_1^2} + x_1\sqrt{1-y^2}] &= S_2[y\sqrt{1-x_2^2} + x_2\sqrt{1-y^2}] \ (5) \end{aligned} \tag{5.3.7}$$

Equation (4) can be written as:

$$x_2 = x_1 + \frac{d}{a}y \ (4a)$$

Using (4a) in Equation (2)

$$\begin{aligned} B &= S_1x_1 + S_2x_2 + S_2dy/a \\ \Rightarrow S_1 &= B/x_1 - S_2(1 + dy/ax_1) = (B - S_2x_2)/x_1 \end{aligned}$$

Equation (1) can then be written as

$$\begin{aligned} F &= B\sqrt{1-x_1^2}/x_1 - S_2\sqrt{1-x_1^2}(1 + yd/ax_1) - S_2\sqrt{1-x_2} \\ &= B\sqrt{1-x_1^2}/x_1 - S_2[\sqrt{1-x_1^2}(1 + yd/ax_1) + \sqrt{1-(x_1+yd/a)^2}] \end{aligned}$$

Now S_2 ca be expressed as:

$$\begin{aligned} S_2 &= \frac{B\sqrt{1-x_1^2}/x_1 - F}{\sqrt{1-x_1^2}(1+yd/ax_1) - \sqrt{1-(x_1+yd/a)^2}} \\ &= \frac{B\sqrt{1-x_1^2} - Fx_1}{x_2\sqrt{1-x_1^2} - x_1\sqrt{1-x_2^2}} \end{aligned}$$

Using the expression for S_2 in Equation (3):

$$L - d\sqrt{1-y^2} - a[\sqrt{1-x_1^2} + \sqrt{1-(x_1+yd/a)^2}] = 0 \ (3a)$$

The last part Equation (3a) above is equivalent to $\sqrt{1-x_2^2}$.

By implementing $S_2(x_1, y)$, $S_1(x_1, y)$ and $x_2(x_1, y)$ in Equation (5), the following can be expressed:

$$S_2(y\sqrt{1-x_2^2} + x_2\sqrt{1-y^2}) - S_1(x_1\sqrt{1-y^2} - y\sqrt{1-x_1^2}) = 0 \ (5a)$$

Equation (3a) and (5a) now represent two independent equations.

Letting $f_3(x_1, y)$ and $f_5(x_1, y)$ represent the left side of respectively (3a) and (5a), and introducing the plane for (x_1, y). These three planes can now be plotted together in the same plot and the intersection-line between all three planes will represent the solution. A check for S_1 and S_2 was performed to make sure that these were correct, the check can be found in Appendix C.

The script for plotting the planes numerical can be found in Appendix D. It turned out that equation (5a) varies quite a lot faster than (3a). To improve this, dimensionless values was introduced:

$$\phi = F/L$$
$$\sigma_j = S_j/B \ (j = 1, 2)$$
$$\delta = d/L$$
$$\epsilon = a/L$$
$$\alpha = a/L$$

The scale factor for the analysis in MATLAB was chosen too 0.02. By increasing the value of F, it is now possible to see how this affects the value of tilt-angle, α in the script. An example of a solution represented by the intersection of the three planes can be seen in Figure 5.3.3.

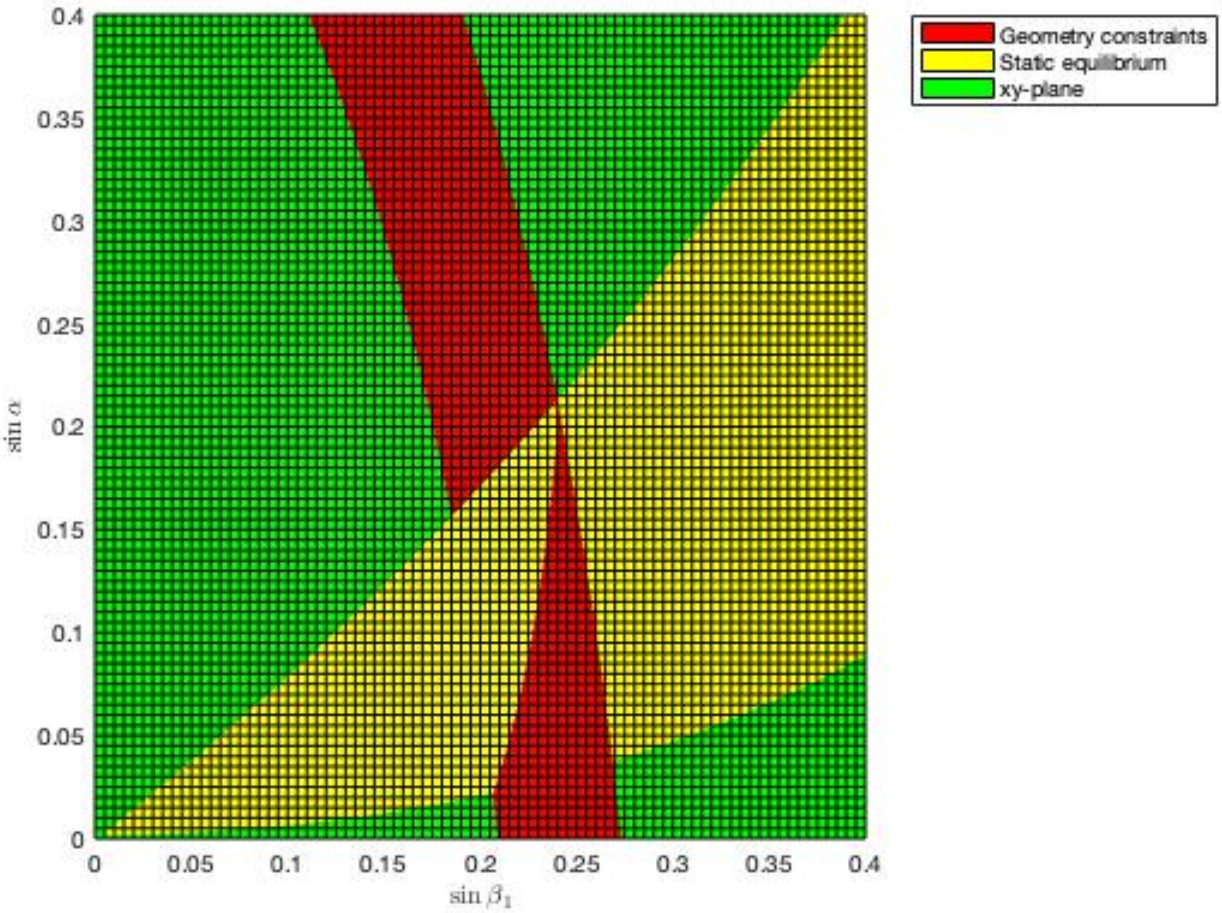


Figure 5.3.3: Graphical illustration of the intersection between the three planes of the 2D problem of the air-dome.

Here the force is set to 10 kN, and a minimum buoyancy force for H_{min} = $10cm$, corresponding to B = 20kn, is used. The red plane is an expression of the geometry, the connection between x_1, x_2 and y, of the air-dome, and are not affected by the change of the force, F. However, if the values of for example d or a is changed, the red plane will change as well. As can be seen from the figure this gives a value of $sin(\alpha)$ = 0.02, corresponding to α = 1.15°. By increasing the value of F the intersection point will move upwards to the right. An F-value close to 0 will move the intersection line close to y = 0. To illustrate the changes, and as a check that the script is working as desired, Figure 5.3.4 and 5.3.5 shows the results from the script when the force, F, is set to respectively 0kN and 40kN.

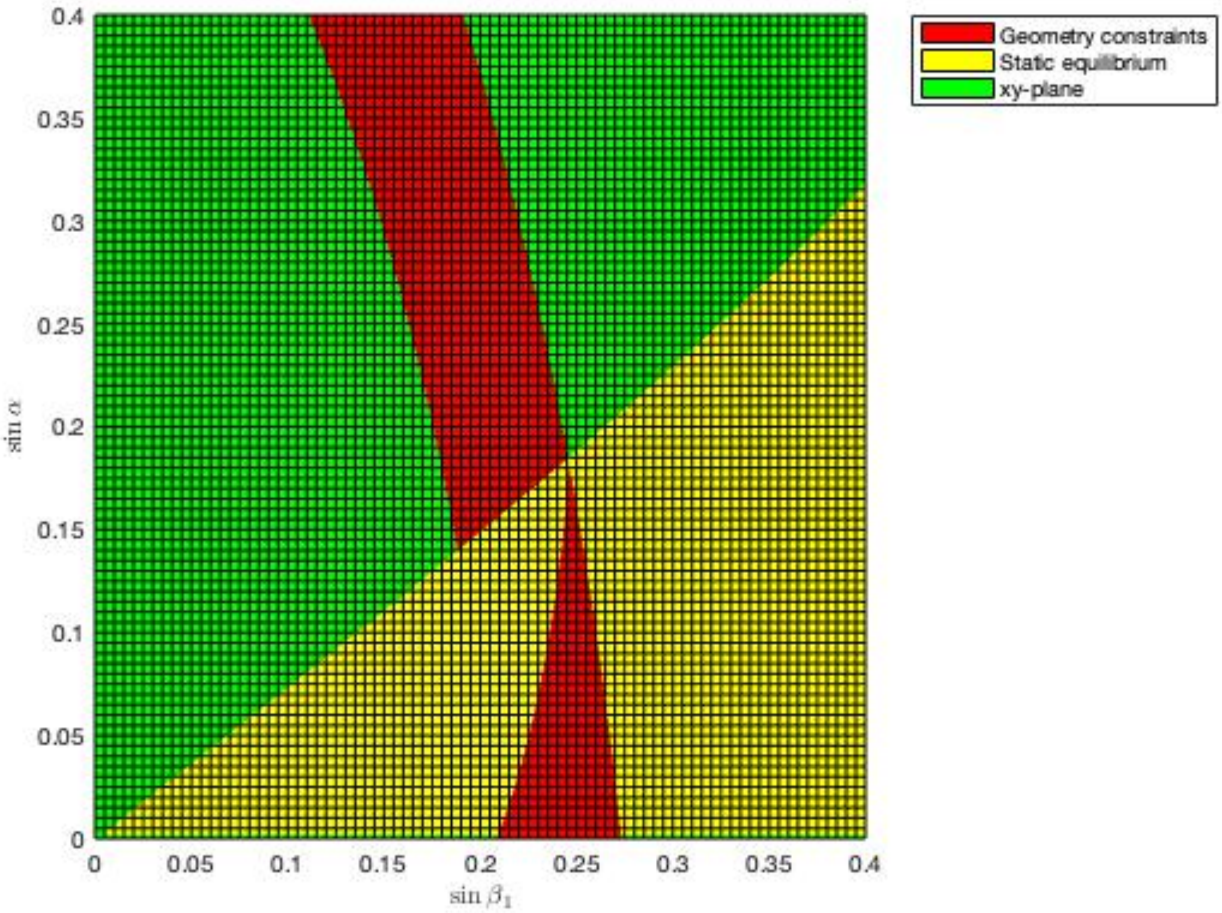


Figure 5.3.4: Graphical illustration of the Intersection between the three independent planes when F = 0

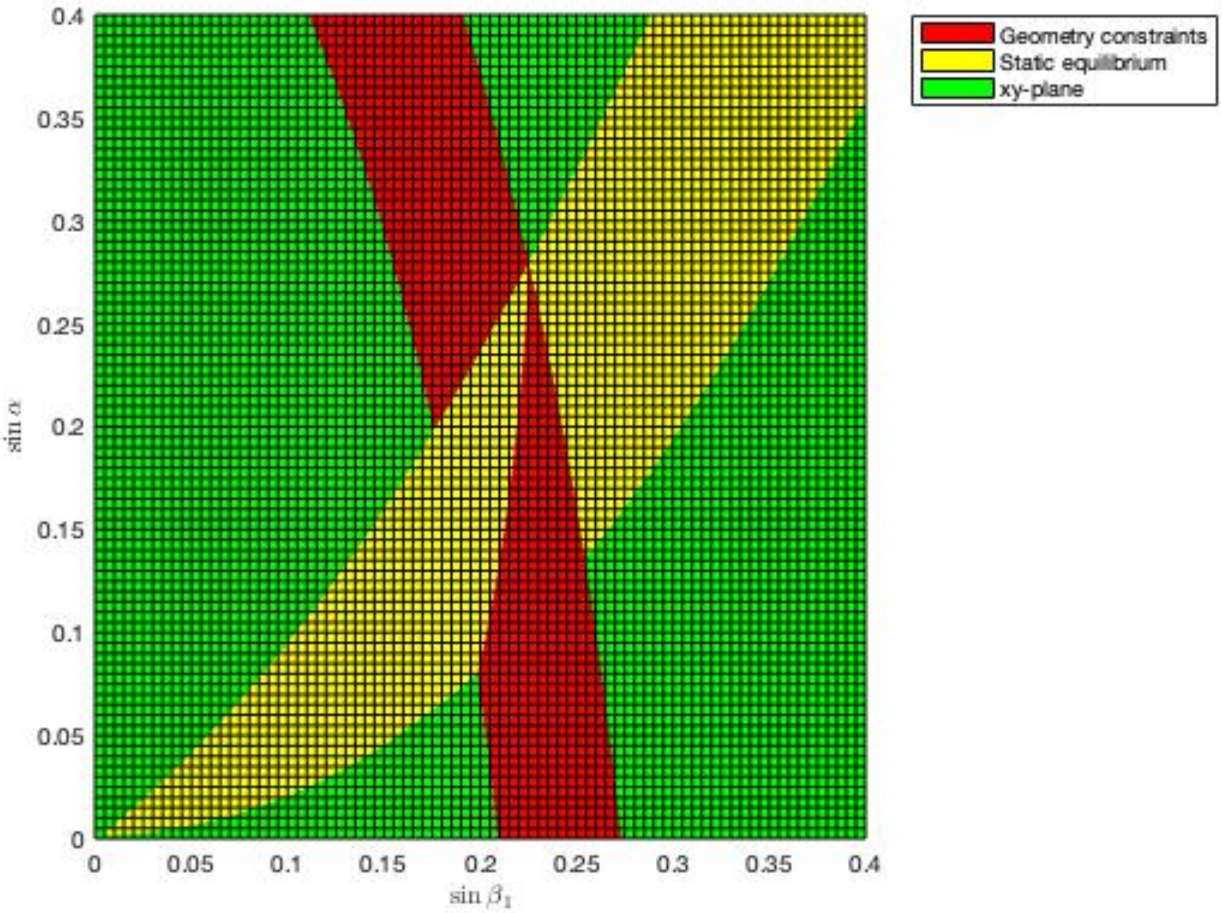


Figure 5.3.5: Graphical illustration of the intersection between the three independent planes when F = 40kN

As can be seen, the yellow plane moves when the value of F is changing and then consequently the intersection-line between the three planes. As seen from Figure 5.3.4, where F = 0kN, the intersection line is lying close to y = 0, as expected. In Figure 5.3.5, where F = 40kN the intersection line has moved quite much higher and to the right. This proves that the numerical script works as desired. And from the result of the numerical script, it is now possible to establish the connection between the amount of force and the tilt-angle of the air-dome.

Discussion

The angles for the mooring lines, μ, are assumed small. Information from AKVA Group set an estimate that the angle would lie somewhere between 5-25 degrees. However, it was informed that angels of the smaller value were more likely than large angles. In the numerical analysis done above μ was assumed to be 10 degrees. This sets the value for the length of the mooring lines, a, between the floating collar and air-dome. In Chapter 6 different results from the numerical analysis will be presented to illustrating how different parameters affect each other and the behavior of the air-dome.

5.3.2 Establishing Maximum Tilt-angle

As mentioned, the main issue for this report, regarding the hydrodynamic aspect, is to find the force, F, causing a maximum allowable tilt-angle α. As mentioned at the beginning of this case study the maximum angle will be set to when the air-dome begins to lose air. The maximum angle α is decided by how large the draft is inside the air-dome. Figure 5.3.6 illustrates how the maximum tilt-angle can be found given the dimensions of the air-dome.

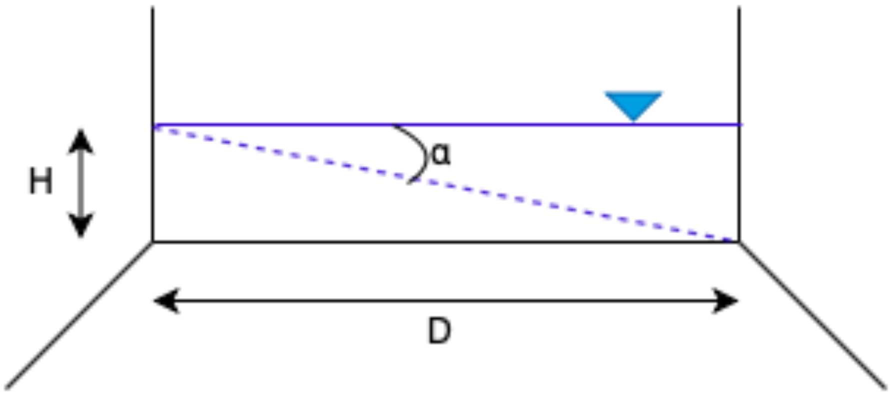


Figure 5.3.6: illustration of how the maximum tilt-angle can be found given the dimensions of the air-dome.

The angle α can then be found through the following equation :

$$\alpha = tan^{-1}(\frac{H}{D}) \tag{5.3.8}$$

Figure 5.3.7 illustrates the connection between the tilt-angle and the draft graphical. As can be seen, the larger the draft the larger the tilt-angle has to be before the air-dome begins to lose air. This is a logical result and it will consequently require a larger force to tilt the air-dome to an angle where it begins to lose air when the angle is large.

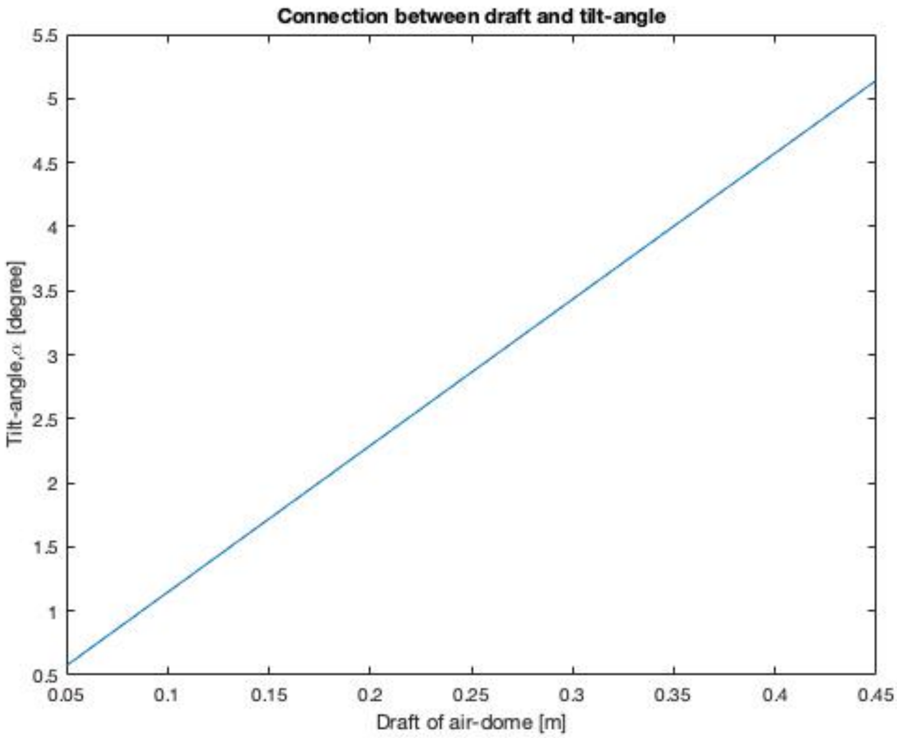


Figure 5.3.7: Illustration of the connection between the draft and the tilt-angle.

Two heights of the draft and then consequently two different maximum tilt-angles where calculated. These two tilt-angles where afterward run through the numerical analysis in MATLAB, conducted in the section before, finding the force causing the respective angles. All values and relations are shown in Table 5.3.1

Table 5.3.1: Hydrodynamic restrictions for air-dome

Draft	Tilt-angle, α	Force, F
10 [cm]	1.2°	10 [kN]
15 [cm]	1.7°	15 [kN]

For these calculations, a, B and μ are assumed constant, while the draft is varying. The force found by the numerical analysis will then be used to set the hydrodynamic restrictions for the tradespace exploration.

5.3.3 Hydrodynamic Restriction for Tradespace Exploration

The force, F, is described by the drag force on the air-dome, caused by the current. To establish the maximum area of the air-dome given the value of the force, F, the total drag on the air-dome is calculated. For the calculations, the air-dome is simplified into a cylinder with a half sphere top, as shown in Figure 5.3.8.

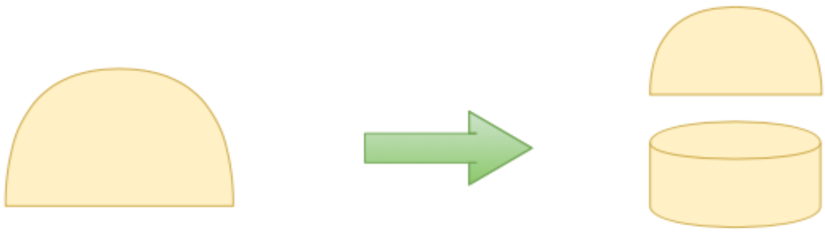


Figure 5.3.8: Illustration of the air-dome simplified into a cylinder with a half-sphere top.

Calculating drag for air-dome

The drag is calculated by the use of Morison's equations as presented below:

$$F_D = \frac{1}{2}\rho C_D A U^2 \tag{5.3.9}$$

Where A is the area of the air-dome, U is the current velocity, ρ is the density of water and C_D is the drag coefficient. The drag coefficient is found by the use of Reynolds number, calculated by Equation 5.3.10 below;

$$Re = \frac{D\rho V}{\mu} \tag{5.3.10}$$

Where, D is the diameter, and V is the velocity of current, ρ and μ for seawater have the following values [50], $\mu = 1.218 \cdot 10^{-3} Kg/ms$, $\rho = 1025 Kg/m^3$.

When Reynolds number has been calculated the drag coefficient is found through the graph shown in Figure 5.3.9.

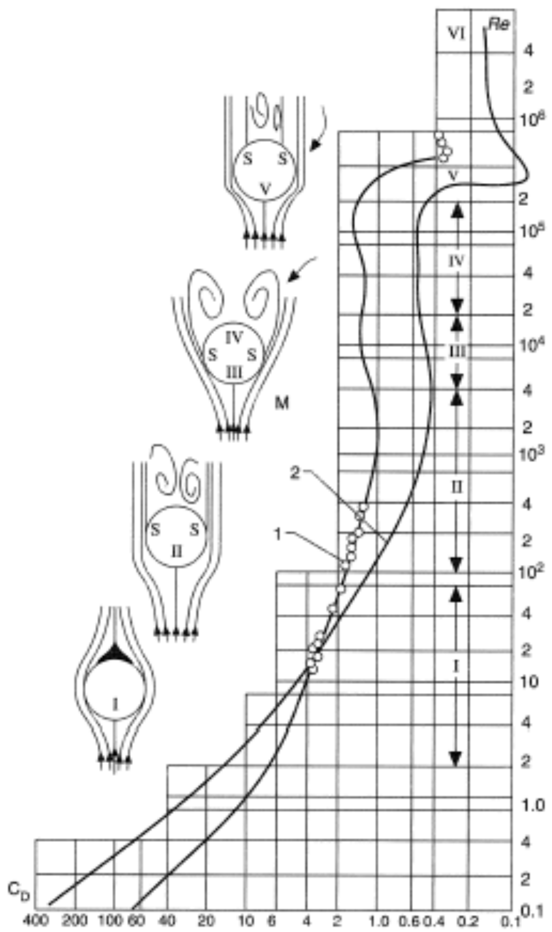


Figure 5.3.9: Illustration of how the drag coefficient for (1) cylinder and (2) sphere can be found from the Reynolds number.

A Reynolds number of $Re = 4.26 * 10^4$ gives as drag coefficient of $C_D = 1.2$ for the cylinder and $C_D = 0.41$ for the sphere-top. The total drag force depending on the different height of the air-dome are presented graphically in Figure 5.3.10. The calculations are done in MATLAB, and the script can be found in Appendix B. The height of the air-dome in the calculations varied between 0.01-0.5m. The height represents the height before the air-dome starts to curve, in other words, the height of the cylinder part when the air-dome is simplified into a cylinder with a half-sphere top.

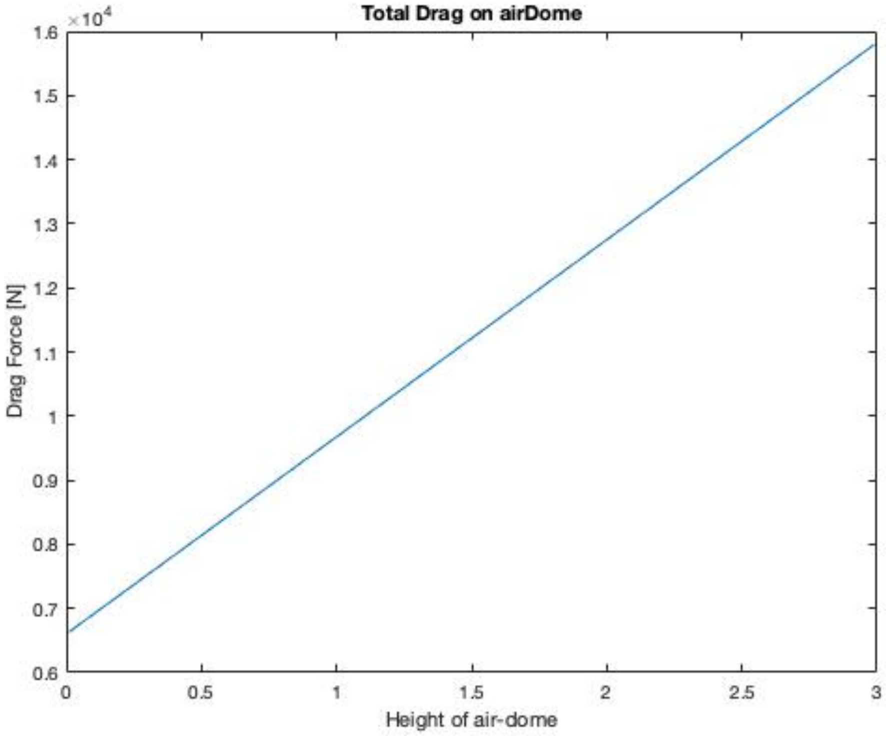


Figure 5.3.10: Graphical illustration of total drag for different heights on air-dome

From the calculations of drag force the maximum height of the air-dome, given the forces from the numerical analysis of the tilt-angle, can be established. Table 5.3.2 summarizes the relations and maximum heights that will be used as the hydrodynamic restrictions in the tradespace exploration.

Table 5.3.2: Hydrodynamic restrictions from drag force

Max tilt-angle, α	Drag force	Max height of air-dome
1.2°	10 [kN]	1.1 [m]
1.7°	15 [kN]	2.7 [m]

For the tradesapce exploration any design option that lies above these restrictions will be removed as an unfeasible design.

5.4 Performance Attributes

After a functional breakdown of the air-dome the following performance attributes were chosen, Table 5.4.1.

Table 5.4.1: Performance attributes

Performance attribute	Unit	Weight
Drag force	[kN]	0.4
Stability(tilt-angle of air-dome)	[deg]	0.6

These performance attributes are chosen since they are assumed to give the most value for the air-dome design. The stability(tilt-angle) were weighted higher since the tilt-angle is the most critical issue for the air-dome. The air-dome may withstand a certain amount of drag force but any degree of tilt-angle is considered undesirable. Both height, diameter and curvature will affect the drag force and stability(angle) of the air-dome. The utility for the performance attributes was calculated according to the following equation:

$$U_{design} = \frac{design(i) - Design_{min}}{Design_{max} - Design_{min}} \tag{5.4.1}$$

5.5 Design Variables

Based on the performance attributes four design variables were selected, presented in Table 5.5.1.

Table 5.5.1: Design variables

Design variables	Unit	Min	Max
Height	[m]	0.01	3.0
Diameter	[m]	1	8
Thickness	[m]	0.005	0.015
Curvature	[-]		

Curvature

The curvature of the air-dome will have an effect on the force acting on it and also on the stability in a submerged condition. However, there is no satisfying way to estimate the impact the different curvatures have on the experienced force. The impact from different types of curvature should be tested experimentally to give an idea of how much the different curvatures have to say for the experienced force. Therefore, for this thesis, the air-dome is always simplified into known geometries e.g. the way the air-dome is simplified in Figure 5.5.1, by dividing it into a cylinder part and a spherical part.

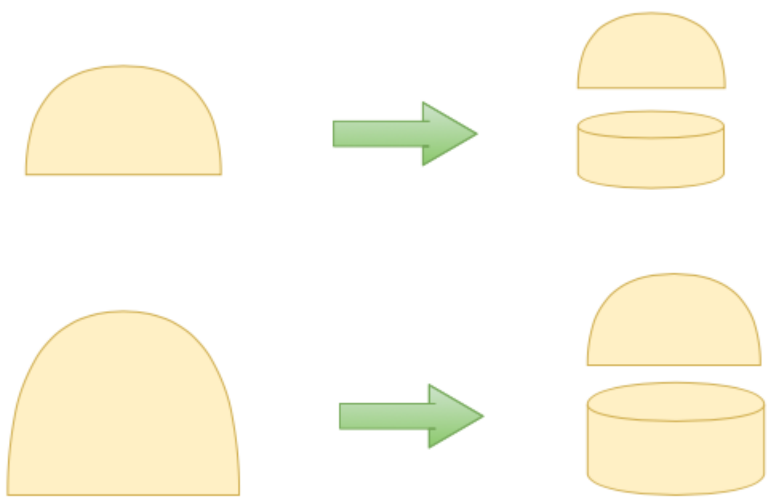


Figure 5.5.1: Illustration how to simplify the geometry of the air-dome

As can be seen from the figure the air-dome can always be simplified into a cylinder with a spherical top no matter the curvature before the simplification, only the height of the cylinder will vary. Based on these simplifications the curvature of the air-dome will not be discussed any further in this thesis and will not be considered as a design variable in the analysis of this case study. The design variables used in this analysis are height, diameter and thickness, with a test range as presented in Table 5.5.1.

5.6 Cost Model

The capital expenditure is seen as a function of:

- **Material of air-dome**
  The size of the air-dome defines the material cost of the air-dome.
- **Equipment**
  The equipment for the air-dome covers everything but the material and are all a

fixed cost.

Equation 5.6.1 presents the total CAPEX function for the air-dome.

$$CAPEX = E + M_c \cdot V_{AD} \tag{5.6.1}$$

Where E represents the fixed cost for equipment, M_c the material cost and V_{AD} the volume of the air-dome. An additional factor that may be considered for the cost model in the future is the cost of buying the development license and convert it to a commercial license. However, this is not taken into account here.

All expenditures regarding the air-dome are illustrated in Figure 5.6.1. To estimate the cost for material, the shape of the air-dome has been assumed. The shape that the calculations are based upon has a geometry like a cylinder with a spherical top as was illustrated in Figure 5.5.1.

Figure 5.6.1: Illustration of expenditure regarding the air-dome

Material

The equation for the total volume of the air-dome, used to calculate the cost of material are as follows;

$$Volume\ of\ half-sphere,\ V_1 = \frac{1}{2}\frac{4}{3}\pi r^3 - \frac{1}{2}\frac{4}{3}\pi(r-t)^3 \tag{5.6.2}$$

$$Volume\ of\ cylinder,\ V_2 = \pi r^2 h - \pi(r-t)^2 h \tag{5.6.3}$$

$$Total\ volume\ of\ airdome = V_1 + V_2 \tag{5.6.4}$$

Here r representing the thickness of the air-dome.
From the bachelor report on material for the air-dome, [40], Polypropylene was recommended as material. Polypropylene has a density of $903kg/m^3$. Making the total mass of polypropylene needed for the air-dome as follows;

$$Mass\ needed\ of\ polypropylene = Total\ volume\ of\ airdome \cdot 903kg/m^3 \tag{5.6.5}$$

The price per kg for polypropylene lies between 9.39-11.1 NOK/kg [40]. A price of 11 NOK/Kg is assumed for this thesis.

Mooring and Air Supply

From the information provided by AKVA Group, it was informed that the air-dome would have 20 mooring lines connected directly to the dome, in addition to the standard mooring. These mooring lines are connected directly to the floating collar going through the roof net and connected at the bottom of the air-dome to keep it stable. The air supply will be provided through some kind of pump system going through the top of the air-dome. The equipment and price concerning the air supply are classified information until further notice. As an estimate regarding the extra mooring lines and the air supply, an overall price of 150 000 is assumed, based on discussions with professors and fellow students.

Camera & Sensors

The cameras are used to observe the feeding activity under water and the behavior of the fish. The cameras can register when the salmon is sexually mature, the appetite of the fish and death rate, as well as general observation of the submerged cage. An example of an underwater camera that is used is *Akvasmart smartEYE*, produced by AKVA Group. Akvasmart smartEYE consists of two cameras which are extra sensitive to light and delivers clear photos even in the darkest areas of the cage. Sensors are used to increase the safety of operations and prevent unwanted incidents e.g escape of fish, human accidents.

A sensor system that is widely used is *AKVA Safe guard*, which is based on observing parameters that early can predict changes for the cage system or the fish, as well as the safety level if operations are to be performed. For one cage system, the estimated price for cameras and sensors with all its equipment is assumed to be 130 000 [45], [7].

Underwater Feeding System

Similarly to the information about the air supply is the information about the underwater feeding system also classified information. However, a few new underwater concepts have been developed over the past few years. One of them is *AKVA Subsea feeder*, where the feed is applied down to the cage through an ordinary feed hose and compressed air. Then the feed is spread through 12 distribution pipes for best possible spreading. The estimated price for this type of feeding system with all its equipment is approximately 110 000 NOK,[45], [7]. Keeping in mind that this is not the system that is used to feed through the air-dome it is assumed the same price as for the AKVA Subsea feeder.

Table 5.6.1: Initial estimation of cost for the air-dome.

Material	varies according to shape	NOK
Underwater feeding system	110 000	NOK
Mooring & air supply	150 000	NOK
Camera and Sensors	130 000	NOK
Total estimated fixed cost for air-dome	390 000	NOK

The CAPEX function is an important part of the tradespace exploration, since there always will be trade-offs between more utility and costs when a design is built. The cost regarding the sea lice cost is not taken into consideration in the tradespace analysis since it assumed that the sea lice problem will be solved by lowering the cage down to 10-15m.

5.7 Tradespace Evaluation and Pareto Front

Through a tradespace evaluation utility for each point design will be calculated according to the described performance attributes and cost model. The script for the tradespace exploration can be found in Appendix E. To find the optimal designs that will give the highest utility for a specific cost a Pareto front is established. The Pareto front algorithm goes through all the possible design and saves the optimal designs for each cost, creating a Pareto front. A typical tradespace is shown in Figure 5.7.1. In this figure, every red point illustrates a possible design, while the blue point indicates the designs lying on the Pareto front.

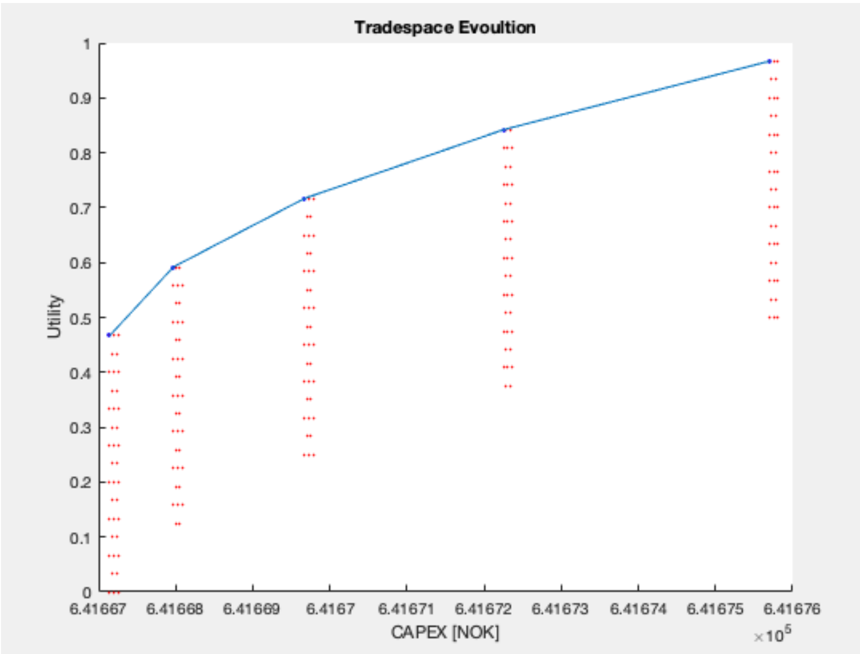


Figure 5.7.1: Example of result form tradespace evolution

Chapter 6

Results

This chapter presents the results from the tradespace exploration as well as some interesting results discovered from the numerical analysis of the hydrodynamic aspect of the air-dome. Discussion on the validity of these results are presented in Chapter 7.

The tradespace exploration was generated based on information gathered through the case study. Each design is plotted according to the performance attribute and cost for the respective design. Design options that lie along the pareto line are the most promising based on the chosen restrictions for the case study and the weighting of the utility function. The figure below illustrates the tradespace exploration where the hydrodynamic restriction is set to a max height is 2.7m for the air-dome.

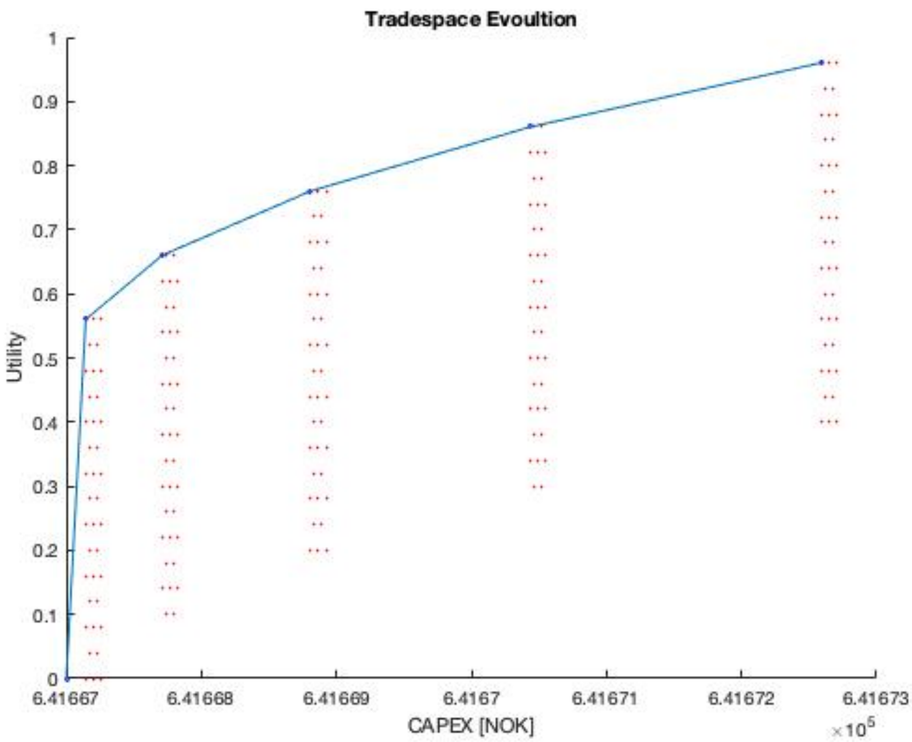
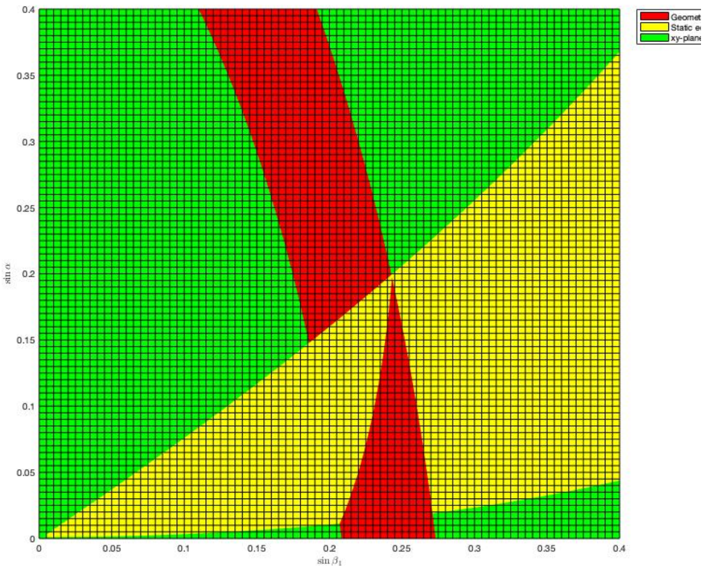


Figure 6.0.1: Result from the tradespace exploration where the hydrodynamic restrictions are set to a maximum height of 2.7m

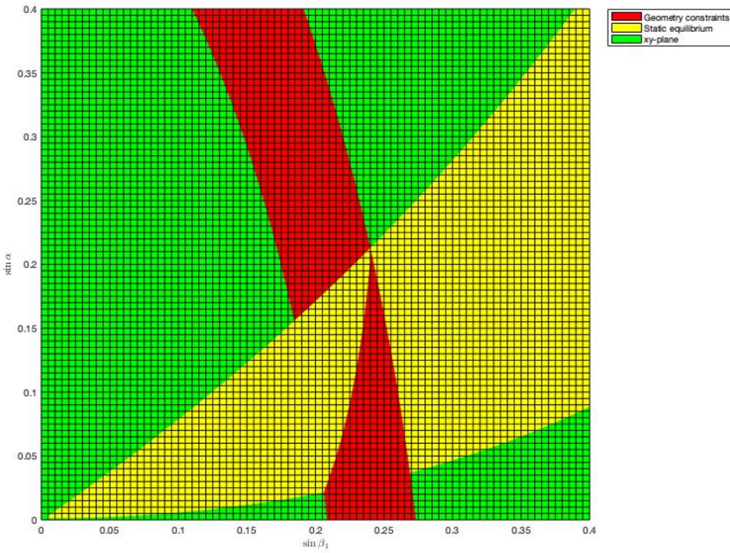
It can be seen that the trade-off between utility and cost is quite small at the beginning, while it is a large gap and then consequently more expensive to go from a utility of 0.8 up to 1. A question for the decision maker would be if this extra utility is worth the extra cost or not. This illustrates the advantages of using tradespace exploration as the methodology for investigating designs. It is easy for the decision maker to go into the analysis which is graphically arranged in the way a tradespace analysis is illustrated. Changing the hydrodynamic restriction from 2.7m to 1.1m does not change the parteo front and then consequently the design that gives most utility. However, the design space gets quite much smaller when the restriction is set to 1.1m compared to 2.7m since several design options are set to unfeasible designs.

The problem, however, with the tradespace exploration performed in this case study is the utility function of the analysis. Due to how the tradespace exploration is performed the decision maker has a severe influence on the outcome of the analysis, due to the weighting of the utility attributes. From the results of the tradespace exploration on the air-dome it came clear that the answer to the result was already "known" before the analysis was performed, based on how the weighting was chosen for the utility attributes. The choice of tradespace analysis for this type of design problem proved to not be the most ideal way to solve this type of concept study. A more thorough discussion of the tradespace exploration and the shortcomings of it will be presented in Chapter 7.

From the case study, performing all the steps points building up the tradespace exploration, it came clear that the stability and drag force were the most important attributes for the air-dome system. Since the tradespace exploration did not give as satisfying results as desired, investigating the drag force and the stability explicit is another interesting approach that can be conducted from the information gathered in the case study. At the end of Section 5.3.2 two results from the numerical script were presented to check that the script worked as desired. Here the force was changed to illustrate that the tilt-angle consequently also changed. Below six graphical illustrations are presented to investigate more deeply the connection between the force and the stability, represented by the tilt-angle.

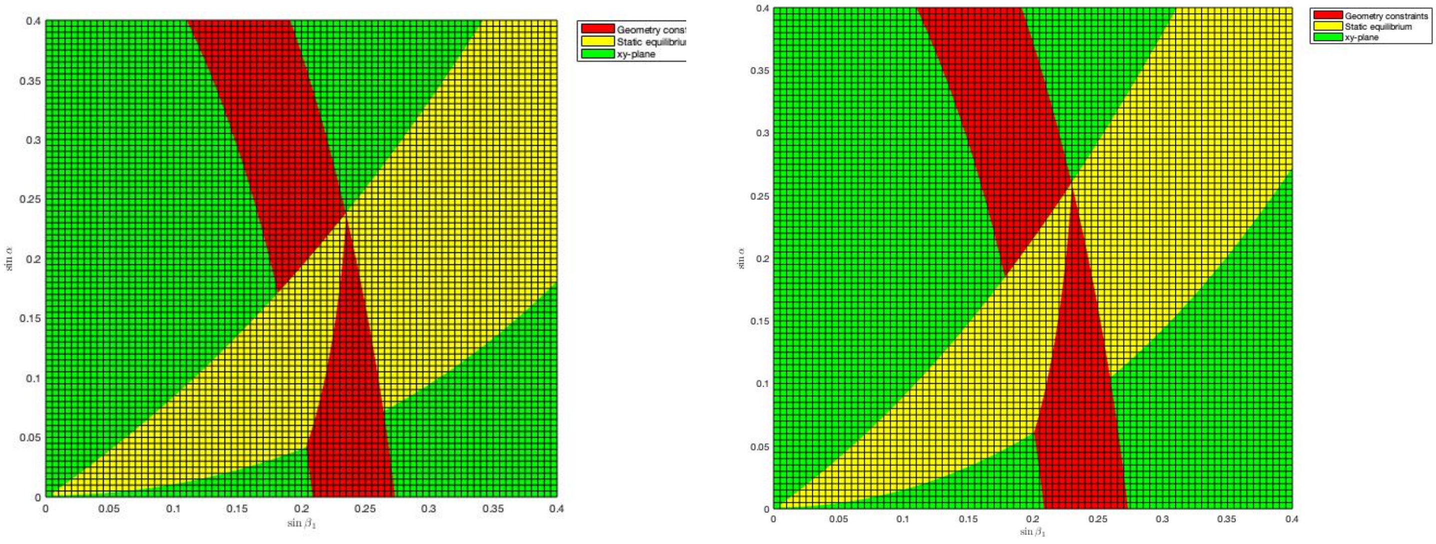


(a) Graphical illustration of the intersection line when F= 5000kN, giving a tilt-angle α = 0.6.



(b) Graphical illustration of the intersection line when F= 10000kN, giving a tilt-angle α = 1.15.

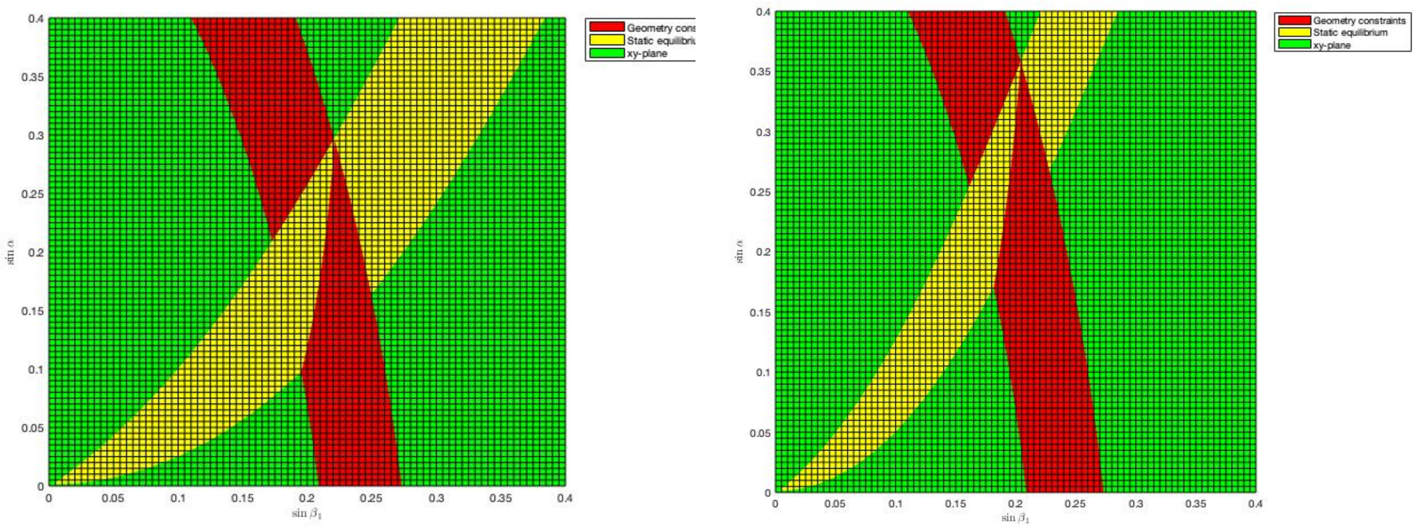
Figure 6.0.2: Illustration of hoe the stability change when the force changes from F=5000kN to F=10000kN.



(a) Graphical illustration of the intersection line when F= 20000kN, giving a tilt-angle α = 2.3.

(b) Graphical illustration of the intersection line when F = 30000kN, giving a tilt-angle α = 3.4.

Figure 6.0.3: Illustration of hoe the stability change when the force changes from F=20000kN to F=30000kN.



(a) Graphical illustration of the intersection line when F= 50000kN, giving a tilt-angle α = 5.5.

(b) Graphical illustration of the intersection line when F= 100000kN, giving a tilt-angle α = 9.8.

Figure 6.0.4: Illustration of hoe the stability change when the force changes from F=50000kN to F=100000kN.

In the six plots presented above all other parameters, including buoyancy force and mooring length, and mooring angle μ are held constant through all the investigations to explicit present the connection of the force and the stability. As can be observed from the plots of the intersection line, the amount of force has a great impact on the stability of the air-dome. For example, by increasing the force twice as much, from 10000kN to 20000 kN, it can be seen that the tilt-angle increases almost twice as much as well. The force set to 100kN is unlikely to occur but indicates what amount of force that is required to reach a tilt-angle of almost 10°.

In addition to the tradespace evolution and the investigation of drag force and stability, the investigation from the hydrodynamic aspect of the air-dome gave some interesting results about the connection between other parameters. The MATLAB script generated to illustrate the connection between the force and the tilt-angle, α, can also be used to investigate how changing other variables will affect the air-dome. For instance, changing the angle for the mooring line, μ, proved to change the intersection line drastically, between the three planes. The two figures below illustrate the change when the angle of the mooring line is set to respectively μ = 5° and μ = 15°.

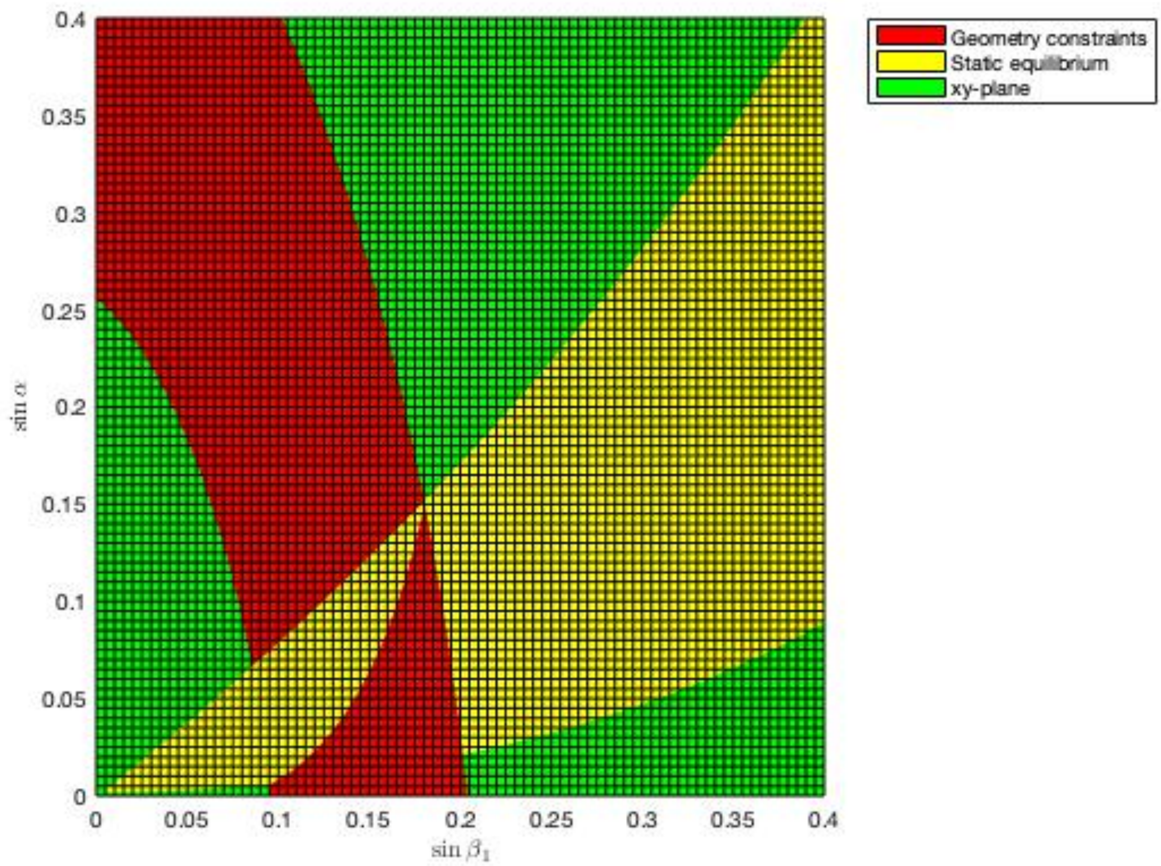


Figure 6.0.5: Intersection between the three independent planes when F = 10kN and μ = 5°

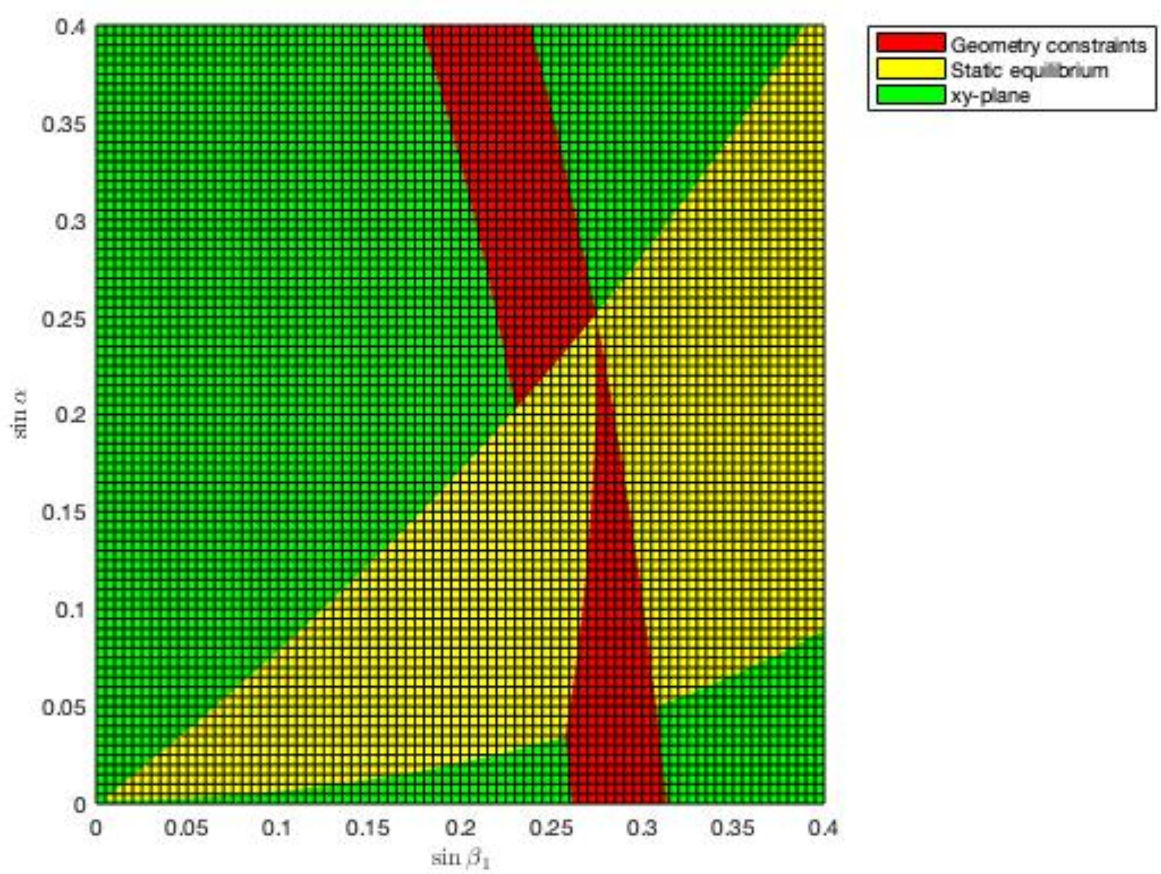


Figure 6.0.6: Intersection between the three independent planes when F = 10kN and μ = 15°

Here the force and buoyancy force is held constant for both results to show the effect of changing the angle of the mooring line, μ. As can be seen from the two figures, when the air-dome is affected by a given force a large mooring angle, μ, gives a large tilt-angle, α. Compared to a small mooring angle, which gives a small tilt-angle. This indicates that a small mooring angle can withstand a larger force, it requires a larger force before the tilt-angle becomes as large as when μ = 15°. In other words, the system is more stable when μ is small. This is logically comparing it to a real system as well.

The effect by the amount of buoyancy was also investigated through numerical analysis. When the buoyancy force is large it is expected that it will require a higher amount of force to create the same tilt-angle as for when the buoyancy force is small. The two figures below illustrate the impact of two different values of the buoyancy force.

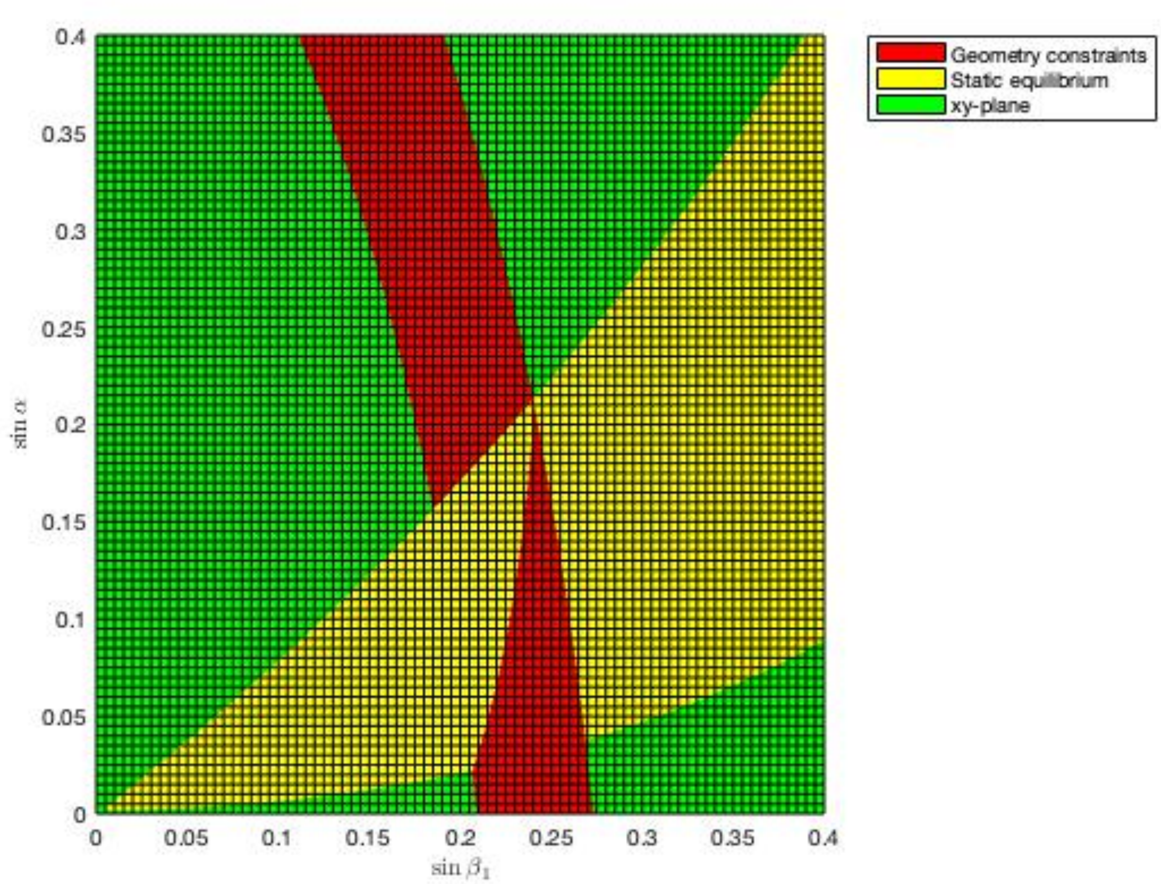


Figure 6.0.7: Intersection between the three independent planes when B = 20kN and F=10kN

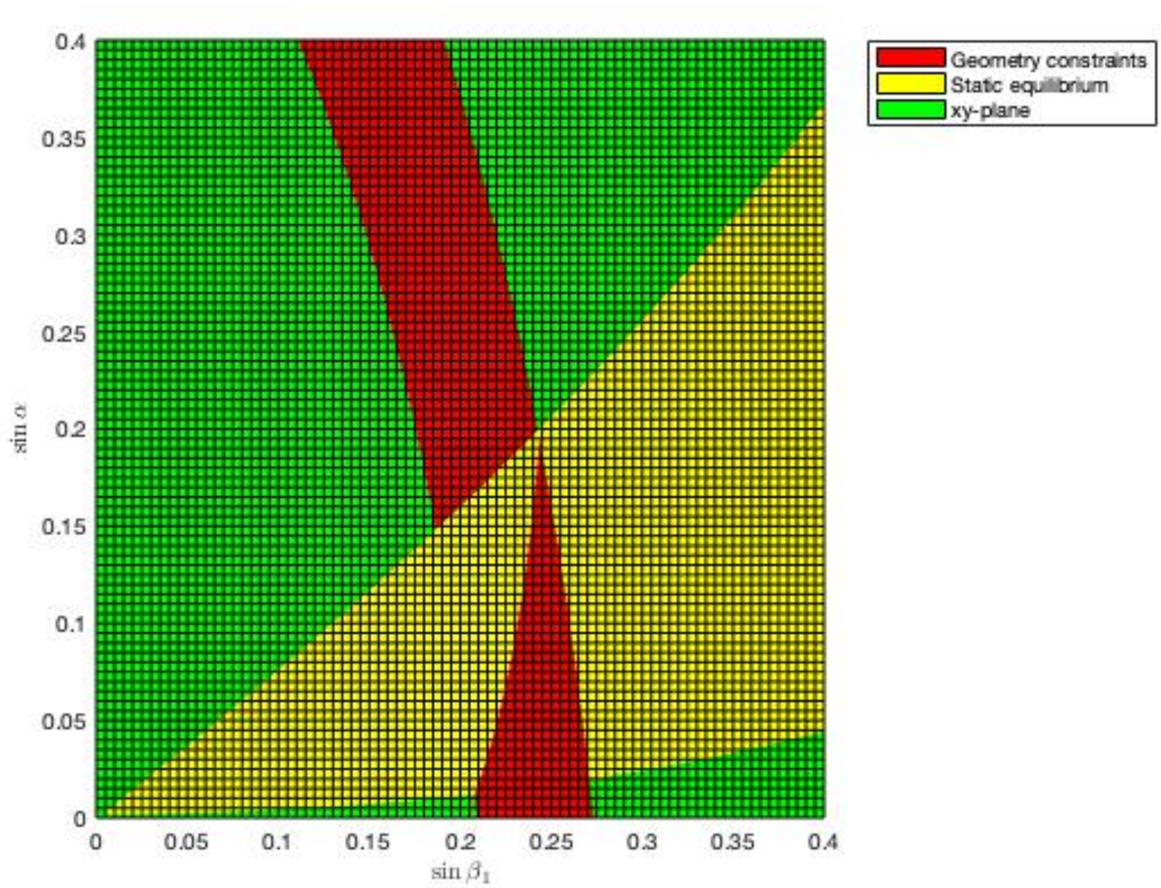


Figure 6.0.8: Intersection between the three independent planes when B = 40kN and F=10kN

As can be seen from the two graphic representations above the tilt-angle, α, is a bit larger for B = 20 kN than for B = 40kN. This is logically and as expected, since this indicates that it requires a larger amount of force to tilt the air-dome when the buoyancy force is larger. To achieve the same tilt-angle, α, when B = 40kN, as for B = 20kN, the force has to be equivalent for approximately 20kN, twice as much as it was originally.

Chapter 7

Discussion

This thesis can be seen as the first approach of conducting a concept study of the new concept of an air-dome supplying oxygen to the fish in a submerged fish farm. An overall challenge with this master thesis was to connect the hydrodynamic aspect of the air-dome with the design aspect of the air-dome. The design theory, related to the function and form domain which were introduced in the design theory, aims to understand the best possible way to find the best possible form of the design. However, implementing the hydrodynamic aspect proved to be more difficult than first expected. Due to the fact that this concept is still under development and most of the information still is classified, some assumptions throughout the report has been made. The assumptions are based on information and knowledge of aquaculture in general, as well as basic understating of the hydrodynamic aspects of a submerged geometry, similar to the air-dome. This thesis has focused on small angles and small values for the draft, height, etc. This choice was made based on that small values were most likely to be closest to the real problem. However, should the aim of focus change is the model conducted in this thesis, with all calculations and numerical analysis, easy to change for different values of interest.

From the investigation of the economic feasibility study, it came clear that the companies which are granted a development license have a great advantage even if the new concept, that was granted the development license, is not a success. This is because the companies can buy a commercial license from the development license after a given amount of time. Since the market is the way it is today a commercial license is worth up to 90mNOK, which means that the companies that are granted the development license can invest several million, in addition to buying the commercial license and still make high profit. The cost for material for the air-dome is calculated quite accurate, which gives a good estimation of the cost for the material depending on the choice of design variables. However, the rest of the cost parameters regarding the air-dome are based on assumptions that they are identical to the equipment used on a standardized floating fish farm, etc similar products. This is due to the fact that the submerged fish farm from AKVA Group is still under development, so anything regarding the equipment for the air-dome and price is held back for competitive reasons. The price estimate in this thesis will as a consequence probably differ somewhat from the actual price. Nonetheless, the aim of investigating the air-dome cost was to compare it against the delousing cost to get an idea of how much the industry would save by choosing a fish farm with this type of air-dome system. This comparison gave the impression that the air-dome and the submerged fish farm could get quite expensive and still be very profitable.

The calculations regarding the hydrodynamic aspect of the air-dome were simplified by breaking the air-dome system into a static 2D problem. The air-dome is, in reality, a 3D problem and by simplifying it to a 2D problem some of the aspects of the problem are lost. The incoming flow from the current is a 3D flow acting around the air-dome and does not act like a point-force in one point of the air-dome as assumed in the 2D simplification. However, when the flow comes in from the side, most of the forces are taken up in the first mooring lines of the air-dome. While the other ropes will experience much less force compared to the first ones. A 2D simplification is, therefore, a valid assumption for the case study performed in this thesis. The effect from the flow is dependent on the shape and since the air-dome was simplified into a very thin cylinder, this is not an accurate estimation of how the flow affects the air-dome in real life. The forces acting on the air-dome is a complex system and the movement of the air-dome will, in reality, be affected by more than the force, F, caused by the current. The air-dome is connected to 20 mooring-lines to the floating collar. The movement of the floating collar due to the current will have a great impact on the behavior of the air-dome and also how much the air-dome will tilt. However, the calculations from Chapter 5 where aiming to say something about the relationship between the force from current and the tilt-angel. The MATLAB script conducted to provide information on this issue proved to work well and was tested with known states to make sure it provides the correct relations. Keeping in mind that the script solves a 2D version of the air-dome, this script is a good starting point to understand the behavior of the air-dome better. The estimated force from the numerical analysis in MATLAB was assumed to be equivalent to the drag force acting on the air-dome. This transition is however not totally accurate since the for, F, in the 2D problem is a point force while the drag force is calculated as a 3D force around the air-dome. Keeping this in mind, the hydrodynamic investigation still provides good information on how the air-dome acts when different parameters are changed in respect to each other.

The tradespace exploration proved to not be a good choice of method to solve this new concept of the air-dome. The main problem of the tradespace method is the utility function. The utility is an aggregated estimate of asset and since the weighting of the different attributes is decided by the decision maker, the outcome is already set by the weighting before the analysis is performed. For this concept study, it was given which of the design that would end up on the pareto front and which design variables that would vary on the pareto front before the analysis was performed, due to the way each of the attributes were weighted beforehand. One of the main shortcomings of tradespace exploration is that one loses the insight that the analysis actually could give in the result, because of the way the utility function is built up. The utility attributes are known parameters from before, and the decision maker who decides the weighting among these utility attributes sits with all the power of deciding what will give the most value for the design and most likely end up on the pareto front of the tradespace exploration. This makes the tradespace exploration approach very subjective. Another approach that could have been investigated further is the trade-off between the drag force and the stability, given that these were the attributes that proved to give the most value for the air-dome system. As well, as an alternative, plotting these against the established CAPEX function and then analyzing the trade-off between the amount of stability and cost. To establish an even better understanding of the stability of the air-dome the issue regarding the righting moment and GM could have been an interesting approach. This issue was briefly discussed in Chapter 3.3.3, but was not calculated any further in the case study.

Most of this thesis focus on the design aspect of the air-dome, and the importance of the stability and the forces acting. One very important aspect to keep in mind when developing the technology and the design of the air-dome is the utilization of the air-dome. The draft, mooring angle, shape, etc of the air-dome will most likely affect how the salmon respond and uses the air-dome. If the salmon does not use the air-dome, it does not matter if the air-dome is perfectly stable.

Chapter 8

Conclusion

The purpose of this thesis was to gain a better understanding of how the air-dome behaves in a submerged condition when it is affected by forces from the current. In addition, to be able to achieve a satisfactory design of the air-dome which keeps it stable without air escaping from the air dome when it is submerged. The research questions were answered by simplified hydrodynamic approaches and calculations, and by performing a tradespace exploration.

We were able to establish the connection between the current and the tilt-angle of the air-dome numerical. By breaking the system down to a static 2D problem the solution was found by expressing the problem through three nonlinear equations. By developing a numerical script for this context, it was possible to investigate how the air-dome system behaves when the value of the various parameters was changed. This enables the designer and stakeholders to see which design parameters that affect the air-dome the most in a submerged state and which restrictions that need to be considered for the air-dome to not lose air.

The results from the tradespace exploration, unfortunately, did not give the insight which was first predicted. However, even though the actual result was not as desired, the work performed behind the tradespace analysis provided a good insight on how the system of the air-dome is built up and what are the most important design variables and attributes of this kind of system. This thesis is a first step in analyzing a brand new concept that has not yet been launched on the market. A large part of the work to design a new product is to find out what does not work. The fact that tradespace and the use of the utility function can be excluded as a good choice of the design method is therefore also a result that should be taken into consideration for further work.

8.1 Further work

The following section presents some suggestions for further work, based on the material presented in this thesis.

The topic of this thesis is a new and innovative problem. This makes room for new innovative solutions that can develop and solve many of the problems in the Norwegian aquaculture. The hope is that the work done in this thesis would inspire someone to continue to try to find the best solution and design for the air-dome for a submerged fish-farm.

This thesis only focused on one type of design for the air-dome, which is similar to a cylinder with a curved top. At the end of chapter two, several potential forms of the air-dome were presented. For further work it could have been interesting to carry out the same type of analysis as in this thesis, but where different types of design of the air-dome are compared and that the curvature is taken into account and how this will affect the rest of the design. In addition, other design techniques to solve this type of design problem should be considered and closer cooperation with the industry which is developing the same type of problem is to be recommended.

The hydrodynamic aspect of the air-dome proved to be more complex than first assumed. Even by simplifying the model to a 2D problem and trying to solve it as a static problem appeared to be quite an extensive analysis. For further work, and to understand both the calculations on paper and the behavior of the air-dome in real life, experiments should be performed. Both simplified experiments, as just a rod with to lines, would be interesting to look at. To see how much the angles change when a force is applied to get at a better understanding of the calculations of the 2D problem on paper. For the behavior of the air-dome in a submerged condition simplified experiments in a wave-tank would be a good approach. Then different current-speeds and hence different forces can be tested on the model, as a 3D model, which would improve the understanding of the air-dome to a new level. From the experiment, it should be possible to establish the amount of force that maximum can be applied to the air-dome before it starts to tilt and lose air. Then different types of designs can be tested in the same way and it should be easier to see which design that proves to be the best when forces from current are applied. If it is desirable to take the experiments even a step further, the effect of waves could be an interesting issue to investigate.

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Appendix A

Analysis of net-roof area

When the air-dome is connected to the net-roof the shape of the net-roof will look like a rounded pyramid like a frustum, see Figure. The length of the sides can be found using

$$s = \sqrt{h^2 + (R_{FC} - R_{dome})^2}. \tag{8.1.1}$$

R_{FC} is the radius of the floating collar, in this case 25 m. R_{dome} is the radius of the air dome's baseline, in this case 2.5 m. h is the distance from the center of the floating collar to the dome baseline. It can be calculated from the angle of the ropes, θ:

$$h = (R_{FC} - R_{dome}) \cdot sin(\theta). \tag{8.1.2}$$

Area of the frustum is found using

$$\pi s(R_{FC} + R_{dome}), \tag{8.1.3}$$

and furthermore the volume is

$$V = \frac{1}{3}\pi h(R_{FC}^2 + R_{dome}^2 + R_{FC}R_{dome}). \tag{8.1.4}$$

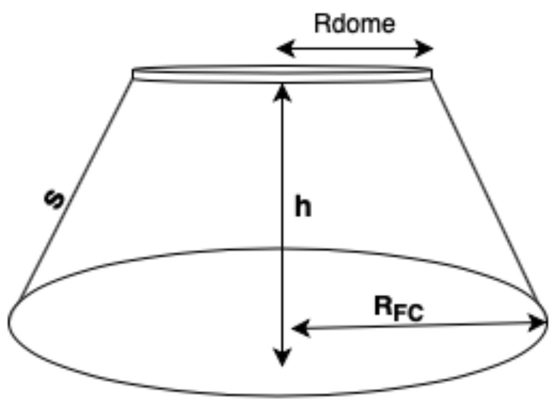

Illustration of net-roof

The following table shows how different angles affect the total lateral surface area and volume of the frustum shaped net roof.

Area and volumes of net roofs with different angles.

θ [°]	h [m]	Area [m^2]	Volume [m^2]	Area comp. to 5°	Volume comp. to 5°
5	1.97	1951.3	1431.2	0.0 %	0 %
10	3.97	1973.9	2884.2	1.2 %	102 %
15	6.03	2012.5	4380.8	3.1 %	206 %
20	8.19	2068.6	5950.0	6.0 %	316 %
25	10.49	2144.7	7620.9	9.9 %	432 %
30	12.99	2244.6	9437.1	15.0 %	559 %
35	15.75	2372.8	11442.3	21.6 %	699 %
40	18.88	2537.5	13716.2	30.0 %	858 %
45	22.5	2749.0	16346.1	40.9 %	1042 %

Appendix B

Matlab-script: Drag force air-dome

```matlab
% Calculating drag force for cylinder and half sphere

clear all
clc

%-----------------------------------------------
%Variables
rho = 1025; %[Kg/m^3]
D = 5; %Diamter [m]
dyn_visko = 1.218*10^(-3);  %[Kg/ms]
U = 1; %[m/s]

%-----------------------------------------------

H = [0.01:0.02:0.5]; %Height of cylinder

%-----------------------------------------------
%Calcualting Reynolds number and estimating Drag coefficient

Re = (D * rho * U) / dyn_visko ;

Cd_cyl = 1.2;
Cd_sphere = 0.41;

%-----------------------------------------------
%Calculating area of the cylinder and half sphere

for i = 1:length(H)
    Area_cyl(i) = D * H(i);
end

Area_sphere = 2* pi* D;

%------------------------------------------------------------
%Calculating the drag force

for i = 1:length(H)

Fd_cyl(i) = 0.5 * rho * U^2 * Cd_cyl * Area_cyl(i);
Fd_sphere = 0.5 * rho * U^2 * Cd_sphere * Area_sphere;
Fd_tot(i) = Fd_cyl(i) + Fd_sphere;

end


figure(3)
plot(H, Fd_tot)
xlabel('Height of air-dome')
ylabel('Drag Force [N]')
title('Total Drag on airDome')
```

Appendix C

Checking equations for S_1 and S_2 for the 2D problem of the air-dome

$$F = -S_1\sqrt{1-x_1^2} + S_2\sqrt{1-x_2^2} \ (1)$$

$$B = S_1 x_1 + S_2 x_2 \ (2)$$

$$L = d\sqrt{1-y^2} + a(\sqrt{1-x_1^2} + \sqrt{1-x_2^2}) \ (3)$$

$$0 = ax_1 + dy - ax_2 \ (4)$$

$$S_1[-y\sqrt{1-x_1^2} + x_1\sqrt{1-y^2}] = S_2[y\sqrt{1-x_2^2} + x_2\sqrt{1-y^2}] \ (5)$$

Checking if equations for S_1 and S_2 are correct, as presented in the report.

$$(1)\cdot x_2 + (2)\cdot\sqrt{1-x_2^2}$$

Eliminating S_2:

$$Fx_2 + B\sqrt{1-x_2^2} = S_1(x_2\sqrt{1-x_1^2} + x_1\sqrt{1-x_2})$$

$$\Rightarrow S_1 = \frac{Fx_2 + B\sqrt{1-x_2^2}}{x_2\sqrt{1-x_1^2} + x_1\sqrt{1-x_2^2}}$$

$$(= \frac{S_1 - teller}{Snevner})$$

$$(1)\cdot x_1 - (2)\cdot\sqrt{1-x_1^2}$$

Eliminating S_1:

$$Fx_1 - B\sqrt{1-x_1^2} = -S_2(x_1\sqrt{1-x_2^2} + x_2\sqrt{1-x_1^2}$$

$$\Rightarrow S_2 = \frac{B\sqrt{1-x_1^2} - Fx_1}{x_2\sqrt{1-x_1^2} + x_1\sqrt{1-X_2^2}}$$

$$(= \frac{S_2 - teller}{Snevner})$$

Putting these in Equation (5a) illustrates that S_1 and S_2 are correct.

Appendix D

MATLAB-script: Numerical calculation of tilt-angle, α

```
% Numerical calcualtion of tilt-angel alpha

clc
clear all
format long

%-------------------------------------------------------
%Variabels

L = 50;            %Diameter of floating collar [m]
d = 5;             %Diameter of air-dome [m]
a = 23;            %Mooring line length (between flaoting collar and air-dome [m]
B = 20000;         % Vertical force (buoyancy) [N]
F = 19000;         % Horizontal force (drag) [N]
my = acos((L-d)/(2*a)); %Angel of mooring lines, between the floating collar
                        %and air-dome at F=0 [rad]

%---------------------------------------------------------
%Establishing dimensionless variabel of L, d og a

lambda = L/L;
Δ = d/L;
alfa = a/L;

%-----------------------------------------------------------
%x1 = sin(beta1); at F=0 is x1=sin(my)
x1 = 0.000:0.005:0.4;
%y  = sin(alpha); at F=0 is y=0
y  = 0.000:0.005:0.4;

%------------------------------------------------------------
%Making 2D grid-coordinates
[x1, y] = meshgrid(x1,y);

%------------------------------------------------------------
%from (4) in the report x2 can be written as:
x2 = x1 + Δ.*y/alfa;

%from (2) og (1) S1 and S2 are expressed in the following way:
S1teller = B.*sqrt(1-x2.^2) + F.*x2;
S2teller = B.*sqrt(1-x1.^2) - F.*x1;
Snevner = x2.*sqrt(1-x1.^2)+x1.*sqrt(1-x2.^2);
S1 = S1teller./Snevner;
S2 = S2teller./Snevner;

%-------------------------------------------------------------------------
%Making dimensionless variabels for the forces acting on the air-dome
%Trying to scale the forces som that f3 og f5 varies approximately the
%same.

scale = 0.02;
phi = (F/B)*scale;
sigma1 = (S1/B)*scale;
sigma2 = (S2/B)*scale;

%--------------------------------------------------------------------------
%Establishing f3 and f5, the left side of (3a) and (5a) from the report
f3 = lambda - Δ.*sqrt(1-y.^2) - alfa.*(sqrt(1-x1.^2)+sqrt(1-x2.^2));
f5 = sigma2.*(y.*sqrt(1-x2.^2)+x2.*sqrt(1-y.^2))-sigma1.*(x1.*sqrt(1-y.^2)-y.*sqrt(1-x1.^2));

%--------------------------------------------------------------------------
%Making a matrix with zeros to mark the (x1,y)-plane in the figure
x1yplane = 0.0.*x1.*y;

%--------------------------------------------------------------------------
```

```
%Plot
%Plotting f3, f5 and (x1,y)-plane in the same figure


figure(1)
h1=surf(x1,y,f3,'FaceColor','r');
hold on
h2=surf(x1,y,f5,'FaceColor','y');
h3=surf(x1,y,x1yplane,'FaceColor','g');
legend([h1,h2,h3],{'Geometry constraints','Static equilibrium','xy-plane'})
zlabel('f3 og f5')
xlabel({'$\sin\beta_1$'},'Interpreter','latex')
ylabel({'$\sin\alpha$'},'Interpreter','latex')
view(2)

%Initially the z-intervall are set manualy to get a good figure
zlim([-0.015 0.015])
```

Appendix E

MATLAB-script: Tradespace Evolution

```

%This script runs the tradespace analysis

clear all
clc

%--------------------------------------------------
%Design variables

H_min =  0.01;   %minimum height of air-dome
H_max =  3.0;    %maximum height of air-dome
D_min = 1;       %minimum diamter [m]
D_max = 8;       %maximum diamter[m]
T_min =  0.005;  %minimum thickness of air-dome
T_max = 0.015;   %minimum thickness of air-dome

H= [0.01:0.01:3];
D= [1:0.5:8];

for i = 1:length(H)
    for j = 1:length(D)
        Area(i,j) = H(i) * D(j);
    end
end

area_min = 0.01;    %Minimum area of air_dome (cylinder-part)
area_max = 30;     %Maximum area of air-dome (cylinder-part)
% Mass_min = 0.061;  %Minimum mass of air-dome
% Mass_max = 6.761;  %Maximum mass of air-dome

%--------------------------------------------------------
%Generating design vectors for each design variable

H_range = linspace(H_min,H_max,5);
D_range = linspace(D_min,D_max,5);
T_range = linspace(T_min,T_max,5);
area_range = (area_min:2:area_max);
% Mass_range = (Mass_min:1:Mass_max);

%--------------------------------------------------------
%Calculating length of each design vector

n_H_range = length(H_range);
n_D_range = length(D_range);
n_T_range = length(T_range);
n_area_range = length(area_range);
%n_mass_range=length(Mass_range);

%-----------------------------------------------------------------
%Calcualting design space
n_DS = n_H_range*n_D_range*n_T_range*n_area_range;


%-----------------------------------------------------------------
%Possible design matr1ix for the air-dome

AirDome=combvec(H_range,D_range,T_range,area_range);

%-----------------------------------------------------------------
%Design variables
% 1. Height
% 2. Diameter
% 3. Thickness
% 4. Area



% ---------------------------------------------------------------
```

```
% Removing infeasible designs

%This is the restriction from the hydrodynamic aspect of the air-dome

Drag_max = zeros(1,n_DS);
for i = 1:n_DS
    Drag_max(1,i) = 2.7;
    if AirDome(1,i) > Drag_max(1,i)
        AirDome(1:4,i) = 0;
    else
        AirDome(1:4,i) = AirDome(1:4,i);
    end
end


 % ---------------------------------------------------------------
 % Utility

U_dragF = zeros(1,n_DS);
 for i = 1:n_DS
     U_dragF(1,i) = (AirDome(4,i)-area_min) / (area_max - area_min);
     if U_dragF(1,i) < 0
         U_dragF(1,i) = 0;
     end
 end

U_Stability = zeros(1,n_DS);
 for i = 1:n_DS
     U_Stability(i) = (AirDome(2,i)-D_min) / (D_max - D_min);
     if U_Stability(1,i) < 0
         U_Stability(1,i) = 0;
     end

 end


%----------------------------------------------------------------
%Utility

Utility = 0.6* U_dragF + 0.4 * U_Stability;

%------------------------------------------------------------------
%Capex
capex = zeros(1,n_DS);
for i = 1:n_DS
    capex(i) = 641667 + (11 * pi* (AirDome(2,i)/2)^2 * AirDome(1,i)) +...
        (11 * (0.5 * 4/3 * pi * (AirDome(2,i)/2)...
        - (0.5 * 4/3 * pi * (AirDome(2,i)-AirDome(3,i))/2)));
end



%-------------------------------------------------------------------
% Establishing Pareto Front using pareto(Y,X)
% which labels each bar with the associated value from X

[Pareto_Set] = Pareto(Utility,capex);

%This function identifies the Pareto front.

[num, n_DS] = size(Utility);
pareto_utility = Utility;

 %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(pareto_utility(1,:));

 %Adding point design to Pareto array.
 Pareto_Set(1,k) = b;

 %Setting current max utility to -1 to avoid rechecking.
 pareto_utility(1,b) = -1;
```

```

 %Setting utility of all elements with a larger cost to -1

 for j = 1:n_DS
     if capex(j) ≥ capex(b)
         pareto_utility(1,j) = -1;
     end
 end

 %Stopping "while-loop" when the lowest cost is reached or max
 %utility is 0

     if (capex(b) == min(capex(:))) || (max(Utility(1,:)) ==0)
         i = 1;
     end

 %For finding next element in Pareto array.
 k = k+1;
 end



Flip_Pareto = fliplr(Pareto_Set);

tic
Pareto_utility=zeros(1,length(Pareto_Set));
Pareto_capex=zeros(1,length(Pareto_Set));
Pareto_AirDome=zeros(4,length(Pareto_Set));

for i = 1:n_DS
 for p=1:length(Pareto_Set)
        while i == Flip_Pareto(p)
            Pareto_utility(p) = Utility(i);
            Pareto_capex(p) = capex(i);
            Pareto_AirDome(:,p) = AirDome(:,i);
            Flip_Pareto(p) = -1;
        end
 end
end
toc

%---------------------------------------------------------
%Finding the best deisgn if the air-dome

Good_design = zeros(1,length(Pareto_Set));
for i = 1:length(Pareto_Set)
Good_design(1,i) = Pareto_utility(i) / Pareto_capex(i);
end


%-------------------------------------------------------------------
% Plot

figure(1)
tic
for i = 1:10:n_DS
scatter(capex(i),Utility(i),1,'r')
ylim([0 1])
hold on
end
toc
hold on
scatter(Pareto_capex,Pareto_utility,4,'b')
line(Pareto_capex, Pareto_utility)
ylim([0 1])
%xlim([0 3.3])
xlabel('CAPEX [NOK]')
ylabel('Utility')
title('Tradespace Evoultion')
%saveas('');
hold off
```