Developing Sustainable Fish Farms

Recommendations for Offshore Fish Farm Location and Design for Sisal, Yucatán

CEGM3000 - MultiDisciplinary Project
Group MP374

TUDelft

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by

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Preface

This report is written as part of the course Multi-Disciplinary Project (CEGM3000) by a group of five master's students from the Technical University Delft. This is a 10-week course that gives students the opportunity to conduct research abroad as part of their studies. The group consists of students from the master's programs in Civil Engineering, Offshore and Dredging Engineering and Construction Management and Engineering.

This research, conducted in collaboration with the Universidad Nacional Autónoma de México (UNAM), focusses on the development of sustainable solutions for aquaculture along the coast of Sisal, Mexico. The goal is to contribute to sustainable practices and in addition to to expand opportunities for local researchers in aquaculture and support the region's fisheries. To achieve this, we are providing recommendations for various fishing cage designs, specifically tailored to meet the needs of the local community and their environment.

We, Group MP374, would like to extend our heartfelt gratitude to Alec Torres Freyermuth for his dedicated supervision of our work in Sisal, as well as to Alex Robledo and Carlos Rosas-Vazquez. Their support, guidance and hospitality were invaluable to the success of this project. We also wish to thank José Álvarez Antolínez for introducing us to the project and serving as our primary supervisor, along with Erik-Jan Houwing and Henk Jonkers, whose expertise helped us achieve our objectives.

Group MP374
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Summary

This study investigates the development of sustainable offshore fish farms in Sisal, Yucatán. Local fishermen face seasonal restrictions on fishing due to environmental regulations. Given the socioeconomic dependence of the region on fishing, the community of Sisal has been experiencing increasing instability of livelihoods. Offshore fish farming has emerged as a potential solution to this challenge, offering an alternative income source outside the traditional fishing season. However, previous industrial attempts to introduce fish cages failed due to a lack of local engagement and inadequate design, leaving Sisal residents sceptical. To address these past issues, this research seeks to design affordable, durable, and locally accepted fish cages that meet the unique environmental and social conditions of Sisal.

Valuable insights were gained from fish farms in Celestún, a nearby village with successful community-led offshore aquaculture. Celestún's approach, using smaller, manageable, and collectively funded cage, has proven to be both economically and socially beneficial. This makes it a relevant model for Sisal, though Sisal's steeper coastal gradients and greater exposure to maritime forces require adaptations to ensure durability and long-term success.

The research follows a multi-step methodology, beginning with interviews with local fishermen and experts to understand their needs and preferences for cage design and placement. These insights were integrated with environmental data on wave height, wave period, and current speeds collected through field measurements and the ERA5 reanalysis dataset. Using this input, an Multi-Criteria-Analysis (MCA) was conducted to determine the optimal offshore location for the fish farms. To determine the structural needs for fish cages under Sisal's conditions, the research used ProteusDS simulation software [14] to model various cage dimensions, mooring tensions, and layout configurations.

Key findings indicate that positioning the fish farms at 8 kilometres offshore is optimal for long term success. At closer distances to the coast, water quality decreases, resulting in higher maintenance requirements and compromised fish health. Greater distances increase installation costs and operational costs due to higher fuel demands.

With the optimal location established, the research follows with the determination of key design parameters essential for the structural integrity of the fish cages near Sisal. An extreme value analysis of an ERA5 dataset was performed to estimate the 20-year return level for the wave height, resulting in a design wave height of 4.19 metres. This value was adjusted for local conditions using a scaling factor derived from the comparison between local and ERA5 data, resulting in an adjusted design wave height of 3.40 metres. A power-law regression was then applied to establish the relationship between wave height and wave period, estimating a design wave period of approximately 8.01 seconds corresponding to the adjusted wave height. For the current analysis, the 95th percentile of current speeds was examined, determining a maximum design current speed of 0.50 m/s near the surface. Furthermore, analysis of wave and current directions revealed that extreme waves predominantly come from the north to north-east directions (340° to 20°), while the strongest currents flow toward 70° and 250°, indicating eastward and westward flows.

The optimal cage design determined through simulations includes a cage diameter of 12 metres and a net depth of 4.7 metres to withstand Sisal's environmental forces. Additionally, distinct mooring-tension configurations were tested in the ProteusDS software, including Concept 1 (a single-cage setup), Concept 2 (a two-cage configuration with four mooring anchors), and Concept 3 (a three-cage arrangement with three anchors). Each concept required specific anchor weights and dimensions to endure the high wave and current forces at this location. Orientation adjustments were also incorporated to reduce tension, aligning each cage setup with different wave and current directions, thereby optimizing structural reliability. Future fish cage designs should include adaptive anchoring and precise orientation to enhance stability and involve the local community for sustainable, long-term success.

The study concludes that, to achieve long-term viability, fish cages in Sisal must be affordable, easy to maintain, and capable of withstanding local environmental conditions. Future recommendations include deepening community involvement, implementing enhanced safety and resilience measures, and refining cost analysis to foster broad acceptance among local fishermen. By ensuring that the fish cages are both economically viable and environmentally sustainable, this project aims to secure a stable income for Sisal's fishing community, thereby improving their quality of life while reducing pressure on marine ecosystems

Contents

Abbreviations

Abbreviation	Definition
ADCP	Acoustic Doppler Current Profiler
AHP	Analytical Hierarchy Process
CDF	Cumulative Distribution Function
CI	Confidence Interval
DO	Dissolved Oxygen
DWA	Deadweight Anchor
ECMWF	European Centre for Medium-range Weather Forecasts
ERA5	European Centre for Reanalysis, 5th Generation
EVA	Extreme Value Analysis
FA	Fluke Anchors
FLS	Fatigue Limit State
GPD	Generalized Pareto Distribution
MCA	Multi-Criteria Analysis
MDP	Multi-Disciplinary Project
PA	Pile Anchors
PDF	Probability Density Function
PMF	Probility Mass Function
POT	Peaks Over Threshold
QQ Plot	Quantile-Quantile Plot
RT	Return Time (or Return Period)
SDG	Sustainable Development Goals
SLS	Serviceability Limit State
STD	Standard Deviation
TUD	Technical University Delft
UNAM	Universidad Nacional Autónoma de México
ULS	Ultimate Limit State

1

Introduction

On the northern coast of Yucatan, Mexico lies a small village called Sisal, home to about 2000 residents [40]. The local population primarily makes a living from fishing octopuses and various other fish species. However, due to regulations aimed at reducing overfishing, the fishing season in Sisal (except for Octopus) is limited to only six months per year [52]. During the remaining six months of the year, it is becoming more difficult for local fishermen to earn a stable income. Consequently, the livelihood security of the fishermen in Sisal has decreased.

In recent years, efforts have been made to address this issue. A proposed solution by the government and NGOs has been the use of offshore fish farms [48] . These fish farms can generate income even when fishing is not allowed. Therefore, several large companies have attempted to establish fish farms along the coast of Yucatan, including in Sisal [43]. Unfortunately, these projects have not been successful. Local fishermen were not involved in the process and the fish cages were not suitable for the unique coastline of Yucatan [22]. The cages broke down rapidly and there were unexpectedly high installation and repair costs. The remains of these industrial fish cages can still be seen along the coast of Sisal, left behind by the companies. As a result, the local population developed a strong aversion to the idea of fish cages.

The main problem was the lack of involvement of the local community, who were the intended users of the cages [43]. The fish cages were too costly for the locals to buy, and the repair expenses were burdensome since the fishermen couldn't fix the cages themselves; they were too large for the fishermen to bring back to shore on their own. Moreover, there was little understanding of what the fishermen considered important regarding the fish cages, an example being the maintainability [16].

Despite these failures, the proper use of fish cages is potentially the most promising solution to the growing livelihood insecurity faced by local fishermen in Sisal. The potential success of fishing cages has been shown in another village south-west of Sisal, Celestún, where offshore fish farms have been in use for the last couple of years [35]. This initiative is entirely led by an organisation of local fishermen. In addition to generating an alternative source of income, this project has created significant social benefits. Firstly, there is greater unity among the community and people are learning from each other through cooperation. Furthermore, it has led to a collective effort to protect the coastal environment, as noted by a representative of the Celestún community noted [35].

For these reasons, the National Autonomous University of Mexico (UNAM) has requested research to develop affordable fish farms specifically designed for Sisal. The cages of Celestún were initially considered as a design starting point; however, there are notable environmental and social differences between Celestún and Sisal. Firstly, the coastal area of Sisal deepens more quickly and, due to its geographical position, is subject to increased exposure to maritime forces. In addition, Sisal has a smaller population and its focus is primarily on selling locally rather than exporting to other regions in Mexico. This limits both the financial and social support and increases the per-person cost of acquiring a fish cage, thus raising more individual (financial) risk. Therefore, the fish farms deployed in Celestún

need to be assessed and adapted to the local conditions of Sisal. In order for the Sisal fish farms to be long-term success, it is very important to have a good technical design and community acceptance.

The purpose of this research is to explore how fish farms can be developed and implemented in Sisal to provide a long-term solution to local fishermen. Long-term success is achieved when cages are developed in Sisal that are affordable, durable and appealing for fishermen to use. In order to do that, the fish cages must meet both local needs and environmental conditions. The research question is therefore as follows: *How can fish farms in Sisal positioned and developed best to ensure long-term success, considering local community needs and environmental conditions*?

To answer this main research question thoroughly and in a structured way, three sub-questions have been formulated.

-*What is the ideal distance offshore for cage placement, considering local environmental and community conditions?*

-*What are the key environmental forces at the selected location that will influence cage design?*

-*What design recommendations can support a resilient mooring system tailored to Sisal's conditions?*

These sub-questions logically follow the design and environmental assessment processes, aligning with the main question's aim to create fish cages that will be a success on the long-term.

The study will consist of different parts. First, the knowledge, demands and needs of both fishermen and experts will be mapped out through conducting interviews, which form the basis for the site determination. Thereafter, an analysis is done to assess the environmental forcing conditions, namely wave and current characteristics, at the cage location to establish essential design parameters. By examining local and historical data, the analysis estimates extreme values for wave height, wave period and current speed that the structure must withstand. Additionally, directional patterns for both waves and currents are identified. Using this information, various fish farm design options and concepts will be created and tested against the determined environmental conditions, using the simulation program ProteusDS [14]. Based on the simulation results, recommendations will be made on how to best construct and implement fish farms in Sisal, including an optimal anchor and mooring design to ensure structural reliability.

This project is linked to several United Nations Sustainable Development Goals (SDG). It supports SDG 8: Decent Work and Economic Growth [53] by creating new employment opportunities and providing a stable income source for local fishermen during the off-season, thereby promoting economic growth. By focusing on designing fish cages that are suitable for local environmental conditions and encouraging sustainable aquaculture practices, the project aligns with SDG 12: Responsible Consumption and Production [53], ensuring that fish farming is conducted in an environmentally responsible manner. The project also contributes to SDG 14: Life Below Water [53] by addressing overfishing and promoting the sustainable use of marine resources. Lastly, the collaboration between the local community, government and UNAM touch upon SDG 17: Partnerships for the Goals [53], highlighting the importance of partnerships in achieving sustainable development objectives.

2

Background

This chapter provides an overview of key concepts and regional context that inform the project's approach to offshore aquaculture in Sisal, Yucatán. The global rise in seafood demand has positioned aquaculture as an essential industry, with offshore farming gaining traction due to its potential for sustainable, large-scale production. This background explores the growth and challenges of offshore aquaculture, the current status and practices in Yucatán and the unique social characteristics of Sisal.

2.1. Aquaculture

The global seafood industry is valued at approximately $ 358.68 billion in 2023 [18] and is projected to grow significantly, reaching $ 837.17 billion by 2032 [25] due to the increasing global demand for seafood. Aquaculture, which is the farming of fish and other aquatic species, plays a crucial role in this industry and is one of the fastest growing segments. Currently, it accounts for around 47 percentage of global seafood production [26]. And it is expected to grow at a rate of 4,5% annually over the next decade [26]. This growth is mainly driven by the increasing need for (sustainable) seafood [25].

Aquaculture is defined as 'the raising of water animals such as fish for food, or the growing of plants in water for food' [41]. In this project, the focus lies only on offshore aquaculture. Offshore farming has several advantages compared to onshore farming. First, offshore aquaculture includes access to larger, cleaner water bodies with stronger currents, which improve water quality and reduce the risk of disease transmission between fish. In addition, offshore operations can mitigate space constraints and environmental impacts typically associated with coastal or land-based farms, allowing higher production capacity and less competition with land use [48]. Offshore aquaculture is a relatively new but growing industry that is used to address global food, economic and ecological challenges.

With a growing world population and increasing demand for seafood, it appears that natural fish populations cannot continue to keep up with demand. Aquaculture offers a sustainable solution to meet this growing demand. It provides a stable and predictable supply of fresh fish, which will help to meet the uncertain increase in the demand for seafood in the near future.

Due to this increasing demand, global overfishing is becoming more prevalent. Many coastal fish populations are being over-exploited, leading to the degradation of entire ecosystems, such as coral reefs. A possible way to minimise overfishing could be the sustainable use of offshore aquaculture.

Although offshore aquaculture is still a relatively small part of the global seafood industry, it is growing rapidly. Many countries, such as the U.S., Norway and China are investing heavily in offshore technologies to expand their capacity for sustainable fish production. In Norway, offshore aquaculture is already in use and operates successfully [17]. They have a lot of aquaculture in fjords and open ocean environments. The country has developed technologies to manage offshore conditions such as strong currents to ensure high productivity and environmental sustainability. The offshore farms have benefited from clean, deep ocean waters, which allow for better quality and fish health. Norway's success in offshore aquaculture has placed it as the world's largest producer of farmed salmon [9].

However, despite the numerous benefits of offshore aquaculture such as access to cleaner waters and improved fish health, there are also risks and pitfalls associated with these operations. Firstly, remote locations of offshore farms can challenge monitoring and regulation, increasing the potential for environmental impacts such as nutrient pollution, fish escape and habitat disruption. Furthermore, reliance on wild caught fish for feed can counteract sustainability goals by placing additional pressure on marine resources [28]. Therefore, while offshore aquaculture holds promise, it requires careful management and regulatory oversight to mitigate these challenges and ensure its environmental and economic viability. Achieving this can be facilitated by working closely with the local community— listening to their needs while also informing them about the aquaculture processes and their benefits.

A critical component for the possible indicated problems of offshore aquaculture might lie in addressing the social dimensions of these ventures. Social acceptance, community engagement, and ensuring equitable benefits for local stakeholders can significantly enhance the sustainability of these operations [5]. Involving local communities helps address regulatory challenges, as they provide valuable, location-specific insights into effective monitoring and environmental management [3]. Recent studies indicate that social factors can be just as influential as technical or environmental ones in determining the success of aquaculture projects, positioning the social dimension as a potentially key element in overcoming the operational challenges faced by offshore aquaculture [29]

2.2. How does it work?

In offshore aquaculture marine or fishing cages are being used. Marine cages are structures designed to confine fish while allowing free water flow. Nets are used to confined and the cages are anchored in open water, generally many kilometres offshore. In the open water, the cages are naturally cleaned or 'flushed' and provide fresh water for the fish. This method allows the farming of species like, sea bass, tilapia and shrimp and lots more. It offers the advantage of more large-scale and reliant production than on-shore farming. Because at sea there is more space and cleaner water available to prevent diseases. Though this method still comes with challenges; building and maintaining offshore farms is often considered to be technically challenging due to strong currents and high waves. Besides that, offshore farming is considered more capital intensive compared to on-shore farming [46].Specialized materials and transportation significantly increases costs compared to land-based operations.

The cages are often anchored to the seabed in clusters. The configuration of each cluster can vary: three cages can be linked together or five or possible seven (as shown in Figure 2.1). The two main methods for introducing the fish into the cages are as follows: The first involves catching juvenile fish and placing them in the cages, where they will grow until they are ready to be harvested. The second, more expensive option, is to raise the fish from eggs to juveniles before transferring them to the cages. Although this second method requires higher initial investment, it does not stress the wild stocks of the fish and its environment as the fish are 'homegrown'.

Figure 2.1: Clustered fishing cages

2.3. Aquaculture in Celestún, Yucatan, Mexico

In Mexico, there is a growing interest in aquaculture, particularly in regions like Yucatan where efforts are underway to implement this practice. This is, as mentioned before, primarily driven by the increasing

demand for seafood in the area and the need to reduce pressure on wild fish stocks. Additionally, economic factors are also a significant motivator. Aquaculture represents a significant potential for job creation. Although it currently plays a minor role compared to traditional fisheries, aquaculture has the potential to diversify income sources and contribute to economic development [34]. Experimental projects with aquaculture are being conducted in various areas along the coast of Yucatan.

One of the challenges faced by fish-communities in Yucátan is that, without the help of large companies, they lack the capital and knowledge needed to acquire the (expensive) industrial cages. However, there are examples that prove that simplified and affordable fish farms on smaller scale can be developed. An example of this can be seen in the fish farm of Celestún [39]. They have developed a strategy that also seems to work for the smaller fish communities .

A group of 56 people working in the fishing industry, consisting of 28 men and 28 women, from Celestún formed an organization which the locals call a "cooperativo". In collaboration with a company named Ingeniería de Jaulas Marinas De México [27], they developed fish cages specifically designed for Celestún. The focus was on making the cages affordable and maintainable for the local fishermen. In the end, smaller cages were created using cheaper materials. All the fishermen contributed to the payment and maintain the cages together.

Currently, three cages are active and connected to each other. They were financed collectively by the 56 people and everyone has its own role in de organization. In anticipation of extreme weather, the nets are removed from the cage frame and transported to shore. The rest of the cages are left in place as they are robust structures engineered to endure severe weather conditions. The aquaculture process uses fish that are already a few centimetres in size. These young fish are nurtured at a research centre in Sisal, operated by UNAM, before being moved to Celestún. This form of aquaculture appears to be very promising, with very profitable yields [51]. Refer to chapter 7 & Appendix C for more information about these cages.

Celestún has been using fish cages for a few years. Their main reason for adopting this method is to recover the costs expended in protecting their fishing refuge [35]. However, interviews conducted for this project revealed several challenges related to the management and use of these cages. These include maintenance demands, broken parts and the acceptance of using the cages by local stakeholders. This information offers valuable lessons to be learned and can be used for the development of fishing cages such that the known failures and weaknesses which were exposed in Celestún are prevented in the future.

Figure 2.2: The Gulf of Mexico, Sisal and Yucatan

2.4. Sisal, Yucután, Mexico

Sisal is a small port town, located in the municipality of Hunucma , 47 kilometres from Mérida, the state capital (Figure 2.2). Historically, Sisal served as the main port of the region from the 16th to the

early 20th century, before being replaced by Progresso [21]. The village hosts a rich coastal ecosystem where the area's nutrient flow, changing salinity and protective mangroves create ideal conditions for biodiversity and productive fishing. In addition, a characteristic of the coastal area of Sisal is the extremely mild slope of the continental slide. To reach a depth of 10 metres, one must go over 10 kilometres offshore [11]. This shallow gradient is rare and influences the ecological characteristics, making the coastline very unique.

The town is also home to a branch of UNAM campus in Sisal is a centre for advanced scientific research and environmental studies, focussing on coastal and marine ecosystems [38]. Researchers at UNAM Sisal conduct pioneering studies in oceanography, aquaculture and marine biology, contributing valuable insights into the health and preservation of coastal environments. Additionally, the campus collaborates with international institutions, promoting an interdisciplinary approach that combines science, conservation and technology to address urgent environmental challenges in the region [54].

The Sisal region's fishery industry is all manual and relies heavily on species such as octopus, lobster and various fish [42]. These activities form a crucial part of the local economy, providing livelihoods for many coastal communities. However, with the decline in certain fish populations due to overfishing and environmental pressures, there has been increasing interest in developing sustainable aquaculture practices.

More than a decade ago, a large company attempted to establish offshore farms in Sisal. However, this project ultimately failed. The industrial fish farms were not suitable for the unique coastline of Sisal. They were set up with heavy machinery, posing a risk to the local underwater environment. Additionally, local fishers were not involved in the project at all, which meant this company lacked knowledge about the area and its specific needs [22]. Eventually, the cages broke down all the time, leading to escalating costs and the company eventually went bankrupt. Remnants of the cages on the beach still (Figure 2.3) serve as a daily reminder to the fishers of the potential dangers fish cages pose to their environment.

Figure 2.3: Remnants of industrial cages at beach of Sisal

In recent years, however, there has been increasing support for using fish cages in a more sustainable and affordable way. The UNAM department in Sisal has been a strong advocate of this idea within the local community [54]. The university regularly organizes local meetings to explain the benefits and use of fish cages, aiming to develop them in a way that is both sustainable and cost-effective for Sisal. More and more fishers in Sisal are showing interest in the idea of collectively using fish cages, especially as they observe successful examples in other similar towns, like Celestún.

Despite growing support for fish cages, many fishers remain sceptical about their use. Their reservations stem from past experiences where cages caused more harm than good. Beyond the technical challenges of designing affordable cages specific to Sisal's needs, there is also a significant social challenge: The entire community must stand behind the idea in order to let it be a success.

3

Methodology

To answer the research question of this project: '*How can fish farms in Sisal positioned and developed best to ensure long-term success, considering local community needs and environmental conditions?*'. To address the main research question, the three sub questions will be answered using a multi-step methodology. The developed methodology and the used steps are outlined in this chapter. The flowchart, Figure 3.1, provides an overview of the process, from site analysis to final recommendations.

First, determining the exact location at sea for the fish farms is crucial. Once the location is identified, the environmental conditions can be assessed through data analysis. Using the design conditions, various fish farm concepts will be developed and tested through simulations. The input variables for these simulations will be derived from data analysis and local community needs. Based on the simulation results, recommendations will be made regarding the design of the Sisal cages.
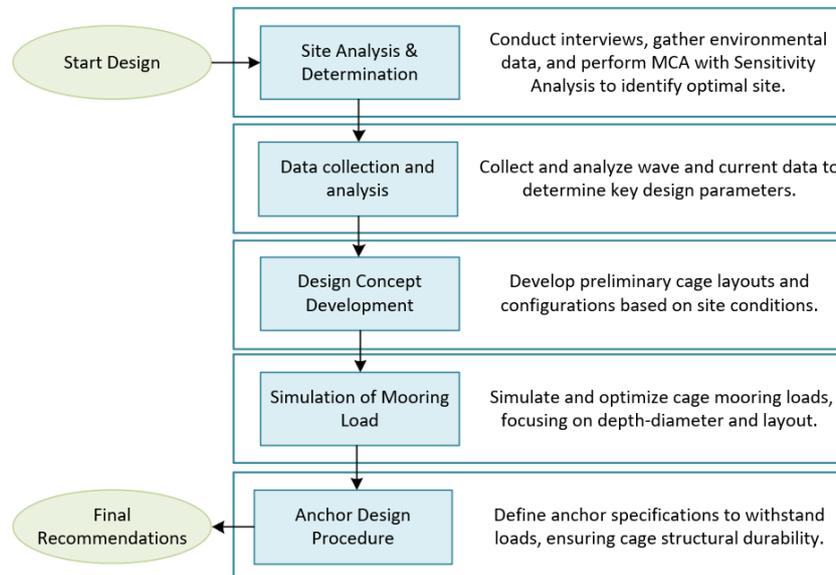
Figure 3.1: Flowchart for determining optimal offshore cage design, location, and mooring recommendations.

3.1. Site analysis & determination

To identify the various criteria that influence the determination of the site, multiple interviews will be conducted. The interviews will be with people working in different fields and jobs such as fishermen, researchers and engineers. These sessions will be used to map out the perspectives of the intervie-

wees, allowing us to assess the importance of each criterion and determine its relative importance. The interview method was chosen because it is useful for specifying information that is difficult to measure. It enables to gather information and helps it to translate abstract concepts into more concrete, usable data. This makes conducting interviews a good tool for understanding and measuring phenomena that cannot be easily captured through standard approaches.

In addition to the interviews, a literature review will be conducted to determine which fish species is best to farm. The biochemical and environmental conditions are measured through fieldwork using specialized equipment, specifically an ACDP, in conjunction with reanalysis information, namely ERA5, to map the differences in environmental and biochemical conditions at various distances. The exact functioning of this equipment will be elaborated on in chapter 4. This approach will allow for selecting the optimal fish-distance combination based on real-time data from Sisal as each fish species has its optimal conditions.

Based on the information collected as described above, a weighted Multi-Criteria Analysis (MCA) will be conducted. MCA is a decision-making tool used to evaluate and rank different criteria by assigning weights to each. These weights represent the importance of each criterion. Criteria are the specific factors used to evaluate and compare different alternatives. The selection of appropriate criteria is crucial, as they directly influence the final ranking and choice of the best location.

Analytical Hierarchy Process (AHP) is a method to determine the weights of each criteria in a MCA. It involves pairwise comparisons of criteria to determine their relative importance, converting subjective judgment into numerical values. These values are then used to calculate weights, which prioritize each criterion in the decision-making process.

In this analysis, the chosen criteria cover different areas: social, environmental and technical. Additionally various offshore distances will be considered as the alternatives. Each alternative will be scored based on the criteria and then automatically ranked. A higher score indicates a more favourable outcome. Therefore, the highest-ranked location will represent the optimal balance of criteria, providing the optimal location for the long-term success of the fish cages in Sisal.

A sensitivity analysis is conducted after the MCA to evaluate how changes in the weights of the criteria affect the final decision. In the determination of the optimal location for fish farms in Sisal the sensitivity analysis helps to determine the robustness of the MCA results. By adjusting the weights assigned to different criteria it is revealed whether the recommended location remains optimal or if slight changes could lead to a different outcome. This process provides valuable insights into the stability of the decision and helps identify which criteria are most influential, ultimately increasing confidence in the final location choice.

3.2. Environmental Forcing Conditions

For this study it is crucial to understand the offshore environmental forcing conditions near Sisal, which directly impact the structural design of fish cages. The analysis will focus on three main components: wave data, current data and the directions of waves and currents.

For the **wave data analysis**, two primary datasets will be utilized: local wave measurements collected near Sisal and the ERA5 reanalysis dataset, which provides a longer historical record of oceanic conditions. The objective is to estimate the *design wave height* and *wave period* that the fish cages must withstand over their operational lifespan. An Extreme Value Analysis (EVA) will be conducted using the Peaks Over Threshold method to model the extreme wave heights. By fitting a statistical distribution to the data exceeding a certain threshold, the return levels of wave heights will be estimated for different return periods. A 20-year return period will be chosen to match the expected lifespan of the fish cages. To adjust the results for local conditions, a scaling factor will be applied based on the comparison between the local data and the ERA5 dataset.

In the **current data analysis**, measurements from an Acoustic Doppler Current Profiler (ADCP) at various depths will be examined to determine the *design current speeds over depth*. Since direct measurements near the surface are limited, current speeds at shallower depths will be estimated through extrapolation using polynomial regression. The horizontal current speeds will be calculated by combining the east-west and north-south velocity components. The design current speeds at each depth will

be determined using the 95th percentile of the observed speeds, providing conservative estimates that account for extreme current conditions without overestimating them.

The analysis of **wave and current directions** will involve examining the predominant directions from which waves originate (*wave direction*) and the directions toward which currents flow (*current direction*), especially during extreme events. By analysing the directional data for both typical conditions and instances when wave heights and current speeds exceed their 95th percentiles, prevailing pattern will be identified. This information is vital for structural design, as it informs the orientation of the fish cages and ensures they can withstand forces from the most critical directions.

In summary, the data analysis will aim to determine the following key environmental parameters essential for the structural design:

- **Design wave height**
- **Design wave period**
- **Predominant wave directions**
- **Design current speeds over depth**
- **Predominant current directions**

These values will provide a comprehensive understanding of the environmental forces acting on the fish cages and are critical for ensuring their structural integrity and operational longevity.

3.3. Design Procedure

To provide the best design recommendations, the design procedure is divided into two parts. In the first part, several concepts are simulated and tested under resulting environmental conditions of Sisal at the selected location. To model this, the advanced simulation software ProteusDS [13] is used, with the main focus on determining the maximum loads on the mooring lines.

The second part uses these maximum mooring line loads to determine the design of the Dead-Weight Anchor (DWA), following the method of Bañuelos-García et al. (2021) [4]. This approach ensures that all aspects of the Ultimate Limit State (ULS) are considered, so that the final design meets the engineering standards effectively.

3.3.1. Simulation of Mooring Loads

To provide effective design recommendations, the following steps and concepts are implemented using the ProteusDS software to simulate realistic mooring loads. More information about the software and further configurations of the cages are worked out in Appendix H:

1. **Depth against Width Ratio Optimization**
   To determine the optimal net depth-to-cage diameter ratio, three single cage sub-concepts **1a, 1b and 1c** were developed, each maintaining the same internal volume to minimize the impact on fishing activities. Simulations were conducted using ProteusDS software, with a 60-second render generated for each sub-concept. The simulations provide graphs of mooring tensions against time of all three mooring lines. The sub-concept that shows the smallest maximum mooring tensions across all three lines was selected as having the optimal depth-to-diameter ratio. Once this ratio was established, the resulting dimensions were applied in the cages designs of further concepts.

2. **Layout Optimization**
   The selected cage dimensions are tested in three different layout configurations. Concept **1** has one cage, while Concept **2** has two cages with four mooring anchor systems. Concept **3**, modelled after the setup in Celestún (section 2.3), features three cages and three anchor moorings. This computational approach provides a more data-driven foundation for optimising Celestún's current anchor system design.

3. **Orientation Optimization**
   All layouts (concepts **1(a, b or c), 2 and 3**) are tested in different orientations relative to the wave and currents, determined by chapter 6. Each concept is evaluated in six different orientation

angles towards the wave and current direction. Again, the ProteusDS software is used to calculate the mooring tensions and force distributions for each orientation. The resulting values are analysed by examining the graphs of mooring tensions over time. The orientation that shows the smallest maximum mooring tensions and thus the most balanced force distribution is identified as the optimal configuration.

4. **Design Mooring Force Determination**
Finally, the optimal and least optimal dimensions and orientations are tested under more detailed current and wave conditions to determine the maximum mooring forces for each concept. This is done using a more extended and precise simulation, to provide a clearer view of the maximum resulting forces. After the maximum forces have been determined a safety factor is applied to obtain the design mooring force.

3.3.2. Dead-Weight Anchor design procedure

The obtained maximum design mooring forces in combination with the angles between the mooring line and the seabed will be used to approximate a required Dead-Weight Anchor (DWA) dimensions and weight.

Ultimate Limit State Design

1. **Preliminary Design**: The initial design begins by defining key parameters, such as the design criteria and the mechanical properties of the concrete used for the anchor. This includes estimating the anchor's weight to resist sliding and counteract the overturning moment.

   - **Structural Analysis**: The system's response to axial force, shear force, overturning moment, and displacements is assessed.

   - **Anchor Weight and Diameter**: The anchor's weight is calculated to ensure stability, and the width is adjusted to handle the applied forces.

   - **Overturning Moment**: The design is refined to effectively resist the calculated overturning forces.

2. **Geotechnical Capacity**: This phase assesses the interaction between the anchor and soil, ensuring that the anchor's design is sufficient for the soil conditions, with properties gathered from literature.

   - **Effective Dimensions**: The anchor's width and depth are determined based on soil properties and load requirements to achieve adequate embedment and resistance.

   - **Sliding Resistance**: Evaluates the anchor's ability to resist horizontal forces by ensuring sufficient frictional resistance between the anchor and soil.

   - **Design Revision**: If the anchor's resistance to applied forces (axial, lateral, or sliding) is insufficient, the design is iteratively revised to achieve balance and stability with the surrounding soil.

3. **Structural Capacity**: This phase focuses on the strength and durability of the anchor material (concrete) to withstand applied loads.

   - **Axial Capacity**: Assesses the concrete's ability to support vertical loads without compressive failure.

   - **Lateral Capacity**: Ensures the anchor's structure can withstand horizontal loads without experiencing deformation or material failure.

   - **Sliding Resistance**: Confirms that the anchor's shape and concrete properties can resist lateral movement when subjected to shear forces.

4

Site analyses

The determination of the optimal location for an offshore fish farm on the coast of Sisal, Yucatán, is critical to the long-term success and durability of the farms. Before you can determinate the best location it is crucial to have a good site analysis. This site analysis consists of three parts. First, the local demands of the fishermen in Sisal will be examined. This will be done by interviewing various local fishermen and experts. These interviews will help identify what local fishermen consider important. This approach encourages participation and allows fishermen to have a say in the final design of the cages. Next, a data analysis will be conducted on the environmental conditions, including factors such as depth, currents, temperature, for the coast near Sisal. Ultimately, literature research and the expertise of researchers at UNAM will determine which fish species is best suited to be farmed in the cages in Sisal.

4.1. Local demands

The local fishermen are the most important stakeholders in this project as the long-term success of the Sisal fish farms will depend on their willingness to use the farms. Therefore, they need to be convinced of the effectiveness of fish farms so that they have an alternative during the six months when they are not allowed or able to fish. This will help to improve the overall livelihood of the farms. To do that, it is essential to identify and analyse the interests, preferences and requirements of local fishermen.

The information about these subjects is gathered by conducting interviews (Appendix A), with local fishermen, attending fishing community meetings in Sisal (Figure 4.1), and incorporating the expertise of Professor Carlos Rosas from UNAM, who has worked with the local fishermen for many years. Another important source of information is the use of the expertise of the fishermen of the town of Celestún. As mentioned before, they already have successful low-cost fish farms in operation. Although Sisal and Celestún have their differences in both environmental and social aspects, a lot can be learned from the experience and knowledge of the people of Celestún. A large group of fishermen have indicated in local meetings, Figure 4.1, that they are positive about the use of fish farms. However, as mentioned in chapter 2, several industrial fish farms have failed in the past, which has led a group of fishermen in Sisal to be sceptical about the use of these cages. To convince these fishermen, it is crucial to understand their preferences, needs, and concerns. An overview of all interviews and meetings can be found in Appendix A. The main text will mostly use the conclusions drawn from the interviews and meetings to support claims and decisions.

Figure 4.1: Meeting with the local fishers of both Sisal and Celestún: *Location: Local football field Sisal, 06-09-2024*

One of the most important topics that emerged from the questions about the site location was the use of fuel (section A.1). The fishermen of both villages stressed that it is very important that the fish farms be located as close to the shore as possible, as this would significantly reduce time and fuel costs. At the same time, fishermen understand that farms need to be far enough offshore to ensure that fish can survive, but their main preference still remain the farms to be as close as possible. This in order to make the farms profitable.

Another issue, which both groups of fishermen consider important, is the size, or volume, and mainte- nance of the cages (section A.1). The size is important for two reasons: first, it determines the ease with which the farms can be towed to their location at sea and back to shore for maintenance. Sec- ondly, the volume affects the number of fish the cage can hold, which increases the income per cage, shortens the payback period and boosts the total annual profit. In addition, the fishermen noted the importance of being able to repair the cages themselves when they break (section A.3), as this would greatly reduce repair costs. The cages in Celestún are somewhat self-repairable, but the fishermen there believe there is room for improvement. One example they mentioned is that once a floating tube on one of the cages breaks, the cage must be brought back to shore and a third party needs to be hired to repair the connection, resulting in high costs.

In addition, overall construction costs are considered very important. The large one-time investment required is particularly discouraging for local fishermen, especially in Sisal. Furthermore, the remaining remnants of the industrial fish cages do not serve as an indication for the local population that fish farms will actually succeed (section A.7). To ensure the long-term success of the project, it is important to show these local fishermen that it is possible to build cages with smaller budget that can still withstand the extreme weather conditions that Sisal sometimes faces. In Celestún, operational cages have been built for a relatively small investment compared to aquaculture projects of a similar size (see section A.3). This was achieved by constructing the cages in a simpler way and taking the specific environmental conditions more into account (section A.5). It should be noted that Celestún has different environmental conditions. Storms and currents are generally less severe there (see section A.1) due to the depth of the water and its location relative to the rest of the coast. Therefore, it might be necessary to adjust the cages based on research to withstand the weather conditions in Sisal.

Another important factor is the emerging tourism industry in the area. During the meetings (section A.1, section A.5), discussions about the attraction of tourists through fish farms arose. Tourism is a relatively new topic for both areas, but recently there seems to be growing interest in it as a new source of income. Fish farms could profit from, and contribute to this by offering tourist tours around the farms, possibly

even combined with the opportunity to swim with the fish. The key considerations for this are that the fish farms should not be too far or too close to shore. On one hand, if the farms are to far, it might be inconvenient for tourist, who may not join the tours due to high fuel costs and long travel times. In addition, fewer trips can be made per day, reducing the potential income. On the other hand the farms should not be to close; leads to smaller cages. This is important because the cages need to hold enough fish to attract tourists and they should be large enough to allow both fish and potential tourists to swim inside section A.4. Moreover, a greater distance can enhance the experience, as many people enjoy a boat trip across the sea. So, there are contradictory aspects to consider, and a optimal distance could be found to maximise tourism opportunities.

There are many different interests, requirements, and preferences among local fishermen regarding fish farms. For the location, they prefer the farms to be as close to shore as possible, mainly for economic reasons. However, they want to have a high number of fish per cage, this depends on the offshore location. At the same time, they are also interested in taking advantage of potential tourism, which can also influence the decision about location. All these factors must be taken into account to determine the ideal location and create the ideal cage. In addition, it is crucial that fishermen can repair and move the cages themselves. As for construction costs, they should be kept as low as possible, but with the requirement that the cages can withstand the extreme environmental conditions in Sisal, so that they can be used for a long period.

4.2. Environmental conditions

The environmental conditions play an important role in the design and success of aquaculture systems. The current speed must be considered at various depths to determine the optimal location for aquaculture systems. These factors are crucial in estimating the structural integrity and stability of cages, as deeper waters tend to have stronger currents and higher waves [30]. To assess this, the current speeds are compared at four and ten kilometres offshore. In addition to these physical forces, water characteristics such as temperature, salinity, dissolved oxygen and density also affect location suitability as these are essential for fish health and growth. These environmental factors are considered together to ensure that the chosen location supports both the operational needs and the species of fish that will be farmed.

4.2.1. Water level

Since local fishermen clearly indicate that the location of the cages close to shore is a key factor in the success of the farms, the cages should preferably be as close to shore as possible. To know where that is and how deep the cages can be, it is crucial to understand the bathymetry of the waters of Sisal.

As shown in Figure 4.2, the water depth off the coast of Sisal rises to more than 5 metre within the first kilometre, but beyond that, the seabed remains shallow and slopes gradually. The water depth measured at 10 kilometres offshore is just over 10 metres, which is considered shallow for offshore environments [30]. If the minimum required water depth for the cages exceeds 5 to 6 metres, even a small increase in this requirement can lead to a significant increase in the distance between cages and shore, as a result increasing fuel consumption and complicating the accessibility and maintenance of the cages.

To assess conditions beyond the measured 10 km, a polynomial fit was applied to the data of Sisal and Celestún, and extrapolated up to 20 km. The linear polynomial fit provides an approximation of the depth gradient based on the existing measurements. The extrapolated data predicts that the depth reaches approximately 17 metres at a distance of 20 kilometres from the shore for Sisal. For Celestún, the depth at the same distance from the shore is approximately 11 metres. The location where the water depth was collected can be found in Appendix B

However, since this extrapolation is based solely on a mathematical model and no reliable measured data were available for distances beyond 10 kilometres, the results come with a certain degree of uncertainty. Factors such as local seabed irregularities, potential underwater features or changes in sediment composition can significantly alter the actual bathymetry. As a result, this extrapolation should be interpreted with caution and it is recommended that future efforts include more detailed surveys for this region to validate the predictions.
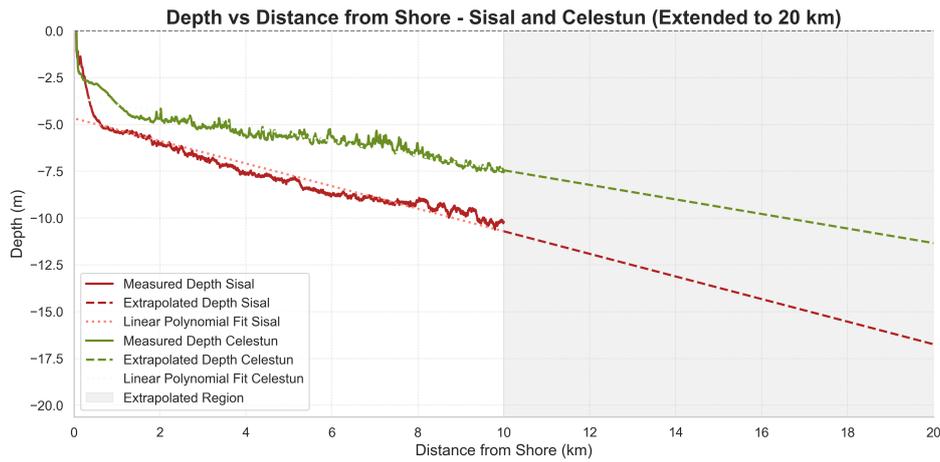
Figure 4.2: Depth vs distance offshore the Sisal coastline.

4.2.2. Current

To show the effect of the distance from the shore and the mean current, various visualisations and statistical analyses were performed. The boxplot shown in Figure 4.3 illustrates the distribution of mean current speeds for both locations. The 10 km offshore location exhibits a wider range of current speeds, with a greater number of extreme outliers compared to the 4 km offshore location. The boxplot highlights that both locations have a similar median current speed, but the spread of the data is noticeably different, with the 10 km location having more variability and a slightly higher mean.
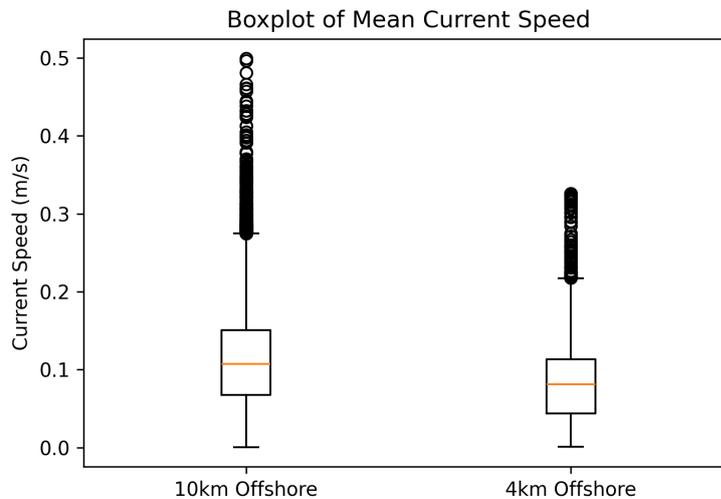
Figure 4.3: Boxplot of Mean Current Speed at 10 km and 4 km Offshore.

The histogram and the cumulative distribution function (CDF) for both distances from shore are presented in Figure 4.4. The histogram shows that the distribution of current speeds is generally similar between the two locations, but the 4 km offshore location has more frequent low to moderate current speeds (below 0.1 m/s), while the 10 km offshore location has more instances of higher current speeds (between 0.1 and 0.2 m/s). The CDF confirms this observation, with the 4 km offshore location showing a steeper increase, indicating that the majority of current speeds are clustered at lower values compared to the 10 km location.

Statistical analysis further supports these observations. A t-test conducted between the two datasets resulted in a t-statistic of 28.33 and a p-value of almost zero, indicating a highly significant difference
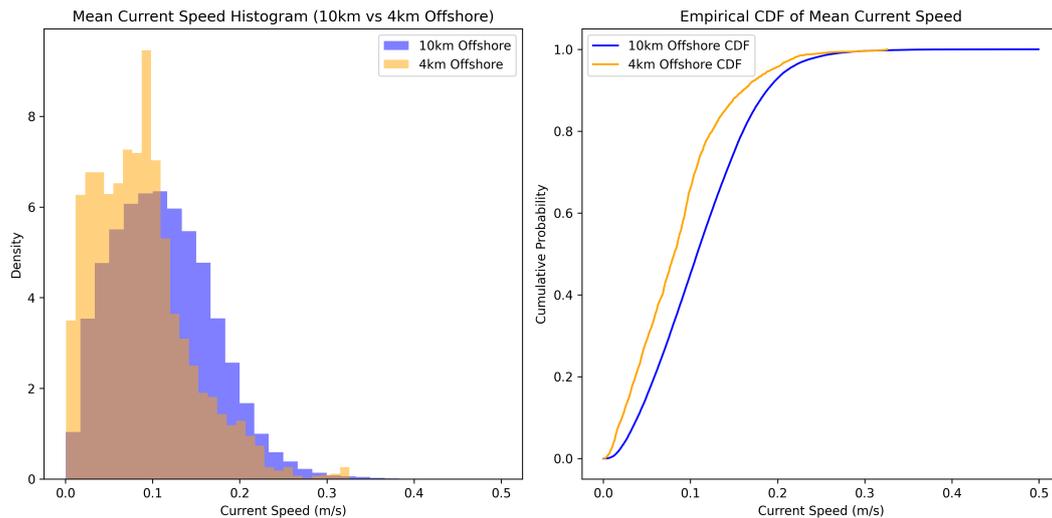
Figure 4.4: Histogram and CDF of Mean Current Speed at 10 km and 4 km Offshore.

between the mean current speeds at the two distances. Furthermore, the 95th percentile values show that the 10 km offshore location experiences slightly higher current speeds at extreme values, with a 95th percentile of 0.21 m/s, compared to 0.19 m/s at the 4 km location.

The analysis reveals that the 10 km offshore location generally experiences higher current speeds and more extreme outliers. Although the dataset includes only two points with limited data, it can be assumed that the further away from shore, the higher the current speeds and the more frequent extreme outliers. This pattern suggests that increasing distance from shore leads to more variability in current speeds. These differences could significantly impact the design and placement of the fish cages, where stronger currents and more frequent extremes influence both structural stability and aquatic conditions.

4.2.3. Seabed conditions

Understanding the characteristics of the seabed is especially important for the selection and placement of mooring and anchoring systems. The type of sediment, such as mud, sand or rock, determines the choice of anchor type, with drag, deadweight or pile anchors being most suitable. Unlike the seabed in most parts of the world, the seabed of Mexico's Yucatan coast consists mainly of limestone covered by a thin layer of finer sediment [2], a common type in tropical and subtropical areas. For this soil type, deadweight anchors (DWA) and pile anchors (PA) are best suited [7].

In addition, knowledge of seabed composition helps identify areas where mooring lines may be damaged, especially during heavy waves or strong currents. Long mooring lines can sink during storms and wear out when they come in contact with sand or rocks.

4.2.4. Temperature & Dissolved Oxygen value

The water temperature plays an important role in the success of aquaculture as it directly affects the metabolism, growth rate and overall health of the caged fish [23]. From Conductivity-Temperature-Depth (CTD) profiles, taken at December 2023, March 2024 and September 2024 offshore Sisal coast (detailed information about CTD testing can be found in the appendix C), it can be seen that the water temperature fluctuates about 3 degrees seasonally and decreases with an increasing water depth both horizontal and vertical (see Figure 4.5a). Notably, the water temperature in the upper layer is slightly higher, but the difference with the lower 50% of the water column is small, with a maximum difference of around 1 °C. In the area most relevant to us (within 10 km offshore), this difference is no more than half a degree Celsius. Also, the difference in average temperature between locations 2 km and 10 km offshore is minimal, never exceeding 1 °C. This could potentially be explained by strong mixing due to relatively fast currents and the shallow water depth in the region [30].

(a) Temperature profiles

(b) Dissolved Oxygen profiles
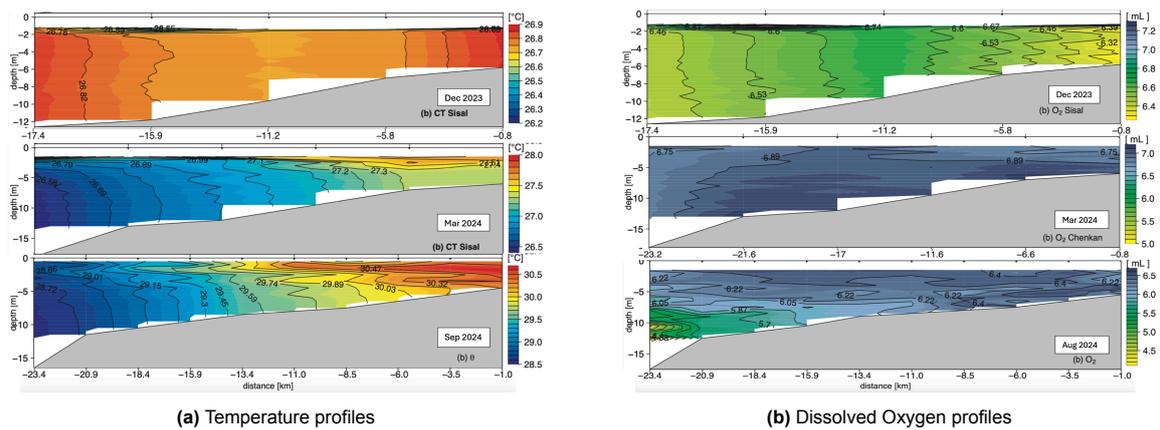
Figure 4.5: Temperature (a) and Oxygen (b) surface distributions for the different surveys off the Sisal coast.

As high temperatures and low oxygen levels can pose risks for fish. Therefore, looking at oxygen profiles is also important in selecting suitable aquaculture sites [33]. The dissolved oxygen (DO) values in figure 4.5b show minimal differences, measured in millilitres of oxygen per litre of water (mL O_2/L), especially in the upper water layers. As long as the chosen fish species can tolerate the included DO range, this should not significantly affect site selection.

On the other hand, temperature has a strong influence on fish growth and reproduction. Warmer water accelerates growth but can result in smaller adult fish and can also accelerate spawning and negatively affect reproductive ratios [45]. Fish larvae are especially sensitive to temperature changes, which affect their survival chances and growth [55]. In the next chapter these consideration will be further taken into account when deciding the optimal location for the cages.

4.2.5. Salinity & Density

(a) Salinity profiles
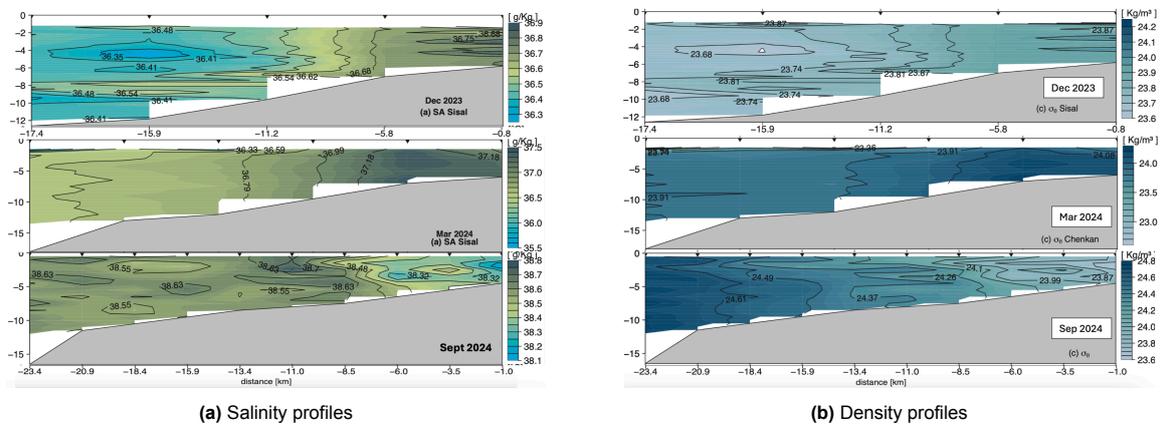
(b) Density profiles

Figure 4.6: Salinity (a) and Density (b) profiles at various water depths and distances offshore, measured on three different dates.

Salinity and water density are key factors in determining aquaculture suitability and fish production. As salinity increases and temperature decreases, density rises. For example, at 25°C, with a salinity of 35 g/kg and 1 atm pressure, seawater has a density of 1023.6 kg/m³ [36]. Figures 4.6a, 4.5a, and 4.6b show that slight variations in temperature and salinity cause only small differences in density.

In Sisal, salinity remains quite stable, making it suitable for many species and varies little with depth and distance (figure 4.6a). Salinity also affects fish growth by influencing their ability to maintain osmotic balance. Outside the optimal salinity range, fish expend more energy regulating water and salt levels, reducing energy for growth [6]. As long as the chosen species can tolerate this salinity range, it will not significantly affect site selection. Density, primarily influenced by salinity, impacts cage design but has minimal effect on species suitability. Both factors will be lightly considered in the next chapter.

4.3. Fish species selection

In this sub-chapter, the fish specie that is going to be farmed, will be analysed. It is important to determine because every fish has its own preferences regarding to environmental conditions, resulting in a different preferred location off shore. In addition, some fish are more suitable for farming than others.

First the local fishes that live in the waters off the coast of Sisal have been identified; A total of five types of fish have been selected. Mexican Snook, Pompano, Red Drum were chosen based on the marine expertise of Professor Carlos Rosas (section A.2) who has been working at UNAM and in Sisal for many years. The Red Grouper and Red Snapper were selected based on literature and the knowledge of local fishermen. Below is a brief literature review on the fish species most suitable for captivity, with the best reproduction rates and highest yields, ultimately increasing local fishers' return on investment.

The Mexican Snook, while capable of living in captivity, presents several challenges. As a protandrous hermaphrodite (starting life as male and becoming female)[10], it has a moderate reproduction rate. In addition, its large size limits the number of individuals that can be housed in a single environment. These reasons make it less efficient for aquaculture [10]. Therefore, despite its ability to adapt to captivity, the Mexican Snook is not the most viable option for farming.

Pompano, on the other hand, has proven to be highly suitable for aquaculture. Although it spawns in the open ocean under natural conditions, induced spawning techniques in captivity have been successful, allowing for multiple egg batches throughout the breeding season [8]. Pompano thrives in captive environments, making it an excellent candidate for aquaculture due to its ability to produce high yields under controlled conditions [8].

Red Drum also has a high reproductive potential, with females capable of producing millions of eggs per spawning season [49]. However, a significant drawback is that the species exhibits cannibalistic behaviour when kept in captivity, which could lead to high mortality rates and limit its scalability for farming [20].

Red Snapper, with its moderate reproduction rate and ability to spawn several times per season, initially appears promising for aquaculture [44]. However, the primary challenge with farming Red Snapper is its costly diet, which is not commercially viable or easily sourced for small-scale [50], artisanal operations like those planned for Sisal. This makes Red Snapper less practical for local fishers, as it would significantly reduce viability.

Red Grouper, also shows promise, especially because its growth improves with higher stocking densities [31]. However, Red Grouper aquaculture is plagued by high susceptibility to diseases, which can result in significant mortality rates. This risk reduces its reliability as a sustainable option for farming [19].

(a) Mexican Snook   (b) Pompano   (c) Red Drum   (d) Red Snapper   (e) Red Grouper
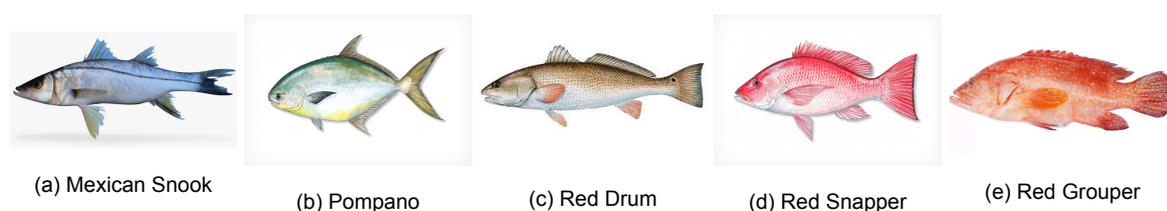
Figure 4.7: The 5 fish species, side view

After reviewing the strengths and limitations of each species, Pompano emerges as the most suitable choice for aquaculture in this context. Its adaptability to captive environments, high reproductive potential through induced spawning, and overall efficiency make it the best option for local fishers seeking to maximise their yield and return on investment. Given these factors, Pompano will be the fish species of choice in the rest of this study.

Now that the local interests, environmental conditions and fish species have been identified, criteria will be established. Using these criteria, a Multi-Criteria-Analysis will be conducted and will determine the ideal location for the long-term success of fish farms in Sisal.

5

Site determination

In this chapter, the location of the offshore fish farms is determined. As indicated in chapter 4, there are many (conflicting) interests and preferences when determining the ideal location. By applying an MCA, an optimum can be found that balances these different interests, allowing for the identification of the best location for the fish farms. After which, a sensitivity analysis is performed. This provides critical insight into the robustness and reliability of the location by showing how the MCA results respond to changes in key assumptions and uncertainties. This ensures that the chosen location is not only optimal under current conditions but also flexible enough to withstand potential future changes.

5.1. Multi-Criteria Analysis
In an MCA, various criteria are selected to determine the ideal outcome. First the different criteria will be discussed, after that the MCA will be performed.

5.1.1. Criteria
To determine the criteria, three main topics were chosen. These topics are based on insights gathered from interviews with local stakeholders, as well as academic knowledge from other studies and experts. The main topics are local preferences, environmental suitability, and structural elements. The first two subjects, namely *Local Criteria* and *Environmental Criteria* are primarily based on the information provided in chapter 4 and Appendix A. *Structural Criteria*, addresses how distance affects structural considerations. For all three main topics, different criteria were selected. A list of the criteria is shown below.

Table 5.1: Relevant Criteria

Local Criteria	Fuel consumption
	Easiness to maintenance
	Capacity cage
	Accessibility tourism tours
Environmental Criteria	Water flow through cages
	Biochemical fish preferences
Structural Criteria	Need for structural robustness
	Material costs
	Installation costs

Fuel consumption: This includes all fuel costs associated with travelling to and from the fish farms. It covers general fuel expenses for operating the cages, such as routine maintenance, for example cleaning and relocating, feeding the fish and emptying/refilling the cages. Fuel costs related to tourist tours and installation are excluded, as tourists indirectly cover their own costs, and installation fuel

costs are addressed in the criterion Installation Costs.

Easiness to maintain: This refers to the ease with which the local fishermen can maintain the cages themselves. Fishermen prefer this to be high (see section A.1), in this way they can handle the maintenance themselves without needing third-party assistance for every minor issue; in addition to time, this also reduces costs.

Capacity Cage: This represents the total volume of the cage and therefore the amount of fish that can be farmed per cage. As cages are placed further offshore, they can be deeper and have larger volume, which means more fish per cage and consequently means higher revenue (see section A.5). However, fishers do not want them to become too large, as they must still be transportable. This is a condition set by the fishermen of both Sisal and Celestún (see section A.1.) Therefore, there is a certain maximum for the capacity of the cage.

Accessibility tourism tours: This measures the extent to which tourists are willing to participate in tours around the fish cages. The ideal location should be close enough to minimise travel costs and time, but also far enough offshore to accommodate larger cages resulting in the possibility to swim in the cages (see section A.3 and section A.1)

Water flow through cages: This refers to the amount of fresh water flowing through the cages. It is important to keep cages clean, which also directly benefits fish health [15]. The farther offshore the cages are, the more fresh water flows through them. Resulting in less daily maintenance work; something the fishermen found very important (see section A.1 and section A.3).

Biochemical fish preference: The pompano fish has specific environmental conditions that are optimal for its survival. These conditions will be compared with available data on the seawater off the coast of Sisal. A separate analysis of the optimal location for the pompano fish can be found in Appendix D.

Need for structural robustness: This criterion evaluates the strength that the entire cage system must withstand. A higher need for structural robustness is unfavourable because it increases costs. This is bad for the willingness to use/invest in the fish cages, which is not favourable for the long term success. In general, the farther offshore the cages are placed, the higher the current speed (see chapter 4), requiring the cages to be more robust.

Material costs: This covers the cost of materials such as nets and tubes. Different distances may require more materials since the cages become larger. It may even require the use of different (more expensive) materials, as cages located further offshore are subjected to greater forces. Materials that can withstand more force are in general more expensive, for example due to bigger anchors. Higher material costs are unfavourable to the long-term success.

Installation costs: This criterion considers the specific costs of installation. It also includes the costs for the need of third-party specialised equipment. In general, the further offshore the farm, the higher the fuel costs for installation. Additionally, deeper installations are required, increasing costs and reducing the likelihood of long-term success.

5.1.2. Location determination
In order to perform an MCA, first the various potential distances need to be determined. Based on academic research and interviews (section A.2 & Appendix A) it appears that the distance of the fish cages in Sisal will probably range from 2 to approximately 20 kilometres. The first location deep enough to support an operational cage (5 metres depth) is 2 kilometres offshore (see Figure 4.2). It is already expected that more than 10 kilometres might be too far for the local fishermen in Sisal (Appendix A). Therefore, distances from 2 to 10 kilometres will be considered in intervals of 2 kilometres. To demonstrate that a greater distance offshore most likely does not provide long-term solutions, distances of 15 and 20 kilometres will also be included in the MCA.

Now that both the distances and criteria are established, the MCA can be carried out. The MCA follows several steps. In the main text, only the key elements and results of these steps will be discussed. For a complete description and elaboration of the MCA and the choices made during the MCA see Appendix E.

First, all criteria have been compared against the different distances. To determine how good a distance

relatively is for a certain criterion a scale of 1-5 was used. A score of 5 indicates that the distance is very good for that criterion, and a score of 1 indicates that the distance is very poor for that criterion. A score of 2 is poor, 3 is average, and 4 is good. Thus, the score for each distance is, therefore, given relative to the score of that criterion for the other distances. Since the values for all distances are normalised, they can be added together. The distance with the highest value represents the optimal choice for all criteria. The results are shown in Table 5.2:

Table 5.2: Unweighted MCA for determination location

	2 km	4 km	6 km	8 km	10 km	15 km	20 km
Fuel consumption	5	4	3	3	2	1	1
Easiness to maintain	5	4	4	3	3	1	1
Capacity cage	1	2	4	5	5	5	5
Accessible tourism tours	1	2	4	4	3	2	1
Water flow through cage	1	1	3	4	5	5	5
Biochemical fish preference	1	2	2	3	3	4	5
Need for structural robustness	5	5	4	4	4	3	3
Material costs	4	4	3	3	3	2	2
Installation costs	5	5	4	4	3	2	1
Total score	**28**	**29**	**31**	**33**	**31**	**25**	**24**

As can be seen, not all criteria scores are the same at each distance, which aligns with expectations. The optimal value for each criterion has been determined based on scientific research and interviews (see Appendix A). A lot of scores speaks for themselves; fuel consumption scores worse when the distance increases. For the full elaboration and motivation, please refer to Appendix E.

The (unweighted) scores can be added together, resulting in a total score per distance. According to Table 5.2 a distance of 8 kilometre, with a score of 33, is the ideal distance for the cages to achieve long-term success for the fish cages in Sisal. In these scores, all relevant criteria have been given the same 'weight'. However, the interviews reveal that not all criteria are considered equally important in determining the location that ultimately contributes to long-term success. For example, criteria such as *fuel consumption* and *capacity cage* are considered more important than, for example, *installation costs*. To take this weight into account, each criterion is assigned an AHP (Analytic Hierarchy Process) weight in the final MCA. This generates a more representative outcome of the MCA. The calculated weights can be seen in Table 5.3. A weight of 2 indicates that the criterion is considered twice as important for determining the location than a criteria with weight 1, contributing to the long-term success/use of the cages. A weight lower than 1 means that it is considered relatively less important. A full explanation and calculation of the weights can be found in section E.2.

Table 5.3: AHP Weights for each criterion

Criteria	AHP Weight
Fuel consumption	2.16
Easiness to maintain	1.08
Capacity cage	1.89
Accessibility tourism tours	0.27
Water flow through cage	1.62
Biochemical fish preference	0.27
Need for structural robustness	0.81
Material costs	1.35
Installation costs	0.54

It is evident that *fuel consumption* carries the most weight in determining the location. This aligns with expectations; almost all the generated information (see Appendix A) indicated that fuel consumption is extremely important for the long-term success of using fish cages. Following that, the criteria *capacity cage*, *material costs*, *easiness to maintain* and *water flow through the cage* all have a (higher) score than 1, determining the ideal location. In particular, the first three criteria are definitely in line with expectations, as all the fishermen and experts interviewed addressed that these criteria are considered very important for long-term use by local fishermen.

The *water flow through cage*, however, was not initially anticipated. Since it only was addressed in a few interviews (section A.3). Nevertheless, experiences with the cages in Celestún revealed that this is very important. From the interview with the fishermen and the engineer of the cages in Celestún (section A.5), it became clear that a significant flow of fresh water through the cages is essential for keeping them clean, and this indirectly prevents damage to the cages. Without this fresh flow, maintenance becomes extremely intensive. This criterion strongly influences ease of use, leading to a greater chance of success. Therefore, it is reasonable to consider this criterion is relatively important to the other criteria.

The criteria with low weights align with the expectations. *Biochemical fish preference* has the shared lowest weight. This aligns with the conclusion drawn in Appendix D. In this appendix, it is concluded that for pompano, the cage location at sea does not significantly matter, as they perform well under all biochemical conditions that occur off the coast of Sisal. *Accessibility of tourism tours*, is the second criteria that has the lowest weight, which also seems correct. This aligns with the assumption that tourist tours will only be organized once the cages have been functioning well for a longer period. Other factors are considered more important at this stage of the project. *Installation costs* and *need for structural robustness* both have a lower score than 1; these must indeed be taken into account, but they are not direct deal breakers for the success according to the information gathered in the interviews.

Now that both the weights per criterion (Table 5.3) and the scores per distance for each criterion are known (Table 5.2), a weighted MCA can be conducted for each distance by combining these tables. For each distance, all the scores are summed again. The results are shown in Table 5.4.

Table 5.4: Weighted MCA scores for determination for the ideal location

	Weight	2 km	4 km	6 km	8 km	10 km	15 km	20 km
Fuel consumption	2.16	10.81	8.65	6.49	6.49	4.32	2.16	2.16
Easiness to maintain	1.08	5.41	4.32	4.32	3.24	3.24	1.08	1.08
Capacity cage	1.89	1.89	3.78	7.57	9.46	9.46	9.46	9.46
Accessibility tourism tours	0.27	0.27	0.54	1.08	1.08	0.81	0.54	0.27
Water flow through cage	1.62	1.62	1.62	4.86	6.49	8.11	8.11	8.11
Biochemical fish preference	0.27	0.27	0.54	0.54	0.81	1.08	1.08	1.35
Need for structural robustness	0.81	4.05	4.05	3.24	3.24	3.24	2.43	2.43
Material costs	1.35	5.41	5.41	4.05	4.05	4.05	2.70	2.70
Installation cost	0.54	2.70	2.70	2.16	2.16	1.62	1.08	0.54
Total score		32.43	31.62	34.32	**37.03**	35.68	28.65	28.11

In the bottom row, the total score per distance is displayed. It can be observed that, compared to Table 5.2, the shorter distances offshore (2 km and 4 km) have a higher score in the weighted MCA. This is logical because fuel consumption is the most heavily weighted factor. At the same time, the distances of 6 km and 8 km offshore have also increased significantly. This is mainly due to the higher weight of the criteria *Water flow through cages* and *Capacity cage*

Furthermore, the farther distances have increased a little, as they score much lower on fuel consumption. The areas where these distances score higher are *water flow through fish cages* and *biochemical fish preference* but the last criterion has a very low weight (see Appendix D, Appendix E) and therefore does not contribute much to the total score.

From the MCA, it can be concluded that 8 kilometres, with a score of 37.03, is the best distance for the long-term success of the fish cages. 10 and 6 kilometres are close second and third with a respective score of 35.68 and 34.32. The distances 15 & 20 km are the worst performing distances according to the MCA.

5.2. Sensitivity Analysis

A sensitivity analysis is necessary after an MCA to assess the robustness of the results. By testing how changes in the weights of the criteria affect the overall rankings, it allows for the identification of criteria that have a significant impact on the decision. This process helps to verify the stability of the results and ensures that small variations in input values do not lead to drastically different conclusions, thus increasing the reliability and credibility of the analysis.

The selected type of sensitivity analysis is a weight sensitivity analysis. This choice was made to address the uncertainty in determining the weights. The weights are based on the perspectives of fishermen, experts and other interviewed participants. It is challenging to fully capture these perspectives and translate them into precise weights. Therefore, a weight sensitivity analysis is conducted to test the model's robustness in case the perspectives on the various criteria change. For example, a fishermen or another interviewee might consider structural robustness to be slightly more important than originally recorded. This kind of uncertainty is checked in this analysis.

The weight of each criterion is factored by -80% and +80% . An 80% change in values was chosen to ensure that substantial differences could be observed. This allows the model's response to significant adjustments to be assessed, as well as identifying which distances perform best when perceptions shift drastically. A change of only 10 or 20% in weight would result in a minimal alteration, leaving a small remaining weight, which would then need to be redistributed across other criteria, as outlined in Appendix F.

When factoring a certain criterion is done, the other weights need to change as well. This is because the total sum of the weights needs to remain 10, the same sum the factoring. Therefore, the redistribution of the remaining weights has been done proportionately. The formulas and steps of the calculation to perform this redistribution can be found in Appendix F. The tables with the final weights for each changed criterion can also be found in Appendix F.

The weights must be recalculated for each criterion used in the analysis. These include factors such as fuel consumption, ease of maintenance, water flow through the cage, need for structural strength, material costs and cage capacity. These factors were chosen because, when looking at the original weights, it is clear that factors like installation costs, fish biochemical preference and tourism accessibility have very low weights, meaning they wouldn't significantly affect the final results. To confirm this, the criterion need for structural robustness was included in a sensitivity analysis. If changes to this criterion do not greatly affect the original scores, it suggests that the other excluded criteria would also have a very small impact. Therefore, it is more useful to focus on the more significant changes shown through sensitivity analysis.

With the new calculated weights, the sensitivity analysis scores can be calculated by multiplying all of them by the unweighted scores described in the previous chapter (See section 5.1). As these are the extensive calculations, the tables with the results can be found in Appendix F. In Table 5.5 the aggregated results of the performed Sensitivity Analysis are shown. It includes the total score of each distance with the different values of the most important criteria.

Table 5.5: Aggregated results Sensitivity Analysis

	2 km	4 km	6 km	8 km	10 km	15 km	20 km
Fuel consumption							
-80%	28,56	29,77	35,28	38,58	39,14	32,76	32,10
+80%	36,31	33,47	33,37	35,48	32,22	24,53	24,11
Easiness to maintain							
-80%	30,73	30,81	33,77	37,71	36,23	30,46	29,86
+80%	34,87	35,85	39,02	40,49	35,86	27,57	26,11
Water flow through cage							
-80%	35,91	34,97	34,99	36,57	33,46	25,34	24,72
+80%	28,96	28,27	33,65	37,49	37,89	31,95	31,50
Need for structural robustness							
-80%	31,19	30,32	33,92	36,82	35,37	28,55	27,97
+80%	33,67	32,92	34,72	37,24	35,98	28,74	28,24
Material costs							
-80%	31,49	30,57	34,86	37,91	36,39	29,73	29,12
+80%	33,38	32,67	33,78	36,15	34,97	27,57	27,09
Capacity cage							
-80%	36,62	33,79	33,26	34,61	33,00	24,66	24,02
+80%	28,25	29,45	35,38	39,45	38,35	32,63	32,19

For a better graphical representation, two graphs were created; one for the -80% results and one for +80% results. Both are depicted below. In both of the graphs, there is a legend indicating which colour means which criterion change, the red striped line representing the original values.
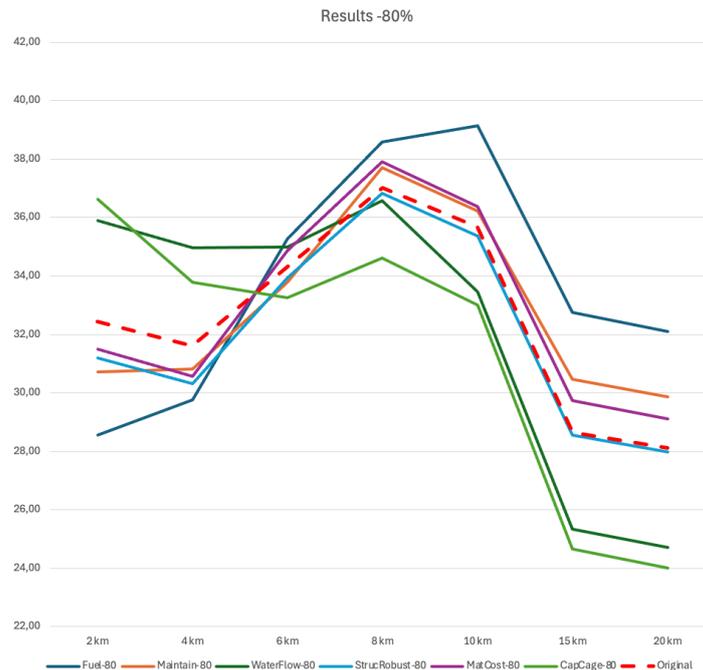
Figure 5.1: Results sensitivity analysis -80%

When the results of the -80% change are examined, three key points become apparent. First, it is observed that when the weight of the Capacity cage criterion is very low, shorter distances tend to score better. This is understandable, as the capacity of the cage becomes limited when placed in shallower waters. Additionally, it can be seen that when the weight of the Water flow criterion is reduced, shorter distances also score better than usual. Here, too, water flow acts as a limiting factor when the cage is

placed closer to the coast. When the weight of Fuel consumption is significantly low, the peak shifts to the right, indicating that a distance of 10 km is optimal in this case. The shift to the right is logical, as fuel costs no longer restrict the placement of the cage further offshore.

Although the changes in Capacity Cage and Fuel consumption cause a different distance to perform best, it can be noted that the model remains fairly robust to other changes. However, it should also be acknowledged that cages must have a minimum capacity to be economically viable, and for local fishermen, fuel consumption is typically prioritized so highly that this situation is not considered very realistic.
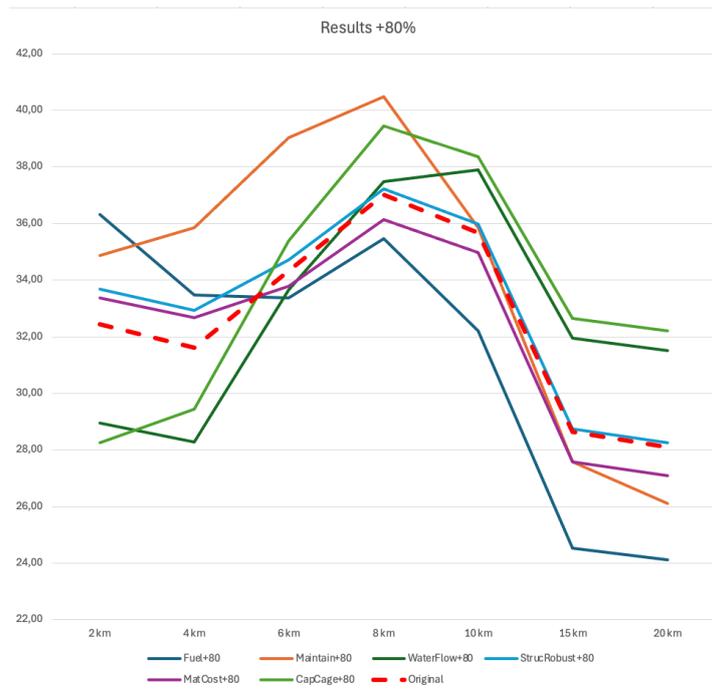

Figure 5.2: Results sensitivity analysis +80%

When the graph displaying the +80% results is observed, several observations stand out. The first is that the orange line, representing the maintenance criterion, rises significantly when the weight of that criterion increases. This was expected, as shorter distances perform much better in terms of maintenance compared to farther distances, ultimately leading to a higher overall score. Furthermore, it can be seen that the dark and light green lines shift to the right and upwards with an increase of +80% in weight. This is also logical, because further distances perform better on the capacity and water flow criteria.

It is also interesting to note that when fuel becomes much more important, the optimal distance shifts to 2 km. This is because fuel consumption already has a relatively high weight, and when this is further increased, combined with the maximum score at the shortest distance, 2 km becomes the preferable distance. Additionally, as previously mentioned, the criterion need for structural robustness was included to assess whether the criteria with the lowest values would have any impact. The graph shows that this criterion aligns closely with the standard values, indicating that the other criteria with lower values have even less influence on the final scores. This applies to both the -80% results and the +80% results. For the rest, the other scores remain clustered around the normal curve. Aside from the shift to a shorter optimal distance when fuel consumption is given very high importance, the model appears to be fairly robust against significant changes in weight and perceptions.

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6

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Environmental Forcing Conditions

A detailed data analysis was conducted to determine the environmental forcing conditions offshore near Sisal, Mexico. Although the fish cage location is determined to be 8 km offshore, the design values are based on data gathered from the 12 km offshore position to minimise errors associated with non-linear environmental changes and the lack of closer measurement points. The complete analysis, including detailed methodologies and results, is available in Appendix G. The environmental forces that are considered are waves and currents.

6.1. Data Collection and Study Area

In this analysis, two primary data sets were used.

- **Local Data**: Collected from an Acoustic Doppler Current Profiler (ADCP) located approximately 12.2 km offshore from Sisal. This dataset includes measurements of wave height (H_s), wave period (T_p), wave direction (D_p) and current velocities at various depths, spanning from March 2014 to April 2023.

- **ERA5 Data**: A reanalysis dataset providing hourly estimates of atmospheric and oceanic conditions, including wave parameters, from 1985 to February 2024. This dataset offers a longer historical record for more robust statistical analysis.

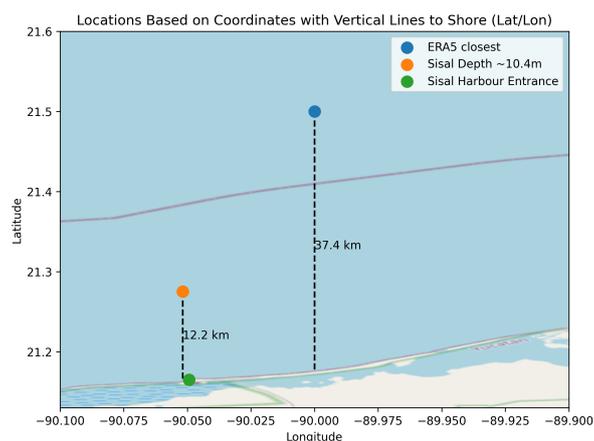Figure 6.1 illustrates the locations of the data collection sites relative to Sisal.

Figure 6.1: Map showing the locations of the Sisal wave measurement site, Sisal harbor and the ERA5 offshore data point.

6.2. Wave Data Analysis

The wave data analysis aimed to estimate the design wave height, the most extreme wave height anticipated throughout the lifetime of the structure, and the corresponding period that the fish cages must withstand over their expected lifespan.

6.2.1. Extreme Value Analysis (EVA)

An Extreme Value Analysis was performed on the ERA5 dataset using the Peaks Over Threshold (POT) method. A threshold of 2.70 metres was determined, subsection G.1.3, to identify significant wave events best fitting the Generalised Pareto Distribution (GPD) and a declustering time of 4 days was applied to ensure independence of extreme events. Figure 6.2 shows the wave height time series with the identified peaks over the threshold.
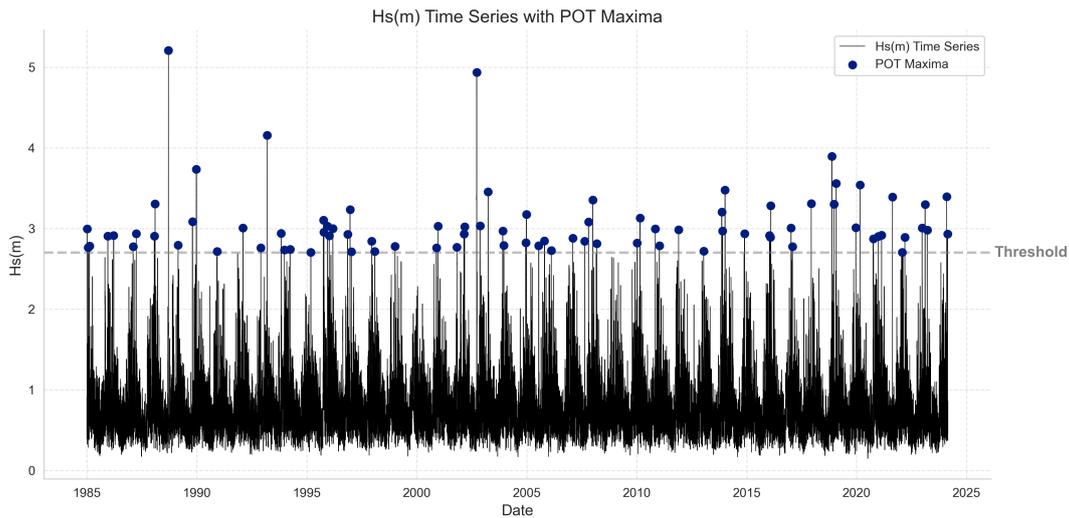
Figure 6.2: Wave height time series with peaks over the threshold of 2.70 metres and a de-clustering time of 4 days.

The exceedances above the threshold were fitted to the GPD to estimate return levels for different return periods. Figure 6.3 presents the return level plot for different return periods, showing how the estimated wave height increases with longer return periods. The GPD fitting can be found in subsection G.1.3.
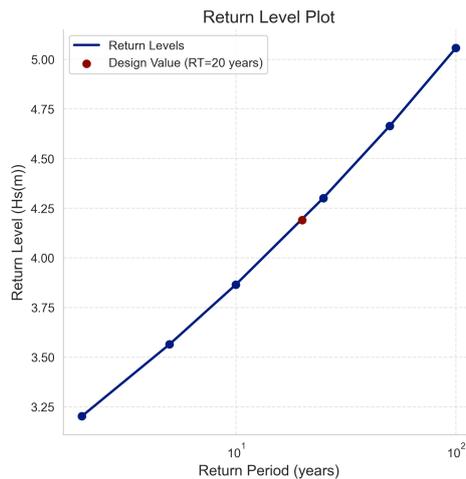
Figure 6.3: Return level estimates over different return periods based on the GPD fit.

For a 20-year return period, the design wave height at the ERA5 location was estimated to be 4.19 metres. The 20-year return period was chosen because it matches the expected operational lifespan

of the fish cages. Designing for a return period that matches the structure's lifespan ensures the cages can withstand extreme wave events that are statistically likely to occur within that period. This approach balances safety and economic considerations, avoiding over-design for excessively rare events.

To adjust this extreme value for local conditions near Sisal, a scaling factor k was calculated. This factor accounts for the differences in wave height between the offshore ERA5 data and the local site. The scaling factor is determined by comparing the Weibull scale parameters of the wave height distributions from both datasets:

$$k = \frac{\text{Scale}_{\text{Local}}}{\text{Scale}_{\text{ERA5}}} = \frac{0.7209}{0.8847} = 0.815 \tag{6.1}$$

Applying this scaling factor, the adjusted design wave height is as follows:

$$\text{Design Wave Height} = k \times 4.19 \, \text{m} = 0.815 \times 4.19 \, \text{m} = \textbf{3.40 metres} \tag{6.2}$$

This adjusted value represents the most extreme wave conditions expected at the location of the fish cage during the design life of the structure.

6.2.2. Design Wave Period

To determine the design wave period corresponding to the design wave height, a power-law regression was applied to the ERA5 dataset to establish the relationship between wave height (H_s) and wave period (T_p):

$$T_p = a \times H_s^b \tag{6.3}$$

The regression yielded parameters $a = 4.85$ and $b = 0.41$. Using these parameters, the design wave period for a wave height of 3.40 metres is calculated:

$$\text{Design Wave Period} = 4.8522 \times (3.40)^{0.4096} = \textbf{8.01} \, \text{seconds} \tag{6.4}$$

A 95% confidence interval was also calculated to account for the uncertainty in the regression model as shown in subsection G.1.5

$$\text{95\% Confidence Interval for } T_p : [6.67 \, \text{seconds}, 9.35 \, \text{seconds}] \tag{6.5}$$

6.3. Design Current Speeds

To determine the design current speeds essential for structural design, a analysis of the current velocity data from the Acoustic Doppler Current Profiler (ADCP) was performed. The ADCP provided measurements at various depths ranging from $-8.8 \, \text{m}$ to $-1.1 \, \text{m}$. However, because of the instrument's limitations, data for shallower depths closer to the surface were not directly available.

6.3.1. Extrapolation to Shallower Depths

To estimate current speeds at shallower depths not directly measured by the ADCP, an extrapolation method was employed. A third-degree polynomial regression was applied to the current speed profiles at each time step. This polynomial fitting allowed for the prediction of current speeds at depths shallower than $-1.1 \, \text{m}$, specifically at $-0.8 \, \text{m}$ and $-0.5 \, \text{m}$. The choice of a third-degree polynomial provided a balance between the simplicity of the model and the ability to capture the curvature in the velocity profile near the surface.

6.3.2. Calculation of Design Current Speeds

The design current speeds were determined using the 95th percentile of the cleaned and extrapolated current speed data at each depth. This means that 95% of the observed current speeds are lower than the design value, providing a conservative estimate for structural design purposes. Using the 95th percentile, the design accounts for extreme current conditions that are likely to occur, but avoids overestimating the loads that would result from possible errors.

Figure 6.4 illustrates the design current speeds over depth. The analysis revealed that current speeds decrease with depth, which is consistent with oceanographic principles, where surface currents are more influenced by wind and wave action, while deeper currents are more stable and slower, as shown in subsection G.2.3. The highest design current speed of **0.50 m/s** occurs near the surface at a depth of -0.5 m.
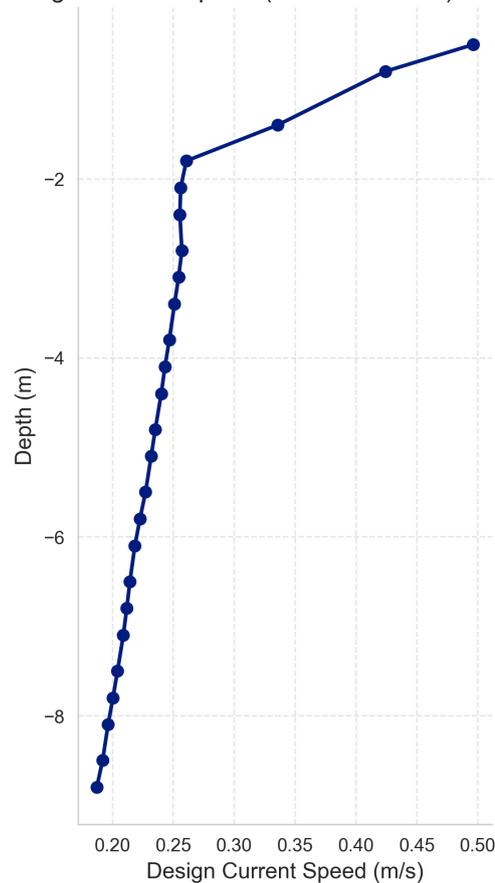
Figure 6.4: Design current speed (95th percentile) versus depth.

6.4. Wave and Current Direction Analysis

Understanding the predominant directions of waves and currents is crucial for designing structures capable of withstanding extreme environmental forces. By analysing directional patterns, especially during extreme events, the design of fish cages can be optimised to ensure their structural integrity and longevity.

6.4.1. Wave Directions

An analysis of the wave directions was performed using both local data and the ERA5 dataset. Histograms of wave directions for all data and the top 5% of wave heights were created to identify the predominant wave directions under typical and extreme conditions.

Figure 6.5 shows that under normal conditions, waves predominantly come from the north to north-east directions (0° to 50°). This indicates that the majority of wave energy impacting the site originates from these directions, consistent with regional wind patterns and oceanographic conditions.

When focusing on the top 5% of wave heights, representing extreme wave events, the histogram reveals a more concentrated directional distribution. The most extreme waves are primarily arriving from the **north** directions (340° to 20°). This slight shift suggests that during extreme events, such as storms or hurricanes, the wave directions tend to align more from the true north, possibly due to large-scale weather systems affecting the area.
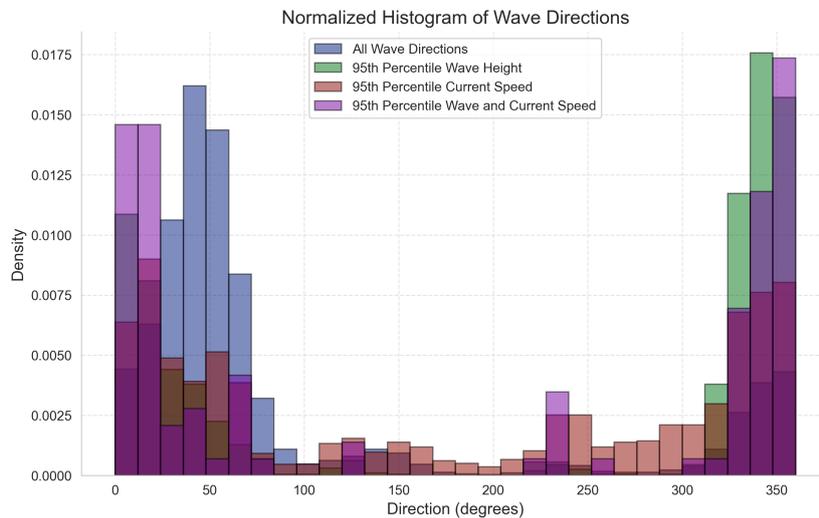
Figure 6.5: Histogram of wave directions for all data and the 95th percentile of wave heights, showing that extreme waves predominantly come from the north to north-east directions.

Understanding these predominant wave directions is critical for the structural design of the fish cages, as it informs the orientation and reinforcement required to withstand the most significant wave forces.

6.4.2. Current Directions

Similarly, current directions were analysed to determine the predominant flow patterns at the site. Histograms of current directions for all data and the top 5% of current speeds were generated.

Figure 6.6 illustrates that under normal conditions, currents predominantly flow from **70° and 250°**, indicating eastward and westward flows. This bidirectional pattern suggests a tidal influence, where currents switch directions based on the tidal cycle.

When considering the top 5% of current speeds, representing extreme current events, the histogram shows that the strongest currents are concentrated toward **70° and 250°** as well. This indicates that even during extreme conditions, the predominant current directions remain consistent, but the current speeds increase significantly.
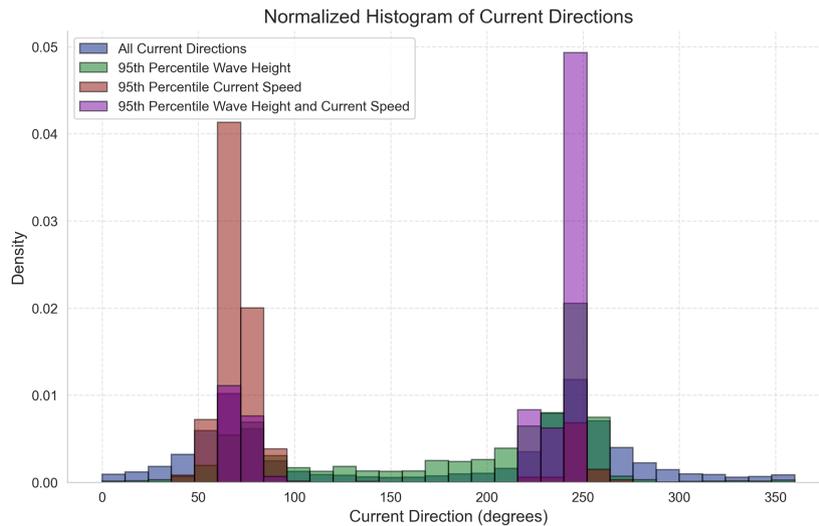
Figure 6.6: Histogram of current directions for all data and the 95th percentile of current speeds, indicating that strongest currents flow predominantly toward 70° and 250°.

Understanding the predominant current directions, especially during extreme events, is essential for assessing the hydrodynamic forces acting on the fish cages and ensuring they are designed to withstand these forces.

6.4.3. Combined Wave and Current Directions

To examine the interaction between waves and currents during extreme conditions, instances where both wave heights and current speeds exceeded their respective 95th percentiles were analysed.

The analysis revealed that while extreme waves and currents tend to occur simultaneously, they originate from different predominant directions. The extreme waves predominantly arrive from the north to north-east directions (340° to 20°), whereas the strongest currents flow toward 70° and 250°.

6.5. Design Values Conclusion

The comprehensive data analysis conducted in this study has provided an in-depth understanding of the offshore environmental conditions near Sisal, with a particular focus on wave and current behaviours. These results are crucial for establishing the design parameters necessary to ensure the structural integrity and longevity of the offshore fish cages. The key design parameters determined from the analysis are as follows:

Design Wave Height
An adjusted design wave height of **3.40 metres** was established, representing the most severe wave conditions anticipated at the fish cage location over its operational life.

Design Wave Period
Corresponding to the design wave height, the design wave period was estimated to be approximately **8.01 seconds**, with a 95% confidence interval ranging from 6.67 to 9.35 seconds. This period is essential for evaluating the dynamic response of the fish cages to wave-induced forces.

Design Current Speeds
Design current speeds were determined using the 95th percentile of current speeds at various depths, ensuring the cages are engineered to withstand extreme current conditions. The highest design current speed at the surface is **0.50 m/s**, decreasing with depth as shown in Table 6.1.

Wave and Current Directions
- **Predominant Wave Directions**: Extreme waves predominantly come from the north to north-east directions (340° to 20°).

- **Predominant Current Directions**: Strongest currents flow predominantly toward 70° and 250°, indicating eastward and westward flows.
- **Combined Forces**: Extreme waves and currents occur simultaneously but originate from different directions, necessitating a design that can withstand forces from multiple directions.

Table 6.1: Design current speeds at various depths.

Depth (m)	Speed (m/s)
−0.50	0.50
−0.80	0.42
−1.40	0.34
−1.80	0.26
−2.10	0.26
−2.40	0.26
−2.80	0.26
−3.10	0.25
−3.40	0.25
−3.80	0.25
−4.10	0.24
−4.40	0.24
−4.80	0.24
−5.10	0.23
−5.50	0.23
−5.80	0.22
−6.10	0.22
−6.50	0.21
−6.80	0.21
−7.10	0.21
−7.50	0.20
−7.80	0.20
−8.10	0.20
−8.50	0.19
−8.80	0.19

7

Design

After determining the location and associated depth, and gathering wave and current design values, along with identifying specific requirements, all data from previous chapters is combined. This information is then used to create initial design recommendations through a simulation-based approach. In order to improve Celestún's operational design, this computational approach is also used to provide a more data-driven foundation for optimising current anchor system designs.

The design process is structured in three main steps. First, three designs of single cages are evaluated, each with different cage diameters and net depth ratios, while maintaining a constant cage volume. The design with the lowest drag is identified by comparing the maximum forces on the mooring system. Second, three layout designs are tested, with an optimal orientation established for each. Finally, a design mooring force is calculated and a safety factor is applied to determine the anchor weight and dimensions. This ensures the anchor can withstand Sisal's environmental forces but avoid unnecessary over-dimensioning. Together, these steps provide design recommendations based on the data sources from previous chapters, combined with a simulation-based approach.

7.1. Base Parameters

To ensure reliable and meaningful results when comparing different fish cage designs, it is essential to maintain consistent parameters throughout the simulations. By keeping most environmental and structural parameters the same across all concepts, variations in results will be due to specific design modifications rather than inconsistencies in external conditions. This uniformity allows each design to be evaluated in the same environmental and operational context.

The key dimensions and materials used in the simulations reflect the specifications of the Celestún cages, as these are readily available and represent the standard materials for local fish cage setups in the Yucatan Peninsula region. The environmental parameters, including values for wave conditions, water density and viscosity, are also set to reflect the conditions typical for the Sisal area, as described in chapter 4. The mooring system pre-tension is set to 1,5 kN for all concepts, it is assumed to be a feasible tension using simple installation equipment. The main environmental and material parameters used in the simulations are shown in Table 7.1 and Table 7.2, further explanation can be found in Table C.1.

Further details on the simulation, including specific inputs, a link to all data files, and step-by-step instructions for using the software, are provided in Appendix H.

Table 7.2: Tubes and Rope/Net Dimensions

Tubes Dimensions:	Amount	Unit
Inner floating tube diameter	0.16	m
Outer floating tube diameter	0.16	m
Distance between floats	0.26	m
Sinker tube diameter	0.1	m
Rail tube diameter	0.12	m
Height of the rail	0.75	m
Rope and Net Dimensions		
Rib line width	10	mm
Briddle line width	16	mm
Net grid width	22	mm
Anchor line width	20	mm
Anchor system		
Mooring line length	36	m
Mooring line pre-tension	1500	N

Table 7.1: Environmental Parameters

Value	Amount	Unit
Water depth	9.5	m
Water density	1024	kg/m^3
Water salinity	35	ppt
Water kinematic viscosity	1.06	m^2/s
Wave height	3.4	m
Wave period	9.35	s
Air density	1.29	kg/m^3
Air kinematic viscosity	1.67E-05	m^2/s

Throughout the simulations, the main differences include wave direction, current direction, current profile/speed and the orientation of the mooring system. A wave period of 9.35 seconds has been chosen for the simulations out of the interval ranging from 6.67 to 9.35 seconds from section 6.5, as it is assumed to generate the highest mooring loads. As most cage properties remain fixed, adjustments are made to the cage diameter-to-depth ratio and the number of cages to explore differences in mooring line forces.

7.2. Cage Dimension Optimisation: Depth versus Width

The first part of the process assesses three concepts of single cage design where the diameter and net depth of the cage are varied, keeping the overall volume of the cage consistent between all concepts, to determine which dimensions result in the lowest mooring forces. The dimensions used in the existing Celestún system (Concept 1B) is selected as the baseline for comparison. From this baseline, two additional concepts were developed: a single cage with a larger depth and smaller width (Concept 1A) and one with a smaller depth and larger width (Concept 1C).

In order to equally test the concepts, single cage layouts with a 3-point mooring system are simulated. Additionally, for this first iteration, both the wave and the current direction have the same heading, which is set parallel to one of the mooring lines (see Figure 7.1). The current is distributed by depth and follows the profile from Table 6.1.

7.2.1. Comparison of dimensions

The table below shows the most important differences in dimensions of the three design concepts. Tube, net and riser dimensions are all set equal to the cages in Celestun. More information is available in Appendix H.

Table 7.3: Comparison of Cage Dimensions for Concept 1A, 1B, and 1C

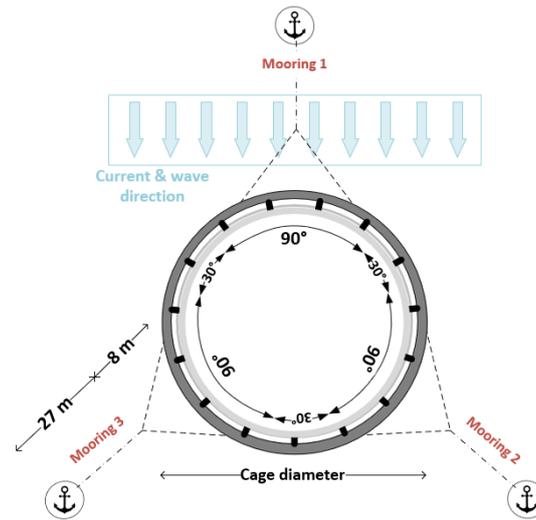|	Concept 1A	Concept 1B	Concept 1C	Unit
Cage diameter	8.42	12	15	m
Cage depth	6.7	4.7	3.76	m
Volume	177.2	177.2	177.2	m^3

Figure 7.1: Mooring setup concepts 1A, B & C

7.2.2. Simulation results

Figure 7.2 presents the mooring forces obtained by the simulations for each of the three design concepts. The simulation time was 30 seconds with an interval of 0.5 sec. The response of the mooring line tensions to waves and currents, and the impact of varying diameter to depth ratio, is small but visible across the different design concepts. By analysing these forces, it is evident that **Concept 1B** has the lowest maximum tension on mooring line 1 at 20,374 kN, compared to 22,29 kN and 22,14 kN for concept 1A and 1C. This suggests that the cage dimensions used in the Celestún system are also the most efficient for the conditions of Sisal in terms of minimising stress on the mooring system.
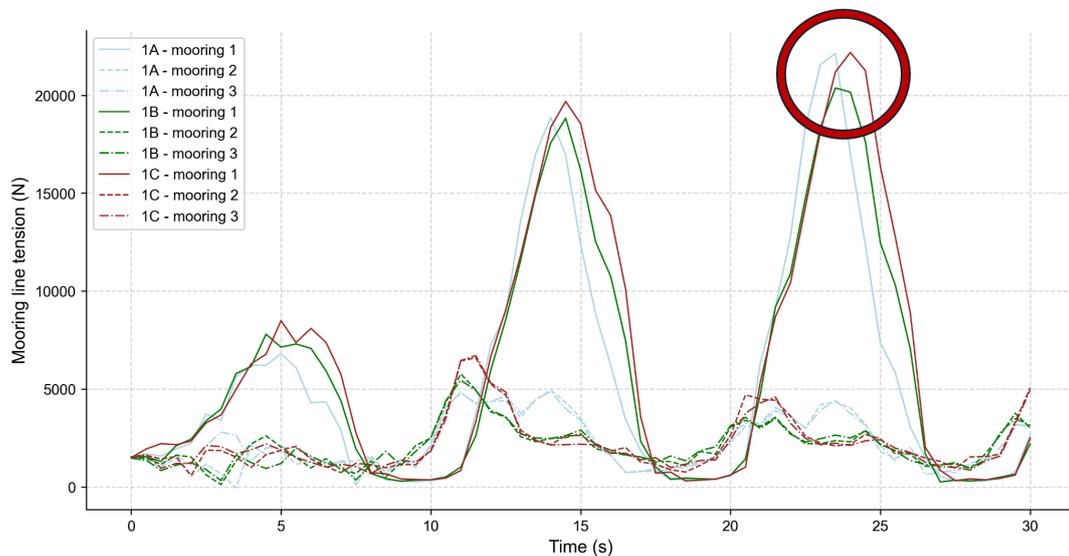
Figure 7.2: Concept 1 Mooring line tension comparison results

7.3. Layout design

Now that the optimal net depth-to-cage diameter ratio has been determined, different layout designs and their impact on mooring forces are evaluated. Three layout designs, including the baseline concept 1B, will be tested to identify the optimal orientation for each layout, as well as the orientation that generates the highest mooring forces to determine the design mooring line tensions. For all layouts, the same cage dimensions as in concept 1B will be used, with mooring line pre-tensions and lengths across

simulations: 1,5 kN and 36 m.

7.3.1. Concept designs

The layout designs for the concepts and their mooring systems have been chosen based on a combination of technical considerations and economical feasible options gathered through interviews. A two-cage and three-cage setup were identified as optimal, with interview feedback emphasising maintainability and installation costs (see section A.5). The three-cage setup is modelled after the existing system in Celestún as it has already proven to be effective and financially viable (see section A.3). This design serves as a baseline for exploring potential improvements using a simulation-based method. The specific layouts are shown in Figure 7.3, and further details are provided below.

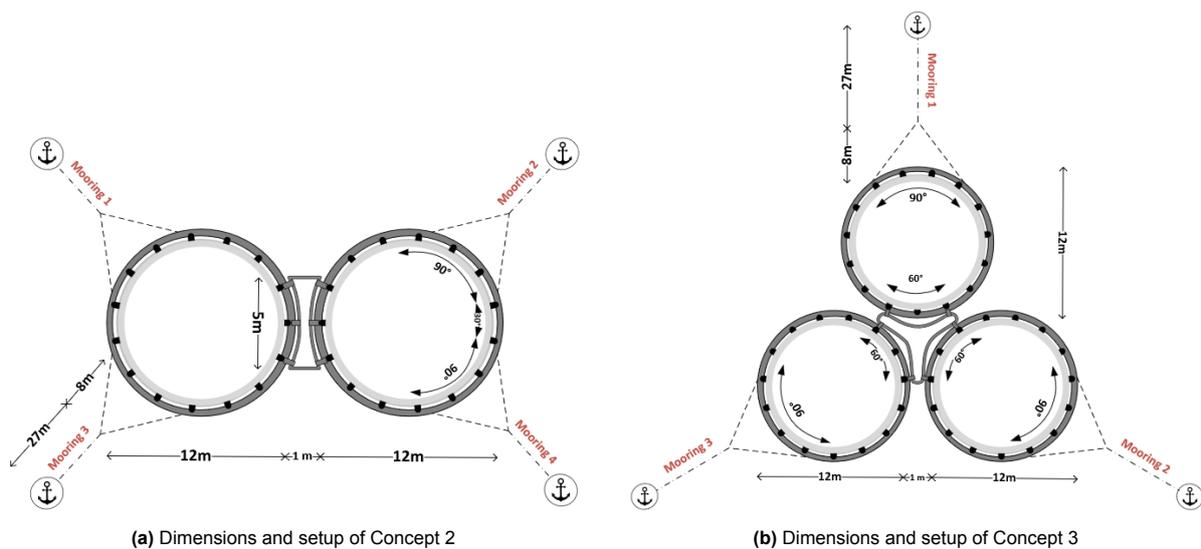**(a)** Dimensions and setup of Concept 2   **(b)** Dimensions and setup of Concept 3

Figure 7.3: Comparison of two design concepts for mooring setup: Concept 2 and Concept 3

Concept 2: Two-cage Setup with 4-point Anchorage System

- **Reduced volume, simplified grid:** This concept has a smaller overall system volume and a simplified grid structure, which helps during the manufacturing and installation process and reduces investment and material costs.

- **Strengthened mooring setup:** A 4-point anchorage system is used to determine whether loads are distributed more effectively, reducing the force on individual mooring lines and enhance the rotational stability.

Concept 3: Three-cage Setup with 3-point Anchorage System

- **Bigger volume, triangle shape**: This concept uses a three-cage configuration, which increases the system's volume. By arranging the cages in a triangle shape, the design aims to reduce the total drag, which will be tested through simulation in different orientations.

- **Improved reliability compared to Celestún setup:** In order to improve the operational design in Celestún, this computational approach is used to give the current anchor system designs a more data-driven background.

7.3.2. Orientation optimisation

Understanding the optimal orientation that results in the lowest maximum mooring line tensions is important to ensure the long-term durability of the aquaculture system. By determining the direction that experiences the least tension, the risk of mooring lines failing due to excessive or repeated tension, caused by periodic environmental forces, can be reduced. This is especially important because the mooring lines must withstand the strongest currents and the highest waves coming from the dominant directions. Optimising orientation in this way minimises the risk of structural damage and ensures the resilience of the system over time.

By placing the moorings in the optimal direction during installation, the structure will be better prepared to handle real-world conditions. All three layout designs will be subjected to the most frequent current and highest waves from the corresponding direction, as obtained in Chapter 6. These environmental inputs are simplified and summarized in Table 7.4. For simulation efficiency, the current is considered uniform throughout the water column, from the surface down to 0.2 m above the seabed, with the average speed derived from the profile from Table 6.1. The waves are modelled as sinusoidal and uniform, arriving from a single direction. The directions used in this analysis are magnetic, ensuring consistency with the navigation and installation practices.

Table 7.4: Current and wave conditions for the optimization simulations

	Value	Unit
Current speed	0.25	m/s
Current heading	70.00	degrees
Current bottom stop	8.80	m
Design wave height	3.40	m
Wave heading	350.00	degrees
Design wave period	9.35	s

The simulated orientations for the three concept designs are chosen based on the symmetrical layout of the mooring systems. For Concepts 1 and 3, which have a three-point anchor system with 120 degrees between each mooring line, steps of 20 degrees are used between the tested orientations. This step size allows for a detailed analysis within the 120-degree intervals while maintaining a reasonable degree of flexibility for installation. Given the wide range of potential wave directions, as shown in Figure 6.5, smaller steps would not add meaningful precision.

For Concept 2, which has a four-point anchor system with 180 degrees between two mooring lines, steps of 30 degrees are used. Using 30-degree intervals divides the 180-degree span evenly, while keeping the total number of simulations throughout the concepts at six. The simulation time for each case is set to 60 seconds, with intervals of 1,0 s. This is sufficient to determine the best orientation once a steady-state response is reached. To ensure accuracy in identifying peak mooring forces, the highest values recorded after 30 seconds are taken.

Once the optimal and worst orientations are identified, they will be subjected to longer simulations with shorter intervals to confirm their performance under extended conditions. The orientation of the layouts relative to the current and wave direction is illustrated in figures 7.4a, 7.5a and 7.6a.

7.3.3. Orientation optimization results
In this analysis, the first step is to look into the lowest maximum mooring line force across all orientations. This is done, to identify the most favourable configuration for minimising stress on the mooring system.

Concept 1
Figure 7.4b shows the simulation results of concept 1. The 350-degree heading shows the lowest maximum tension on mooring line 3, with a value of 11.071 N, indicating the best load distribution. Notably, the tensions across all three mooring lines in this direction are the closest to each other compared to other headings. This suggests that the load is distributed most evenly throughout the system, minimising stress concentration on one mooring line.

What stands out is that it is not the mooring line pointing directly towards the waves or current that takes on the highest load. Instead, the lines on the opposite side carry more of the load. The simulation results of this heading, attached in Figure H.8 , indicates that this is due to a more balanced load distribution between mooring lines 2 and 3, with mooring line 1 taking the least load in this configuration.

The results also show that the influence of waves is more significant than the effect of current. The mooring line that is furthest away from the wave direction consistently experiences the highest tension.
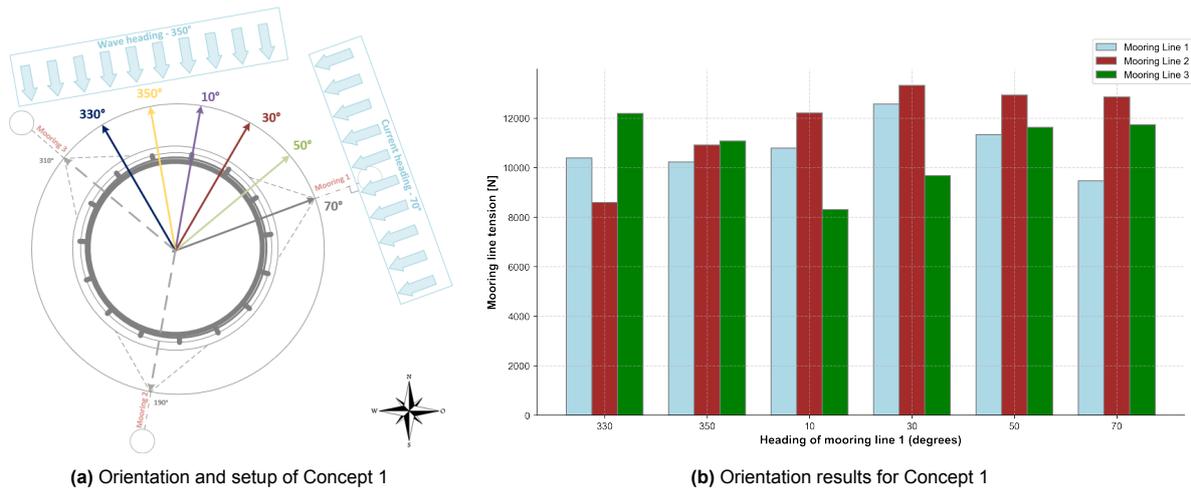
(a) Orientation and setup of Concept 1

(b) Orientation results for Concept 1

Figure 7.4: Comparison of setup and results for Concept 1

Concept 2

In Figure 7.5a, the simulation results for concept 2 are shown. The most favourable orientation among the six cases is at a top orientation of 70 degrees, where the maximum tension on mooring line 2 is 5004 N. Like concept 1, this orientation achieves the most balanced load distribution, with minimal differences between the maximum forces across all four mooring lines.

Once again, wave forces have a greater influence on the mooring lines than current forces. However, in this system, the mooring line facing the wave direction experiences the highest load, while the opposite one takes the second-highest load. The system performs best when aligned with the wave direction (with the narrow side facing the waves). This is also demonstrated by the second most favourable orientation, 280 degrees, which is equivalent to a 100-degree top orientation due to the symmetry of the system. This orientation also aligns with the wave direction experiencing just slightly more drag compared to the 70-degree orientation (see H.9 for full simulation results).

The large variation in maximum forces across different orientations further emphasizes the vulnerability of this layout to waves coming from non-optimal directions. Notably, the maximum forces in this configuration are less than half of those seen in concept 1, despite the cage volume being twice as large. This demonstrates the efficiency of the 4-point mooring system when the loads are evenly distributed. However, it also reveals the system's vulnerability when the forces are not spread evenly, leaving certain mooring lines to bear way higher loads depending on the wave direction.
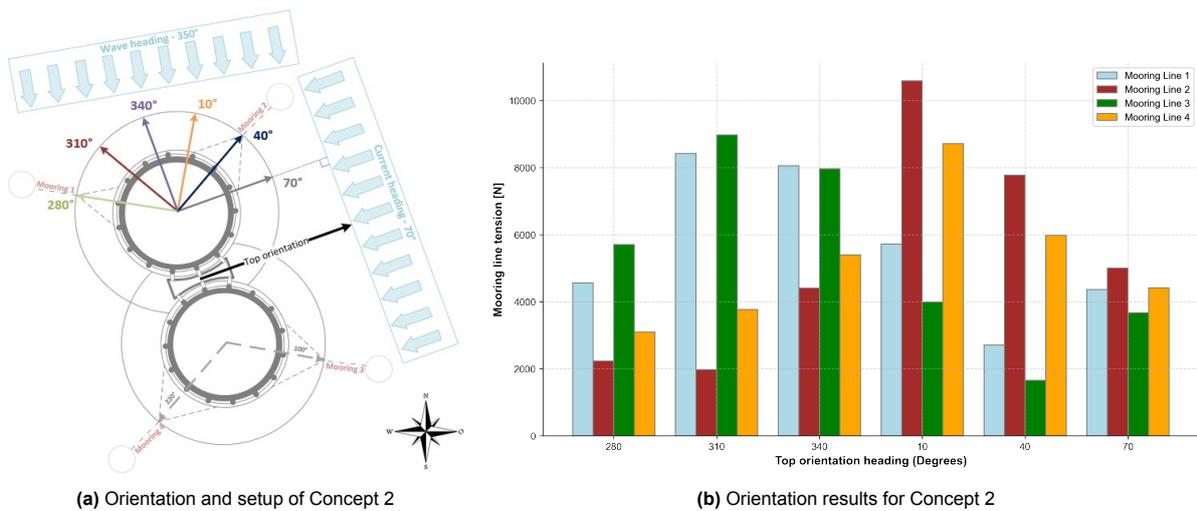

(a) Orientation and setup of Concept 2

(b) Orientation results for Concept 2

Figure 7.5: Comparison of setup and results for Concept 2

Concept 3
In Figure 7.6a, the simulation results for concept 3 are displayed. The most favourable orientation among the cases is at a 50-degree heading, where the maximum tension on mooring line 1 is 14576 N. Unlike Concept 1, where the optimal orientation was 330 degrees, this result suggests that for the triangular cage layout, pointing two mooring lines toward the waves is more efficient (full results in **??**). Orientations where mooring line 1 points more directly toward the wave direction, such as the 330- and 350-degree headings, performed best in Concept 1. These orientations also demonstrate effective load distribution in this layout.

In this configuration, the mooring line facing away from the wave direction experiences the highest load in several cases (330, 350, 10, and 30 degrees). This is due to the system's reaction to wave motion, as the forces acting on the opposite side mooring lines are amplified by the system's movement in response to the waves. A more detailed analysis of this behaviour can be found in Figure H.14, where the full motion profile of the system is presented.

As the minimum maximum load is about 3,000 N higher than that of concept 1, the 3-point mooring system in concept 3 looks efficient for its volume, potentially providing robust performance due to its triangular configuration.

(a) Orientation and setup of Concept 3   (b) Orientation results for Concept 3
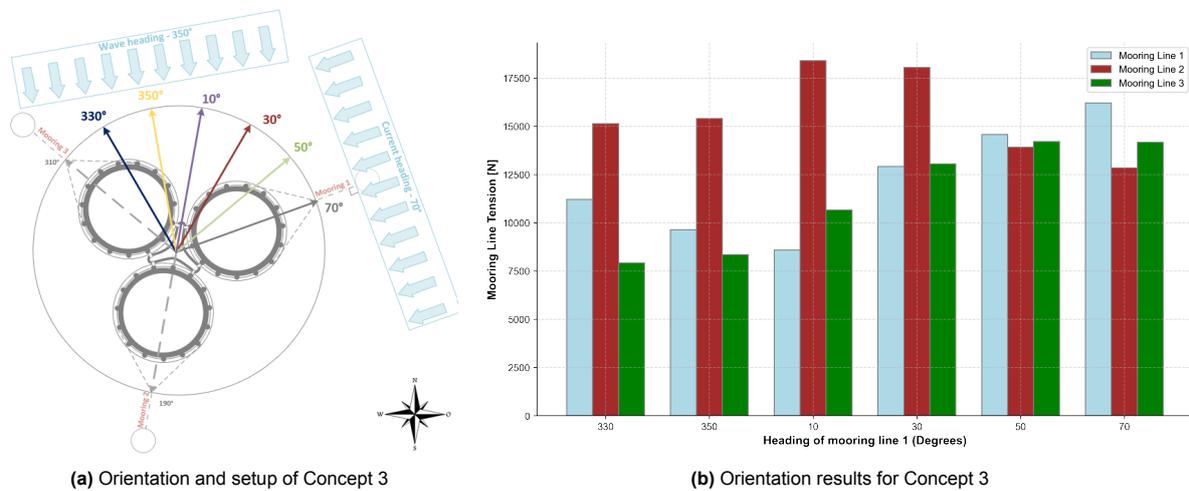
Figure 7.6: Comparison of setup and results for Concept 3

7.4. Design mooring force determination

Based on the depth-to-diameter ratio, layout design, and optimised orientation, the most favourable designs from each concept have been selected. With a wave direction range of 340 to 20 degrees, as detailed in chapter 6, the system must also be capable of withstanding extreme forces from various directions. Therefore, the maximum forces observed on the mooring lines in the worst-case orientation set the minimum force that the mooring system must be designed to handle.

To determine these design mooring forces, a more detailed simulation of 60 seconds with a 0.5 s interval is done. After this, the safety factor will be applied which will then be used in the anchor design in the final part of the chapter. For this simulation, instead of a uniform current, a step current will be used, allowing for a more realistic representation of how currents vary with depth. These values can be found in Table 6.1. Both the step current profile and the shorter simulation interval contribute to higher tension results compared to the simulations in the previous subchapter. The final results can be seen in Figure 7.7.
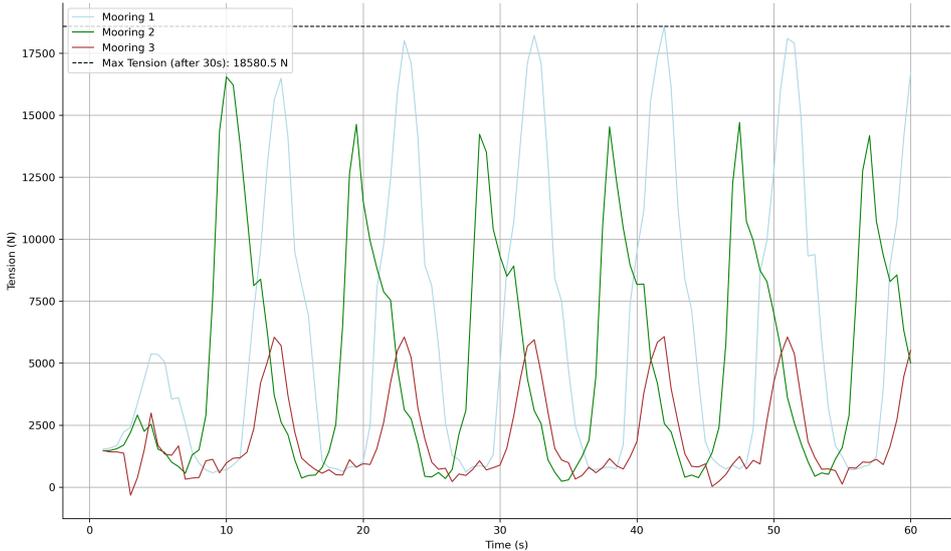
(a) Concept 1 - 30 degree orientation
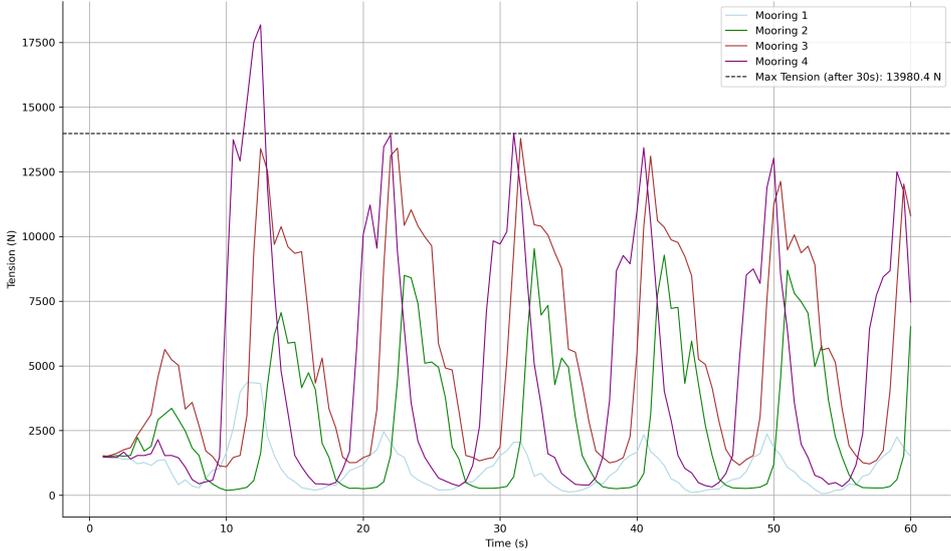
(b) Concept 2 - 10 degree orientation
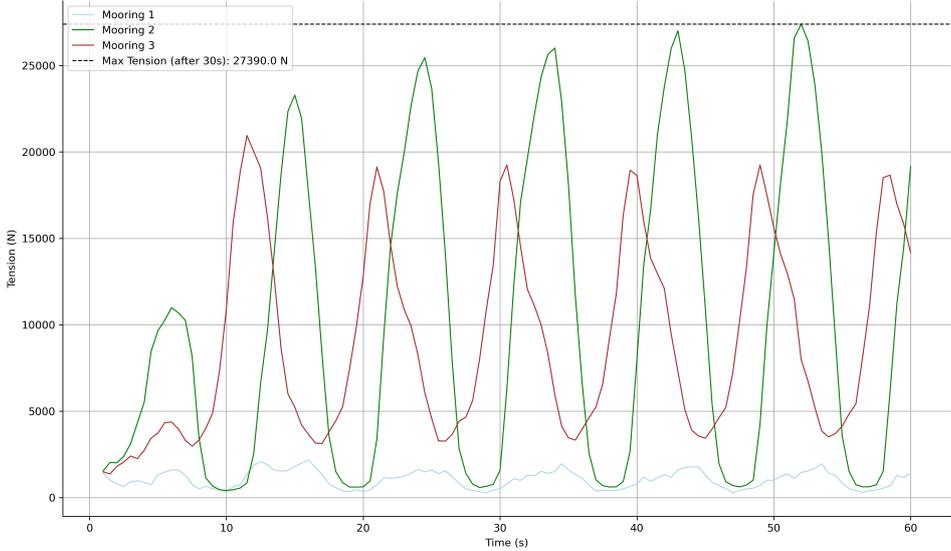
(c) Concept 3 - 10 degree orientation

Figure 7.7: Resulting mooring tensions for Concepts 1, 2 and 3 with the maximum mooring force in Steady state at the worst-case orientation.

Design mooring forces, angles and safety factor
The mooring line angles, which are necessary for the anchor design (see Figure 7.8), are derived from the results of the ProteusDS simulations [14].

The specific values for both the design mooring forces and angles are provided in Table 7.5.

Table 7.5: Design mooring force and safety factors for different concepts

	Concept 1	Concept 2	Concept 3	Unit
Worst-case orientation	30	10	10	Degrees
Max mooring line tension	18580,5	13980,4	27390,0	N
Safety factor	1,5	1,5	1,5	
Design mooring force F_A	27870,8	20970,6	41085,0	N
Mooring line angle ζ	11	10	10	Degrees

For the mooring system's safety factor, the NS9415 ULS (2022) standard has been followed, as it is widely used in aquaculture and ensures structural integrity under operational loads [37]. For the Ultimate Limit State (ULS), a safety factor of 1.5 has been selected from the standard range of 1.5 to 2.0, given the site's shallow bathymetry and the relatively low number of cages, where environmental forces are less severe than in deeper waters.

7.5. Dead-weight Anchor Design

Based on economic feasibility and design choices established in Celestún, the dead weight anchor (DWA) type has been considered most appropriate. Using the design procedure from Bañuelos-García et al. (2021), worked out in Appendix H, the weight and dimensions of the deadweight anchor are determined and tested. Although this design procedure is focused on wind-turbines, the same approach can be used for an estimation of the DWA dimensions because wave, wind and drag parameters are already considered in the simulation.

The DWA is made of concrete, without steel reinforcement, and must be heavy enough to withstand environmental forces and fish-farm loads. Unlike embedded anchors such as piles, DWAs do not require drilling and can be made from common materials. They are also easy to remove from the seabed after use. The size of the anchor, as can be seen in Figure 7.8, is determined through an iterative process to resist sliding and overturning forces.
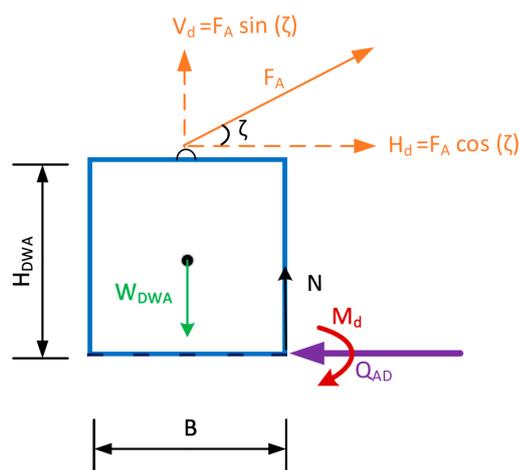

Figure 7.8: Free-body diagram of a DWA [4]

7.5.1. Design

The deadweight anchor (DWA) design follows an iterative approach to ensure the anchor's capacity to withstand environmental forces, based on the Ultimate Limit State (ULS) Design. The procedure starts

with the preliminary design, where the initial parameters, such as the anchor's weight and width, are calculated using standard concrete properties. The anchor weight is determined based on horizontal and vertical loads acting on the anchor, while the width is computed to resist overturning moments and sliding forces.

Once the preliminary anchor size is set, geotechnical capacity checks are performed. The bearing and sliding capacities are calculated based on soil conditions and effective area, ensuring the anchor can handle the applied forces without sliding or being lifted up. If the forces exceed the anchor's capacity, the design is revised.

Finally, structural capacity checks ensure the anchor's structural integrity under axial and sliding forces. If the structural strength isn't sufficient, the design is adjusted. This iterative process balances the anchor's weight, size, and material properties to meet stability requirements under the simulated environmental loads. Table 7.6 show the design parameters used during the design process.

Table 7.6: Design parameters.

Parameter	Symbol	Value	Unit
Structural Concrete			
Concrete Compressive Strength	f_c'	35	MPa
Concrete density	γ_c	23.6	kN/m^3
Sand			
Internal friction angle of the soil	ϕ	30	degrees
Specific weight	γ_s'	17	kN/m^3
Effective overburden pressure	p_0'	10	kN/m^2
Material factor	γ_ϕ	1.2	-
Friction coefficient	μ	0.7	-

7.5.2. Results

Table 7.7 summarises the design results for the three Dead Weight Anchor concepts, detailing the key parameters. The geotechnical and structural capacities are provided in Table H.2

Table 7.7: Design results for the DWA across the three concepts.

Parameter	Symbol	Concept 1	Concept 2	Concept 3	Unit	Formula
Input						
Design mooring force	F_A	27.87	20.97	41.09	kN	-
Mooring line angle	ζ	11	10	10	Degrees	-
Dead Weight Anchor (DWA) Design						
Weight (per anchor)	W_{DWA}	5933.65	4471.03	8760,83	kg	H.1
Length & Width	B	1.81	1.65	2,06	m	H.2
Height	H_{DWA}	0.77	0.70	0.87	m	H.3

The final results show that the weight and size of the Dead Weight Anchors (DWA) differ across the three concepts, with Concepts 1 and 2 having relatively small differences, while Concept 3 requires a much larger anchor. This is likely because Concept 2 uses a four-point mooring system and has a larger volume, which spreads the forces more effectively. In contrast, Concept 1 uses a simpler three-point system for a single cage. Concept 3, with the largest volume and a three-point system, needs an anchor weight of 8761 kg. This weight seems reasonable, as the existing cages in Celestún use 10,000 kg sandbags for each mooring (see section A.1). Although the Celestún design may seem slightly over-sized, it's important to note that the difference between sand and concrete weights has not been considered here.

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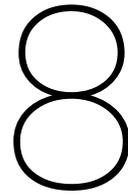
Conclusion & Discussion

8.1. Conclusion

The main research question of this project was: '*What is the ideal distance offshore for cage placement, considering local environmental and community conditions?*'. This question is answered by addressing the sub-questions.

The first sub-question in this research aimed *to determine the ideal offshore location for fish cage placement along the coast of Sisal, Yucatán, considering both local environmental and social conditions.* As revealed in the interviews, the chosen distance of the cages influences a lot of criteria that contribute to the long-term success of the cages in Sisal. Based on expert and interview input, distances from 2 km to 20 km from the shore were evaluated. Analysis shows that 8 kilometres is the optimal location for offshore cages. However, both 6 kilometres and 10 kilometres also appear to be suitable alternatives. Distances beyond 10 kilometres are not ideal for Sisal, as they incur high fuel costs, higher installation expenses and require stronger cages, which further increases costs. Placing cages closer than 6 kilometres also has a lower chance of success. The shallow coastal waters are less clean, leading to increased maintenance needs and poorer conditions for the fish. Moreover, shallower water limits the size of the cage, which significantly affects fishermen's income. Both maintenance requirements and amount of income are very important considerations for the local fishermen.

The second question was aimed *to determine the key environmental forces at the selected location that will influence cage design, which are primarily wave height, wave period and current speed, along with their predominant directions.* The design wave height, adjusted to 3.40 metres based on a 20-year return period, represents the most extreme wave conditions expected over the lifespan of the cages. The corresponding design wave period is estimated at 8.01 seconds with a 95% confidence interval between 6.67 and 9.35 seconds. Current forces, calculated from the 95th percentile, vary with depth, with the highest design current speed reaching 0.50 m/s near the surface at a depth of -0.5 metres. Directional clustering, where waves predominantly come from 340° to 20° and currents from 70° and 250°, indicates that the structure will face combined forces from specific orientations.

The third sub-question aimed *to identify design recommendations for a resilient mooring system specifically tailored to the environmental conditions in Sisal.* Firstly, to support a resilient mooring system tailored to Sisal's conditions, it is recommended to use a cage diameter of 12 metres with a net depth of 4.7 metres, optimising the depth-to-diameter ratio to minimise mooring line forces. Orienting the mooring systems according to specific headings, one mooring line heading to 350 degrees (north-north-west) for Concept 1, a top orientation of 70 degrees (east-north-east) for Concept 2 and one mooring line heading to 50 degrees (north-east) for Concept 3. This orientation aligns them with the dominant waves and currents, reducing the mooring line tensions.

The anchor designs for each concept should be as follows: Concept 1 requires an anchor weight of 5,934 kg with dimensions of 1.81 x 1.81 x 0.77 metres; Concept 2 requires an anchor weight of 4,471 kg with dimensions of 1.65 x 1.65 x 0.70 metres; and Concept 3 requires an anchor weight of 8,761 kg with

dimensions of 2.06 x 2.06 x 0.87 metres. These specifications ensure the anchors can withstand local environmental forces without unnecessary over-dimensioning. Implementing these recommendations will enhance the durability and reliability of mooring systems for fish farms in Sisal, making them well-suited to the extreme local conditions.

In summary, this project provides a set of guidelines for the optimal placement and mooring design of fish cages offshore Sisal. These recommendations reflect a balance between the needs of the community and the environmental forces. This will promote a sustainable approach to long-term success in the offshore aquaculture sector in Sisal.

8.2. Discussion

This research on sustainable offshore cage solutions for Yucatan's aquaculture has provided valuable insights into the technical, social and environmental factors that will shape the future of fish farming in Sisal. Throughout the project, several important considerations and assumptions were made that indirectly impact the results. It is important to interpret and analyse the findings by highlighting the significance of the results and explore their implications and their limits. This knowledge helps to give further recommendations and address future research possibilities. To provide structure to this chapter, each part of the research is discussed separately.

8.2.1. Site Analysis and Determination
Enhancing interview validity

The interview process provided useful insights into local preferences and needs; however, increasing the sample size could enhance the validity of these findings. Interviewing a larger and more diverse sample, including additional fishers, local residents, and tourists, would offer a more well-rounded understanding of the community's needs. Expanding the pool of participants would also improve the reliability of the recommendations and ensure that the cage designs and placements align more closely with local expectations.

Safety considerations of fish farms

Although the theft and demolition of fish farms emerged as a concern during the interviews, it was not incorporated into the primary analysis. Fish farm safety is quite complex, involving questions about responsibility for security and the associated costs, such as patrolling expenses. This aspect requires further investigation, as safety is essential for community acceptance and operational stability. Future projects should explore ways to integrate safety measures and clarify the roles of involved stakeholders to ensure a comprehensive approach to fish farm security.

Uncertainties in perspective influencing MCA and Sensitivity analysis

Although the sensitivity analysis addressed the influence of changes in environmental and community criteria, fully capturing the perspectives of all stakeholders (such as local fishers and community members) is challenging. The MCA framework offers a structured approach to incorporate diverse perspectives, but uncertainty persists due to the subjective nature of these criteria and the inherent complexity of addressing everyone's views comprehensively. Nonetheless, MCA remains a valuable tool, and future studies should explore more refined methodologies to capture a broader range of stakeholder perspectives.

Cost considerations

A final discussion point is related to the costs. One goal of this research was for the fish cages to be adapted to the Sisal environment while remaining affordable. However, it can be seen in the report that cost analyses were not included. This is due to a lack of information on how the costs of such cages are structured. The total cost of the cage used in Celestún is known, as can be seen in the interviews, but specific cost details are not available. Since the design was based on the cages in Celestún, they are assumed to be relatively affordable and thus feasible in Sisal as well. Conducting further research to map out the cost structure of the cages and explore various cost considerations would be beneficial and an interesting future study.

8.2.2. Environmental Forcing Conditions
Data analysis and validation

To improve data validity for optimal cage placement, expanding the range of ADCP datasets beyond the current two locations (four and ten kilometres offshore) would be beneficial. Additional measurements at varied locations and depths would improve the reliability of the analysis.

Data Limitations and Reliability

One of the primary limitations in the design value analysis is the variability and gaps in the local wave and current datasets. Although the ERA5 dataset allowed for a broader historical perspective, it may not capture localised conditions with the same accuracy as direct measurements. Additionally, the absence of data at the specific 8 km location meant that the closest available data from 12 km offshore had to be used, which may not fully reflect the precise environmental conditions at the cage location.

Extrapolation of seabed depth

The extrapolation of seabed depth data for distances beyond the measured 10 km introduces a degree of uncertainty. For instance, predictions about depths at 15 km and 20 km are based on a linear polynomial fit model, which, while informative, cannot replace direct measurements. Future studies should consider additional surveying at these distances to obtain more reliable data. This would improve accuracy in site selection and lead to more confident recommendations regarding cage positioning.

Threshold Selection and EVA Parameters

The threshold and clustering choices in the EVA significantly impact the results. A 2.7-metre threshold and 4-day declustering period were applied, but slight adjustments could alter return levels. Thus, the 3.40-metre design wave height should be viewed as an estimate dependent on these choices. Future sensitivity analysis could provide more robust design values.

Design Values and Assumptions

The selection of a 20-year return period aligns with the assumed design life of the fish cages. However, the assumed design life might be overestimated as a result of the lifespan of the individual components. Similarly, the 95th percentile design current speed, although in line with what was expected as the maximum current speed, may not represent the rarest occurrences. Future designs might consider a more conservative percentile or an alternative method for estimating extreme currents, especially if longer data records become available.

8.2.3. Design and Simulation
Incorporation of fatigue analysis

This study considered only extreme force scenarios, without an analysis of fatigue, which could influence long-term material durability. In real-world applications, cages are subjected to repeated stresses, leading to gradual wear. More comprehensive research, should include a fatigue analysis to evaluate long-term wear on both cage materials and mooring systems, ensuring the cages remain functional and stable over extended periods.

Strength and durability of the system's components

The strength and durability of the entire system (including mooring lines, tubes, and other connecting components) must be carefully considered, as the simulation assumes they can withstand the expected tensions. In practice, these elements need materials with high tensile strength, flexibility, and resistance to marine wear to endure long-term real-life stresses. While only mooring line tensions are used as an output in this simulation, future research should also evaluate the strength of all other components to ensure the systems reliability.

Uniform Mooring Line Lengths and Pre-Tensions

The simulations used identical mooring line lengths and pre-tensions across all designs, though variations in these parameters can significantly affect mooring performance. In future studies it would be interesting to explore different mooring line lengths and pre-tension settings to further optimise the design.

Exclusion of Wind Forces

Wind forces were not included in the initial simulations, despite their potential to impact cage stability, particularly forces on floaters during extreme weather. Future simulations should integrate wind data to provide a more comprehensive environmental assessment and reduce unexpected loads on the mooring system.

Exclusion of Tidal Effects on Mooring Lines

Tidal changes were not included in the simulation, though they can add extra forces on mooring lines due to shifting water levels. Future models should incorporate tidal effects to ensure mooring stability under varying conditions.

Simplified Floater and Net Parameters

The simulation used assumed values for floater mass, buoyancy, and net material strength, which may not fully reflect real-world conditions. Testing with adjusted mass and durability specifications would help ensure better performance and potentially reduce maintenance needs.

Lack of Site-Specific Soil Testing

No soil tests were conducted at the project site, so the anchor design relies on standard values for sandy soils rather than local measurements. This brings uncertainty, as variations in soil properties could affect anchor stability and therefore design.

Exploration of Enhanced Sliding Resistance

As sliding capacity was the most critical factor in the anchor design, further investigation into improving sliding resistance between the anchor or pile and the soil could be valuable. This may include looking into alternative anchor types, deeper embedment, or soil enhancement techniques to improve the anchoring stability.

Assumption of a Flat Seabed Floor

The simulation assumed a flat seabed, simplifying anchor placement and mooring calculations. However, actual seabed morphology off Sisal's coast may vary, potentially affecting anchor stability. Future designs should incorporate seabed mapping to optimize anchor configuration and ensure secure mooring.

Importance of Real-World Validation

While simulations provide a foundation, real-world testing is essential to validate assumptions and refine designs. Field tests can reveal practical challenges and allow for on-site adjustments, ensuring the cage system is robust, stable, and well-suited to Sisal's unique conditions.

Opportunity to Repurpose Washed-Up Industrial Cages

An interesting opportunity for future research is to investigate the potential of repurposing the industrial fish cages that have washed up on Sisal's beaches. Our observations suggest that these cages, despite their initial shortcomings, could provide a more robust solution than the Celestún cages due to their stronger tubing. By reducing the total diameter and improving the connections of these existing structures, it may be possible to create cost-efficient and sustainable fish cages that are better suited to Sisal's environmental conditions. Exploring this possibility could contribute to resource optimization and waste reduction, aligning with sustainable development goals and providing a feasible solution for local aquaculture.
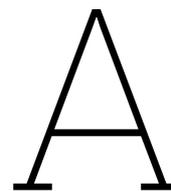
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Interviews

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In this Appendix a summary with the key takeaways of each interview are given. During this research, a lot of information was gathered from meetings and interviews with various involved parties. Since this includes a large amount of information and conversations, we have chosen to provide only a summary of the key conclusions, information, and discussions. In total, there were 7 specific occasions where we had interviews with local people or experts. The context of each occasion will be briefly explained, followed by the key takeaways or answers from each. For lack of clarity or questions regarding the interviews/information, you may request access to the full transcripts of all interviews from the authors of this report.

Overview:

A1 - First interview: Local meeting between fishers Celestun and Sisa (06-09-2024).

A2 - Second interview: Meeting with Dr Carlos Rosas (23-06-2024)

A3 - Third interview: Meeting with Onésimo to visit the fishing cages of Celestun (27-09-2024)

A4 - Fourth interview: Tourists in Celestun (27-09-2024)

A5 - Fifth interview: Abel (engineer who constructed the cages in Celestun) (15-10-2024)

A6 - Sixth interview: Local fisherman Sisal named Fernando (15-10-2024)

A7 - Seventh interview: Local fisherman Sisal (11-10-2024)

A.1. Interview 1: Fishers Sisal and Celestun
First interview: Local meeting between fishers Celestun and Sisal (06-09-2024).

The first interview was held at a local meeting in which the fish communities of Celestun and Sisal met to speak to each other about the importance of engaging the community in creating a fish refuge and making sure that it is protected. Both parties were asked to share their experiences and aspects on this subject. Also the increase of the livelihood of both communities was discussed. After the meeting we were able to interview both fishermen from Sisal and Celestún. The key takeaways include both information gathered in the classical discussion as well as in the specific interviews.

Key takeaways:

The project has three main objectives: to create alternative employment for fishermen, to enable continuous monitoring of a designated refuge area, and to support the community through sustainable practices. Fishing provides income for only half the year, so installing fishing cages near the refuge area offers a dual benefit: feeding the fish and monitoring the refuge. Monitoring is costly due to fuel expenses, and funding is limited, but by raising and selling fish, the community generates revenue to continue patrolling the area. Tourism is also being considered as a way to showcase the project

and bring in additional resources. The social aspect has posed significant challenges, as convincing fishermen to participate in a project without immediate financial compensation has been difficult.

In 2014-2015, sea cucumber fishing brought substantial economic benefits, but concerns about resource depletion led the fishermen to consult a biologist and raise awareness in the local community about sustainable practices. As a result, the Fishing Refuge Area was established, leading to improved fishing conditions and greater participation from the community, demonstrating the project's success.

The marine cages are anchored with sacks of sand, each weighing 10 tons, and secured with silk ropes for durability. These anchors are designed to last over 10 years. While some adjustments, like reinforcing the ropes, are necessary, the installation has remained in excellent condition after two years. The cages themselves are made from a buoyant plastic material used in potable water pipes, which provides natural flotation and resistance to strong currents. There have been minor issues with the size of the tubes, as larger diameters are needed to withstand strong currents and prevent breakage. Additionally, improvements in the mesh design are suggested to avoid larger tears when damaged.

The lack of strong currents has been beneficial for the anchorage system, which has remained in optimal condition for two years without the need for maintenance. A line reinforcement is planned for added safety, but no significant issues have occurred so far. The cages are constructed from a plastic material commonly used for potable water pipes, which is naturally buoyant due to its hollow structure, eliminating the need for additional flotation devices.

The cages are 5 meters deep, with a thinner tube at the bottom filled with water to provide weight and stability. Small weights distributed around the structure help to prevent movement and keep the cage in place, allowing it to withstand strong currents. The cage is attached only at the anchor points in the center and floats without additional anchoring at the bottom.

One identified issue is the need for a larger diameter tube to improve buoyancy and resistance, particularly during strong winds, as the current tube is prone to stretching and cracking under stress. This modification requires specialized equipment for welding, which presents a logistical challenge. Additionally, improvements in the mesh material are recommended. The current mesh can expand significantly when a thread breaks, so a knotted mesh is suggested to prevent larger tears. Different mesh sizes are used depending on the age of the fish, with one designed for juveniles and another for more mature fish.

A.2. Interview 2: Dr. C. Rosas

Second interview : Interview with Dr Carlos Rosas (23-06-2024)

Dr Carlos Rosas has been doing research in Sisal on octopuses. He is working on how octopuses can be cultured in farms and therefore hopes to increase the livelihood of the community of Sisal. Because of that he knows the local community quite well and generally knows what is needed for the cages to be a success.

Key takeaways:

After conducting literature research on suitable fish species, we chose the Pompano fish. This fish is well-suited to the biochemical composition of the seawater off the coast of Sisal. Since Carlos is working on breeding fish from eggs, we asked him if this was a good choice. He confirmed that it was, as they are already breeding Pompano fish in the lab. This is an important factor for adopting the cages, as it removes one obstacle. In Celestún, the fish placed in the cages are caught as juvenile fish and then grown in the cages. Since the fish are being bred, fishermen won't have to incur the cost of catching them, as they can be sourced from the lab.

When asked about the ideal size for a cage in Sisal, he indicated that an industrial cage has a diameter of 20 meters, while the cage in Celestún has a diameter of 10 meters, so the prototype will likely fall somewhere in between. That is his vision.

Carlos mentioned that the cage in Celestún is located about 20 km from the coast. The fishermen feel this is quite far and would prefer the cages to be closer. Since these were the first cages, they didn't

realize it would be such a challenge. The cage was placed so far out because it marks the edge of the fishing refuge. No cages can be placed within that distance as the area is a protected nature reserve.

A.3. Interview 3: Fisher Celestun
Third interview: Meeting with Onésimo to visit the fishing cages of Celestun

Onesimo is one of the fishermen who is part of the organization of local fishermen in Celestun; the group has a total of 56 men. And together they share the costs, maintenance, and responsibility of the operating fish cages in Celestun. Everyone has their own particular task; Oneismo tasks is organizing trips to the cages, in the future these trips will mainly focus on tourist trips.

Key takeaways:

The fish cages provide a critical alternative income source, especially as traditional fishing becomes increasingly difficult due to the need to travel further distances for a successful catch. By establishing the fish cages, local fishermen are able to reduce overfishing pressures on the area's natural resources. Additionally, this aquaculture effort introduces a form of food security for the community, allowing fish to be cultivated and harvested closer to shore. The fisherman emphasized that the cages serve as a protective measure, supporting the breeding of certain species, such as Cananees and Corvinas, reducing the strain on wild populations.

There is a strong potential to develop these fish cages as an attraction for alternative tourism, where visitors can observe and engage with the aquaculture process first-hand. The community organizes twice-monthly tours where visitors can even swim near the cages, feeding the fish and learning about the sustainability efforts of the local fishermen. This approach not only brings tourism revenue but also educates visitors on conservation and the importance of responsible fishing practices. The fisherman highlighted that this tourism aspect is being developed thoughtfully, ensuring a balanced schedule to avoid disruption while also maximizing the potential to promote Celestún as a unique, eco-friendly destination. The fish cage project represents a collective effort among Celestún's fishermen, with 56 local participants pooling resources to finance the cages, which cost $522,000 in total. The community has taken an organized approach to manage and sustain this project, forming a committee with specific roles, such as a president and treasurer, to oversee fundraising, maintenance, and tourist activities. This strong community involvement not only enhances the project's sustainability but also fosters a sense of shared responsibility and ownership among local fishermen, helping to ensure the longevity of the initiative.

The fish cages are strategically located 23 miles from shore to strike a balance between accessibility for fishermen and minimizing the impact on other fishing areas. This distance was carefully chosen to prevent interference with local fishing while maintaining proximity to the shore, reducing logistical costs for transportation and maintenance. Additionally, the location provides an optimal environment for the species in the cages, such as sea cucumbers and red grouper, promoting a suitable habitat for the fish to thrive.

Built by engineers from Mazatlán, the three cages cost $522,000—a price relatively affordable for such a large project in aquaculture (normally twice as expensive). The cages, each 10 meters in diameter, were constructed using thermofused pipes arranged in a circular shape to promote durability and efficiency. The fishermen collectively raised the funds to purchase the cages, showcasing a deep commitment to aquaculture as an investment in the community's future. The price, although substantial, was seen as a worthwhile investment, with the cages providing not only economic benefits but also ecological ones by fostering fish breeding in a controlled environment.

Regular maintenance is essential to ensure the durability and functionality of the cages, which are subject to rapid accumulation of algae, sediment, and barnacles due to local environmental conditions. This growth can compromise the cage structure and hinder fish visibility for tourists, making cleaning a vital task. The community organizes frequent maintenance sessions, which include bringing the cages to shore to dry in the sun and scrubbing them clean with brushes. They also replace damaged parts as needed, such as weights and sections of the cage material, to prevent fish escapes and maintain the quality of the enclosure. This collective maintenance effort is not only physically demanding but also crucial for the project's sustainability and long-term success, especially as it directly affects the

appearance and strength of the cages.

The fisherman reported frequent issues with the nets, which broke twice in one month due to wear and potential attacks from larger fish like barracudas. To address this, the community plans to switch to a stronger "knot net" in the next season, anticipating that this material will be more resistant to environmental wear and attacks from marine predators. However, the knot net is more costly, and the community is exploring potential support from government agencies to subsidize this improvement. The fishermen see this upgrade as essential to ensure that the cages remain secure and functional throughout the season, minimizing the risk of fish escapes and reducing the frequency of repairs.

The project has aspirations to expand by adding more fish cages, which would allow the community to increase fish production and potentially protect a larger marine area. This expansion aligns with their goal of building a more sustainable and resilient fishing economy in Celestún, enabling the community to benefit both from tourism and increased fish yields. By involving more people in the initiative, the fishermen hope to create a larger protected refuge area, which would contribute to the conservation of local fish species and enhance the economic stability of Celestún's fishing community. This initiative showcases the community's efforts to combine sustainable fishing practices with aquaculture and tourism, supporting both economic growth and conservation in the region.

A.4. Interview 4: Tourists
Fourth interview: Tourists in Celestun (27-09-2024)

This interview provides perspectives from two American tourists, Ted and Alicia, visiting Celestún, Mexico. They share their thoughts on the region's natural beauty, discuss potential interest in an aquaculture tour involving fish cages, and consider factors such as pricing, travel distance, and community support. Ted and Alicia's responses offer insights into the appeal of ecotourism and reveal differing opinions on activities involving fish cages, reflecting a mix of environmental awareness and recreational interest.

Key takeaways:

Ted and Alicia were drawn to Celestún for its beautiful beaches and authentic atmosphere. They described it as a more "original" destination compared to other nearby tourist spots, suggesting that Celestún's unique charm and natural appeal played a significant role in their decision to visit. Ted expressed an interest in visiting the fish cages, primarily if the experience included activities like fishing or swimming. However, Alicia found the idea less appealing, especially due to ethical concerns about fish confinement. This contrast highlights how different tourist preferences can shape the demand for ecotourism experiences and underscores the importance of offering a variety of activities to accommodate diverse interests.

Alicia was apprehensive about the ethical implications of fish farming, stating that she found the confinement of fish in cages "dreadful." Conversely, Ted was open to visiting if it offered a sporting or recreational element, like fishing or swimming. This difference illustrates the varied reactions tourists may have toward aquaculture, particularly when it involves visible containment of wildlife. Ted preferred a tour experience that involved a short boat trip (about 15-25 minutes) for a more immersive experience, as opposed to a visible setup from the shore, which he felt might detract from the adventure. Alicia agreed that a trip offering something "out of the ordinary" would be more appealing, indicating that both valued the journey element of the experience.

Both tourists indicated sensitivity to pricing but were open to paying a bit more for an experience that felt worthwhile. Ted, for example, mentioned that he would be more willing to pay a higher fee if the tour provided a unique and valuable experience rather than something easily accessible or visible from the shore. Ted and Alicia both supported the idea of higher tour fees if they directly contributed to the local community. They saw this as a positive aspect, noting that such contributions could help fund conservation efforts and support the fishermen's initiatives in preserving local marine life. They expressed a willingness to make a "small donation" through tour costs, emphasizing that part of their motivation to visit was to help support the area's residents.

The tourists recognized the impact of their travel on local communities and expressed a sense of re-

sponsibility to minimize disruption. Ted noted an awareness of how tourism can affect daily life in places like Celestún, underscoring the importance of conscientious travel. Alicia also echoed this sentiment, suggesting that supporting community-driven projects was one of the few redeeming aspects of aquaculture tours from her perspective.

A.5. Interview 5: Engineer Celestun
Fifth interview with Abel (engineer who constructed the cages in Celestun)

Abel is the engineer of the company who collaborated with the fishers from Celestun to design and develop the cages used in Celestun. Important to note is that his company and the fishers were partners and really worked together.

This interview provides insights from Abel, the engineer responsible for designing and implementing fish cages in Celestún, Mexico. Abel shares detailed perspectives on the design, construction, and strategic considerations behind the aquaculture initiative. Abel is an engineer at the company Ingenieria de Jaulas Marinas De México Abel was asked about the technical aspects and challenges of creating a sustainable aquaculture system in a coastal region. Here are the key takeaways.

Key takeaways:

The fish cages were specifically designed to support aquaculture in an environmentally sensitive area, promoting sustainability while generating income for the local fishermen. The circular cage structure, selected for its strength and resistance to currents, supports species conservation and local aquaculture goals. The engineer emphasized that the design balances durability with ease of maintenance, allowing fishermen to engage in fish farming with minimal disruption to their daily routines.

The cages were built using thermoformed pipes to form a circular shape, a choice driven by both the durability and cost-effectiveness of this material in marine conditions. The engineer highlighted that circular cages experience less stress from tidal forces compared to square designs, enhancing the longevity of the structure. Given the challenges with local conditions, including sediment build-up and exposure to larger fish, the material choice was critical to ensuring the cages' long-term functionality and minimizing repair needs.

Located 23 miles from the shore, the cages were positioned to avoid interference with traditional fishing areas and to optimize habitat conditions for species such as Cananees and Red grouper. This distance reduces conflicts with nearby fishing communities while ensuring a favourable environment for aquaculture. The engineer collaborated with local fishers to select the location based on environmental assessments and practical considerations for accessibility and maintenance. In the maximum diameter of the fish cages in order to let the cage be transportable by the fisherman boats is set at 12 metres.

The project cost $522,000 pesos for three cages, a relatively economical price for aquaculture infrastructure of this size and quality. The engineer worked with the fishermen's community to manage the budget and secure a feasible price, ultimately creating a high-value solution tailored to local conditions. The affordability of the cages was a priority, as the project aimed to introduce aquaculture as an accessible income source for local fishermen. This focus on cost efficiency allowed the community to invest in the project with shared resources.

A central part of the project involved training the fishermen to manage and maintain the cages. The engineer organized workshops and provided guidance on maintenance practices, helping the fishermen develop the skills needed to care for the cages independently. This focus on education empowered the community to take ownership of the project, ensuring sustainability and reducing dependency on external support.

The engineer acknowledged the significant maintenance needs due to local environmental factors, such as algae, sediment, and barnacle build-up on the cage structures. Frequent cleaning is necessary, which involves bringing the cages ashore and scrubbing them to remove accumulated organisms. The engineer highlighted that the circular design facilitates easier cleaning and maintenance, allowing the fishermen to keep the cages functional without specialized tools. Regular maintenance is crucial

to prevent fish from escaping and to maintain the cages' appearance for tourism purposes, a factor considered in the design.

The engineer recognized the challenges with the initial net design, as the material was prone to damage from large predators like barracudas. Based on this feedback, plans are underway to replace the current netting with a stronger "knot net" to provide enhanced durability and resilience against environmental pressures. The engineer also discussed options with government agencies for potential funding to support these improvements, ensuring the cages can withstand marine conditions and reducing the frequency of repairs needed.

The engineer expressed optimism about expanding the project with additional cages, which would enable the community to increase fish production and enhance species protection efforts. The expansion would involve further collaboration with local fishermen and potentially additional funding sources, aiming to create a more comprehensive aquaculture zone in Celestún. The engineer sees this growth as an opportunity to strengthen the economic impact of aquaculture on the community, enabling a sustainable income source while protecting local marine biodiversity.

A.6. Interview 6: Fisher Sisal
Sixth interview Local fisherman Sisal named Fernando

Fernando is a fisherman from Sisal. He is currently a transportation officer, as he describes it himself, for field work. He works with many people from the university like the Faculty of Chemistry, the Faculty of Sciences, and the Institutes of Engineering, and he's involved in almost all the work that happens outside, like guiding trips to cenotes, swamps and working with crocodiles, birds, fish, and collecting water sample. Before he joined the university, he spent years as a fisherman and in the fishing trade.

Key takeaways:

Fernando has never personally used fishing cages but observed them once in a previous project. These cages were set up about 4 km offshore, but the project failed due to technical issues like fish escaping and boards breaking. The company involved eventually went bankrupt, and no tangible results were seen, leading to skepticism from the community.

The local community views the use of cages with suspicion and doubt, mainly due to past failures. Challenges such as lack of commitment, poor species selection, and the harsh weather conditions (like hurricanes) contribute to this negative perception.

Fernando emphasizes that choosing the right fish species (one that grows quickly) and having committed personnel are critical for successful fish farming. Additionally, technical aspects like feed management, cage selection, and fuel costs must be considered. These activities require significant resources and investment.

A lack of knowledge and awareness in the community hinders progress. People need to see working models to trust the system. Furthermore, the region's climate, especially during hurricane season, makes cage farming even more challenging.

The community feels disconnected from the university, which is perceived as taking land without offering sufficient support. Though the university has some involvement (e.g., with an octopus cooperative), it hasn't fully integrated into the local economy or delivered lasting benefits. Fernando believes the university could help more if it engaged better with the community, providing knowledge and technical assistance to improve projects like fish farming.

A.7. Interview 7: Local resident
Seventh interview: Local resident Hunucma and fisherman Sisal

This interview was conducted with a resident of Hunucma who worked as a fisherman in Sisal. We asked him if he considered fish cages to be a good idea.

Key takeaways: The fisherman emphasizes that fish cages are not sustainable in Sisal due to environmental and security issues. He explains that rough weather frequently damages the cages, causing

the nets to break, which allows the fish to escape. This loss is a significant setback, as it negates the time and resources spent raising the fish.

A lack of local security exacerbates the issue, as there is no police presence to deter theft. The fisherman points out that the cages become easy targets for thieves, who come equipped with tools to cut through the nets, taking the fish and leaving the fishermen with nothing. He feels constant vigilance is required just to safeguard his work, adding an element of stress and insecurity to his daily routine.

He shares a specific incident where, due to a broken net, all the fish escaped from a cage located about 3 kilometers offshore. In his words, the fish scattered "like turkeys," illustrating the futility of the endeavor when natural elements and theft undermine their efforts.

While he acknowledges that fish cages can work well in some regions, such as Celestún, where tides and water levels are more favourable, he believes Sisal's low tides and fluctuating water levels create conditions unsuitable for this practice. He feels the natural characteristics of the area combined with the lack of security make the project unsustainable and ineffective.

The fisherman also points to environmental concerns, noting how broken cages often wash up on the beach, adding to the local plastic waste problem. This unintended pollution frustrates him further, as it seems counterproductive to preserving the local environment while trying to sustain a fishing business.

Ultimately, he believes a different approach is needed—one that aligns better with the unique conditions of Sisal and includes measures to protect the fishermen's work from theft and environmental degradation.

B

Data Collection Locations and Depth Extrapolation for Sisal and Celestun

B.1. Data Collection Locations for Sisal and Celestun

The figure below illustrates the locations where the depth data was collected for both Sisal and Celestun. The solid lines represent the measured depth data, and the dashed lines indicate the extrapolated depths used in the depth profile analysis. This figure provides a visual reference for the locations of the data points that were used in the depth vs. distance analysis in the next section.
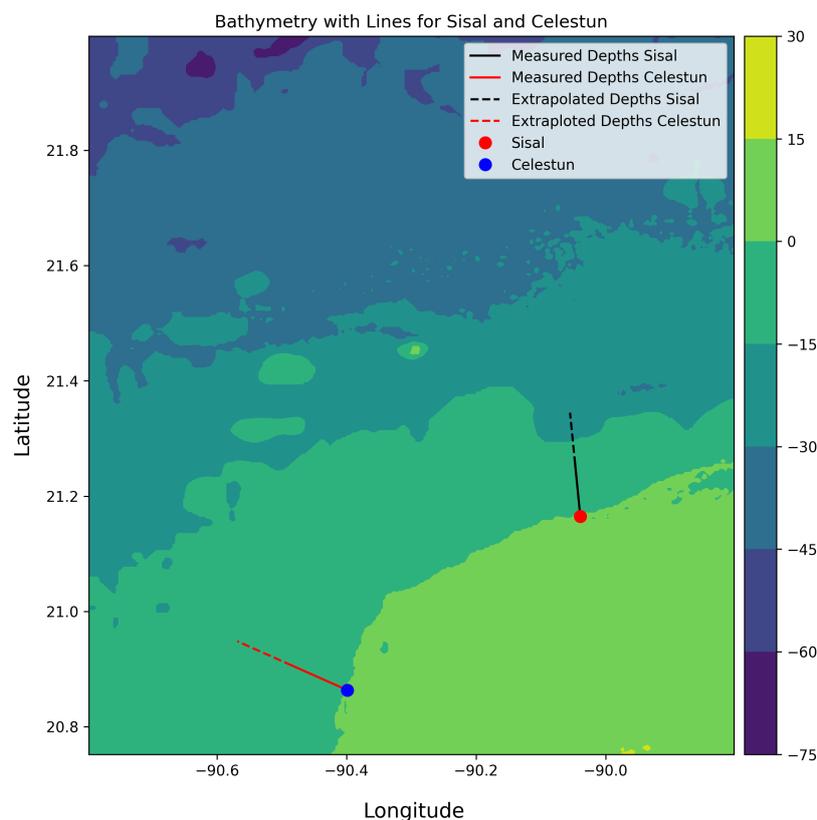
Figure B.1: Locations of depth data collection and extrapolated data for Sisal and Celestun. The lines represent the paths along which the depth data were measured and extrapolated.

B.2. Depth vs Distance from Shore for Sisal and Celestun

This figure presents the depth profiles as a function of the distance from the shore for both Sisal and Celestun. The solid lines show the measured depths, and the dashed lines represent the extrapolated depths up to 20 km from the shore. A linear polynomial fit was applied to extend the depth profiles. This analysis helps determine the depth variation as we move offshore, which is crucial for site selection and structural design.

Figure B.2: Depth vs Distance from Shore for Sisal and Celestun, with linear polynomial extrapolation extended up to 20 km.

C

Fieldwork

Overview

Conducting fieldwork is essential for this project, as designing an effective offshore fishing cage requires detailed data on environmental conditions and insights from previous designs. The fieldwork for this project consisted of two trips: an initial offshore survey off the coast of Sisal and a subsequent visit to an existing offshore fishing cage in Celestún. The aim 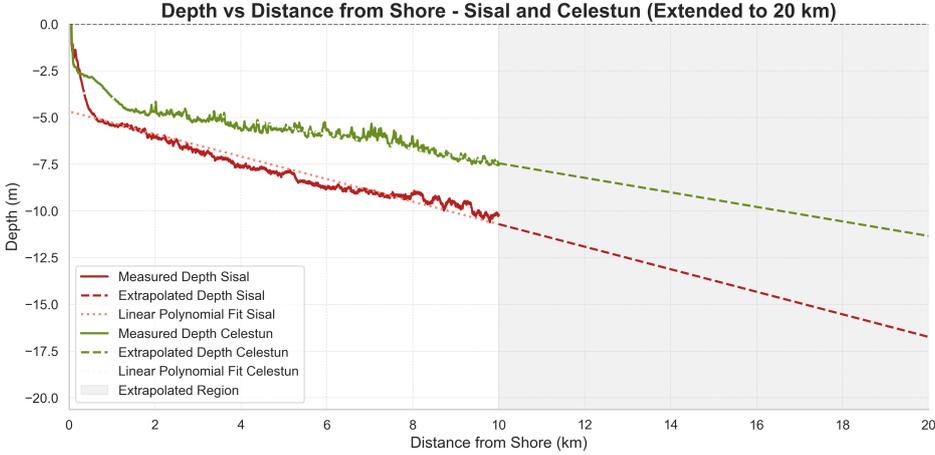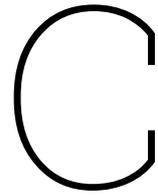of these trips was to collect environmental data, assess the suitability of the site, and observe best practices in offshore cage management.

C.1. Field Trip 1: Offshore Survey in Sisal

Date: 10-09-2024
Location: Gulf of Mexico, from coast of Sisal, Yucatán
Team: Prof. Jorge Alejandro Kurczyn Robledo, Assistent investigator UNAM, local fisherman.
Purpose: Collecting data from 7 different distances and water depths offshore from Sisal Yucatán, using oceanographic equipment to get more insight on the environmental conditions.

Equipment

- **EXO2 Multiparameter Sonde**
  The EXO2 Multiparameter Sonde is a cone-like piece of equipment that measures multiple aquatic parameters such as Conductivity/Temperature, Dissolved Oxygen, ISEs (Ammonium, Chloride, and Nitrate), pH, algae and turbidity [57]. It needs to be manually lowered into the water to collect the data (see figure C.1a).

- **Sentinel V ADCP**
  The Sentinel V Acoustic Doppler Current Profiler (ADCP) is a high-precision instrument capable of measuring water currents and wave profiles across various depths using multiple sampling strategies. It is deployed on the seabed (see figure C.1b), with features like wireless data download, robust design, and the ability to record raw data for detailed analysis [32].

(a) EXO2 Multiparameter Sonde   (b) Sentinel V ADCP [32]

Figure C.1: Oceanographic Equipment

Activities

The field survey involved deploying the EXO2 equipment at seven different locations, approximately 1, 2, 3, 4, 5, 10, 15 and 20 km offshore (see figure C.2). At each of these locations, the EXO2 Sonde and ADCP are used to collect data on water column properties.

Figure C.2: Locations equipment

The field survey was carried out over the course of a day, starting in the early morning with the assistance of a local fisherman, who provided transportation using his boat. This support was crucial, as the fisherman's knowledge of the local waters helped to efficiently navigate to each designated measurement location.

At each measurement point we anchored the boat and deployed the EXO2 were carefully lowered into the water to specific depths to take measurements (see figure C.4). This process required precise handling to ensure that the instruments remained stable in the water column and collected accurate data. After taking measurements at each location, the equipment was retrieved from the water and prepared for the next deployment. This process was repeated for each measurement point.

(a) Lowering the equipment into the ocean

(b) Anchor lowering

Figure C.3: Fieldwork

Challenges encountered

- **Potential Interference by Local Fishermen:**
  A notable challenge was the risk of local fishermen encountering and removing the deployed instruments. In some cases, equipment left for continuous data collection could be taken ashore by fishermen, which pose a risk of losing data or even the equipment itself.

- **Navigational Precision:** Locating the exact measurement points using GPS proved challenging, particularly when revisiting locations to retrieve equipment. The open ocean environment and lack of fixed landmarks made precise navigation difficult.

- **Equipment Retrieval Issue:** During the survey at the 20km location, one piece of equipment was lost. One of the UNAM professors had to dive to locate and recover the lost equipment. This dive added a layer of complexity to the survey and ensured that the equipment was stolen.

Data collected

The data gathered during this survey provides a preliminary understanding of the physical and chemical properties of the water column at varying distances from the coast of Sisal. These findings, combined with the ongoing four-week measurement routine by UNAM, will be analyzed further to identify the most suitable locations for deploying the fishing cage. The data collected during the fieldwork is illustrated below:
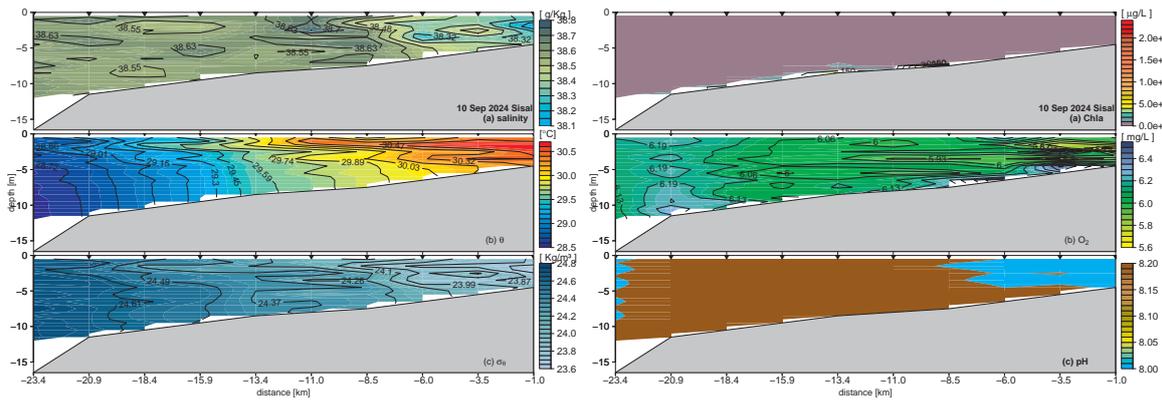
Figure C.4: Results EXO2 10th of septembre 2024

C.2. Field Trip 2: Visit to Existing Offshore Fishing Cage in Celestún

Date: 27-09-2024
Location: 14.1 km offshore of Celestún port at coordinates $20°53'8''N, 90°32'10''W$
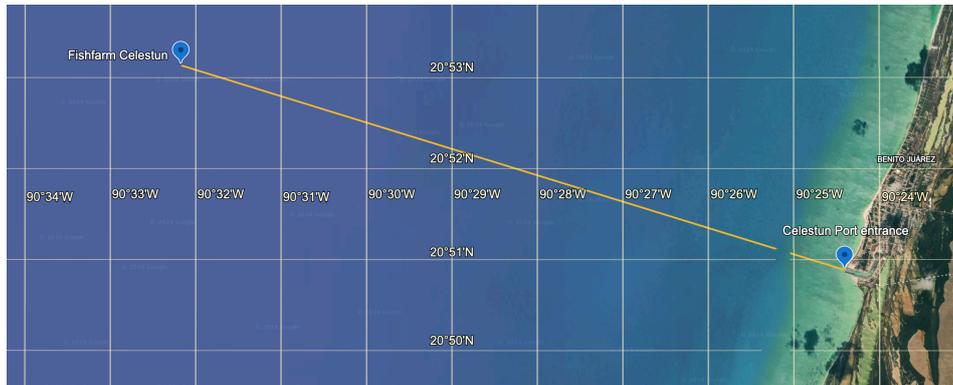
Figure C.5: Location Celestún farm from Google Earth

Figure C.6: Team picture of MDP 374 with Onesimo and Captain

Purpose: Collecting dimensions of the existing fish farm in Celestún to use as a reference for the design and construction of a similar offshore fishing cage in Sisal.

Team:

- Onesimo (Head of Tours, Celestún Cage)
- MDP 374

Equipment Used:

- Snorkeling gear
- GoPro
- Measuring tape
- Water depth meter (rope with lead)

Activities

- **Cage Structure Evaluation:** Examined the design and materials used for the existing offshore cage, including the anchoring system, netting materials, and structural durability.
- **Cage Dimensions Measurement:** Conducted measurements of the cages and it's anchorage system.
- **Operational Observations:** Interviewed Unismo to discuss the cage performance, maintenance routines and costs.

Key Insights

(a) Sketch upper view of the Celestún cages lay-out

(b) Picture of current situation, gathered at fieldtrip
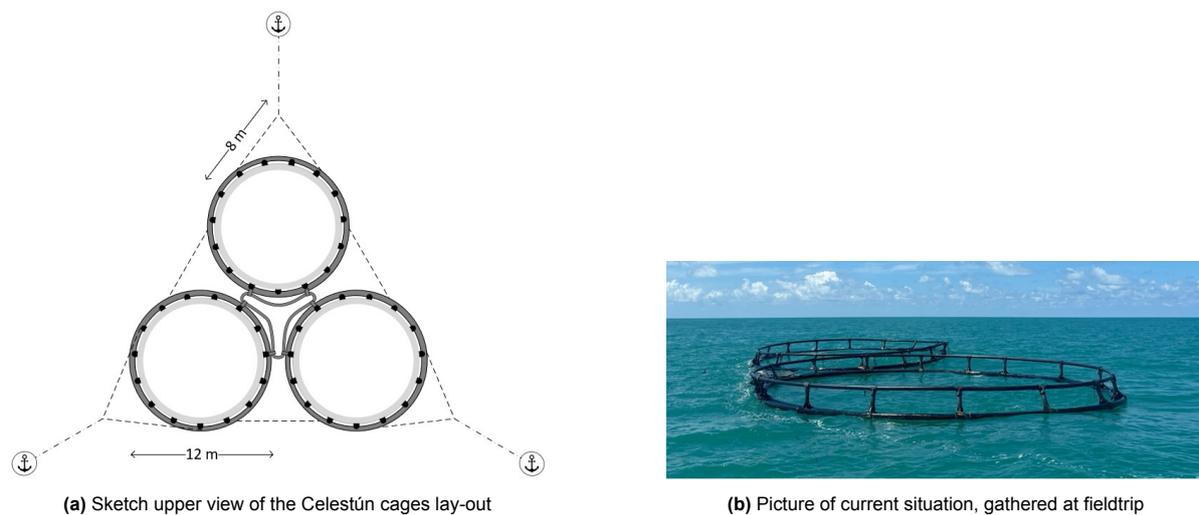
Figure C.7: Celestún situation

Key takeaways

- The integrity of ropes and connections was identified as a critical factor in the overall strength and durability of the cage system (see C.8
- One of the cages was onshore because one of the tubes broke, indicating that larger diameter tubes may be desirable to improve structural strength and reduce the risk of similar failures.
- Maintenance procedures could be improved by using a different net structure, as the current design makes the nets difficult to repair, potentially leading to longer downtime and higher maintenance costs.
- The nets are only deployed each year during the six-month operational period and are removed during storms, providing an opportunity to optimize the management and storage of the nets for greater resilience.

Figure C.8: Connection between tubes in Celestún fish-farm, Yucatan

Cage Dimensions			
Parameter	**Value**	**Unit**	**Description**
Amount of cages	3	-	Amount of cages (shape of a triangle)
Diameter cage	12	m	The cage's diameter at the height of the floating tube
Bottom diameter	12	m	The cage's diameter at the height of the sinker tube
Cage depth	4.7	m	The lowest position of the net, including any cone at the bottom of the net
Cone height	0	m	The vertical distance between the lowest point of the net and the base of the cone
Number of rib lines	15	-	Number of rib lines along the circumference of a net
Rib spacing	2.51	m	Approximate spacing of the rib lines along the top circumference of the net
Number of riser holders	15	-	Number of vertical pipes along the circumference of the floating tubes holding the riser upright
Riser holders spacing	2.51	m	Approximate spacing of the riser holders along the top circumference of the floating tube
Height of the riser	0.75	m	Height of the riser tube above the floating tube
Number of bridles	2	-	Number of lines per cage that attach the cage to the grid
Bridle span angle	118.8	deg	The angle defining the arc length along the tube between the two outermost bridle lines
Bridle arc span	7.54	m	The distance along the tube between the two outermost bridles
Bridle length	8	m	Bridle connectors are lines that secure the bridles to the grid/anchor
Tubes Dimensions			
Inner floating tube diameter	0.15	m	The diameter of the inside floating tube
Outer floating tube diameter	0.15	m	The diameter of the outside floating tube
Heart to heart distance between floating tubes	0.26	m	The distance between the inner and outer floating tube
Sinker tube diameter	0.1	m	The diameter of the sinker tube
Riser tube diameter	0.12	m	The diameter of the riser tube
Rope and Net Dimensions			
Rib line width	10	mm	Line thickness of the rib lines
Bridle line width	16	mm	Line thickness of the bridle lines
Mesh size	30	mm	Distance between lines in the net grid

Table C.1: Dimensions and structural details of the existing offshore fishing cage in Celestún.

Challenges Encountered

- **Murky Water:**
  The poor visibility made diving impossible.
- **Missing Cage:**
  One of the cages was absent due to maintenance.
- **Difficult Measurements:**

Strong currents made taking accurate long-distance measurements challenging, so anchor line lengths are approximations.

Fish Preference

In this appendix, the optimal distance from shore for the pompano fish will be determined. As indicated chapter 4, the pompano fish has preferences regarding oxygen levels, temperature, and salinity of the sea. For the fish cages to function properly, it is essential that the fish feel "comfortable." In a stable and relaxed environment, they can develop better, which is important for the long-term success of the fish cages.

The different variables were analysed at three different points during the year: December, March, and September. This approach provides a comprehensive overview across the year. The results are based on the data and graphs presented in Figure 4.5a Figure 4.5b Figure 4.6a. The preference of Pompano is based on literature review in chapter 4

Environmental conditions		Disctance (km)						
		2	4	6	8	10	15	20
Temperature	Dec	26,9	26,9	26,9	26,8	26,7	26,8	26,8
	March	27,5	27,4	27,3	27,2	27,2	26,95	26,9
	Sept	32	31,5	31,0	30,4	30	29,1	29
Oxygen	Dec	6,3	6,46	6,67	6,6	6,7	6,8	6,9
	March	6,8	6,9	6,9	6,9	6,8	6,9	6,9
	Sept	6,3	6,4	6,3	6,3	6,22	6,22	6,22
Salinity	Dec	36,9	36,65	36,6	36,55	36,5	36,48	36,3
	March	37,18	37,1	37,5	36,99	36,7	36,3	36,3
	Sept	38,32	38,3	38,4	38,5	38,6	38,6	38,5

Figure D.1: Environmental conditions

Water temperature varies the most throughout the year. As expected, it is highest in September (31 degrees) and lowest in December (26,8 degrees). Oxygen levels are highest in March, but don't differ to much. Salinity remains relatively high throughout the year, with normal seawater typically around 35 ppt [24]. In December, salinity is at its highest, and in September, it is at its lowest.

Optimum conditions	Temperature (C)	Oxygen (mg/L)	Salinity (ppt)
Pompano	26-32	5.0-7.0	30-35

Table D.1: Optimum conditions for Pompano fish

Considering the preferences of the pompano fish, it has a relatively large tolerance range for all variables. This is one of the main reasons why the pompano fish was chosen chapter 4. Salinity is the only variable that is not in ideal condition for the pompano fish, but it generally decreases with increasing distance from the shore, approaching optimal conditions. Additionally, the optimal temperature in September may be at risk, especially closer to the the shore. Therefore, it can be concluded that the pompano fish benefits from being placed as far offshore as possible. At the same time, it is likely that

the distance will not have a significant impact, as long as it is not too close (e.g., within 2 km or 4 km from the shore). Based on this data, the fish preference does not really differ. Therefore is not a big influence on the long term success of the fish cages.

MCA

E.1. MCA scores

A multi-criteria analysis consists of several steps. First, each criterion is evaluated based on how it performs at a specific distance. To compare these values, a standardized scale is used. The scale ranges from 1 to 5, where 5 means very good, 4 good, 3 average, 2 poor, and 1 very poor. Each score represents a relative value of that criterion compared to other distances. For example, fuel costs score 5 at 2 km; this distance is relatively very good for fuel costs. At the same time, fuel costs score 1 at distances of 15 and 20 km; these distances are very poor for fuel costs. The results can be seen in Figure E.1 All scores are based on the interviews of stakeholders and expert knowledge Appendix A.

MCA determination location	2 km (unweighted)	4 km (unweighted)	6 km (unweighted)	8 km (unweighted)	10 km (unweighted)	15 km (unweighted)	20 km (unweighted)
Fuel consumption	5	4	3	3	2	1	1
Easiness to maintain	5	4	4	3	3	1	1
Capacity cage	1	2	4	5	5	5	5
Accesibility tourism tours	1	2	4	4	3	2	1
Water flow through cage	1	1	3	4	5	5	5
Biochemical fish preference	1	2	2	3	3	4	5
Need for structural robustness	5	5	4	4	4	3	3
Material costs	4	4	3	3	3	2	2
Installation cost	5	5	4	4	3	2	1
Total score	**28**	**29**	**31**	**33**	**31**	**25**	**24**

Figure E.1: MCA with unweighted scores

Most of the scores are straightforward. For example, the criteria *fuel consumption, easiness to maintain*, and *installation costs* decrease as the distance increases. Fuel costs rise as the distance to travel increases. It becomes more difficult to maintain the cages when they are located farther offshore, as it takes longer to reach them and is more difficult to bring them back to land. The maintenance is typically done on shore as mentioned in the interview (section A.5). Installation costs also increase as the cages are positioned further offshore because they need to be installed at greater depths, making the process more complex.

For water flow through the cage and the biochemical fish preferences, the further offshore, the better. As the sea gets deeper, there is a higher flow of fresh water. This is due to the higher availability of fresh/clean water. This is beneficial for the cages because this results in significantly less maintenance (section A.3). Besides this, it's also good for the well-being off the fish [15]. The fisherman see the amount of maintenance as a potential hazard for the success of the cages (see section A.1).

The other criteria are less straightforward and need some extra elaboration. These will be addressed one by one.

Capacity of the cage: For the capacity of the cages and the distance offshore, certain conditions and boundaries apply. First, fisherman want the cage to have as large volume as possible to farm the maximum amount of fish, as more fish means higher revenue. However, the cages cannot be too large; because a condition is set by the fishermen in Sisal. They want the cages to be transportable (See section A.1). This maximum size has been set at 12 meters in diameter (section A.5). At the same time, a condition is to minimize the forces acting on the cages as much as possible. It has been found that the cages must have a certain ratio to minimize the forces exerted on them. With a diameter of 12 meters, the cage can be 4.7 metres deep (following the best ratio, concept 2). Further elaboration about this subject can be found in chapter 7. Due to these various boundaries and rules, the cage has a maximum volume (if you want a minimal force acting on it). chapter 7 shows that the water depth must be at least 6.7 (4.7 + 2) metres. An additional 2 meters is added because the bottom of the cage must be at least 2 meters above the ground for the cages to function effectively (see section A.2).Under normal circumstances the depth of 6.7 meters is reached at approximately 3/4 kilometres offshore. However, during extreme weather, waves of up to 3.4 meters can occur (chapter 6). The cage will drop by half the wave height, resulting in a 1.7-meter descent (chapter 6). To ensure the cage (when a 12 meter diameter is chosen) is resistant to extreme weather, a minimum depth of 8.4 meters (6.7 + 1.7) is required. Between 6 and 8 kilometres offshore, the depth is approximately between 8 and 9,5 meters (see Figure B.2), which provides enough margin to maintain the minimum depth of 8.4 meters, even during extreme weather Appendix G. This ensures that the cages can withstand the forces and will not break. Since the data only includes extreme weather from recent years, 8 kilometres is chosen to provide an additional buffer for unusual situations as most suitable one and therefore receive a score of 5 in the MCA.

Accessibility for tourism tours: Being too close to shore is not ideal because smaller cages are less attractive to tourists. Initially, greater distances are better; however, there is a limit, as it should not be too far offshore. High fuel costs and extended travel times make the tours less appealing. Besides that cages can't have a bigger diameter then 12 meters and a certain depth because of the need of self-transport and the ideal ratio of dimensions. So there is no benefit in having the possibility to have larger cages further off-shore. Interviews with tourists and fishermen show that the optimal distance is approximated around 6 km to 10 km (section A.4) . At 6 & 8 kilometres distance the cages can be big enough to swim in (section A.3). Therefore the score of 4 is given. Farther away the fuel costs increases which leads to higher costs for tourists, which results in the tours to be less appealing. Therefore a decline in score is given to the followed distances.

Need for structural robustness: Data analysis shows that the currents increase as you move farther offshore (chapter 4), resulting in greater forces on the cages as they are placed further out to sea. This means that the need for structural robustness grows as the cages are placed farther out to sea. Therefore, this criterion scores high for distances closer to shore and gradually decreases. Although it may seem counter intuitive that this criterion scores high closer to shore while "the need" is low; a lower need for structural robustness is actually a positive factor. Therefore, closer distances are better, which is why a score of 5 is assigned for 2 kilometers offshore." The data indicates that the forces do not increase rapidly , which is why a gradual reduction in the score for the need for structural robustness was chosen.

Material costs: This criterion remains constant across almost all the distances. Interviews indicate that there are few locally available materials that are affordable for the local fisherman and can build a fish farm (section A.5). Regardless of the distance, probably the same materials must be used. One of the requirements for the fish cages is that they remain affordable for local fishermen; therefore, the use of local, affordable materials is essential for the success of the project. A possible factor that may cause differences in cost is that the cages can be larger at certain locations than at others. If they are larger, more materials will be needed, resulting in higher costs. Therefore, a score of 4 is given for 2 and 4 kilometres, while a score of 3 is assigned for 6, 8, and 10 kilometres, as at these distances the cage can reach its maximum volume (See chapter 7), requiring the maximum amount of material. It is also assumable that a different anchor might be required for the furthest distances (15 and 20 km) to withstand the forces at this depth. For this reason, it has been cautiously assumed that a more

expensive anchor must be used for the cages at this distance, which negatively impacts material costs (scores 2).

E.2. AHP weights

These weights can be determined by an AHP (Analytic Hierarchy Process) score. To calculate this score, a pairwise comparison matrix must first be generated. This matrix shows if criterion A is more important than criterion B. A number of 1 or 0 can be given to a relation. 1 means that A is more important than B, 0 means that A is less important. The results are shown in Figure E.2

Pairwise comparison matrix

	Fuel Consumption	Easiness to maintain	Capacity cage	Accesiblity tourism tours	Water flow through cage	biochemcial fish preference	Need for Structural robustness	Material costs	Installation costs	Som criteria
Fuel consumption		1	1	1	1	1	1	1	1	8
Easiness to maintain	1		0	1	0	1	0	0	1	4
Capacity cage	0	1		1	1	1	1	1	1	7
Accesibility tourism tours	0	0	0		0	1	0	0	0	1
Water flow through cage	0	1	0	1		1	1	1	1	6
Biochemical fish preference	0	0	0	0	0		0	0	0	1
Need for structural robustness	0	0	0	1	0	1		0	1	3
Material costs	0	1	0	1	0	1	1		1	5
Installation costs	0	0	0	1	0	1	0	0		2

Figure E.2: Pairwise Comparison Matrix

Looking at Figure E.2 the most left column represents criteria A and the upper row represents B. You can see that the last column the total score of each criterion is calculated. If a criteria scores high (8) than this means that this criterion is very important in determining the right location for long term succes of fish cages in Sisal

The relative importance of each criteria is again based on information and findings from interviews and discussions with local experts and fishermen (see Appendix A). The primary focus remains *contribution to the long-term success of using fish cages*. Fuel consumption is the most important criterion for determining the ideal location. This aligns with expectations, as all interviewees identified this as one of the most important criteria. It could be a potential deal-breaker for everyone involved. If the fuel costs become too high, fishermen will not want to use the cages, which will not benefit the probable success of the cages

The capacity of cages is considered more important than almost all other criteria. This is because in this project the long term success of the cages is considered. Since the capacity of the cage will decide what the revenue per cage is, this plays a more pivotal role in the long-term success in comparison to the other criteria. section A.5). In the end the revenue that fisherman obtain from the cages will be more decisive for usage off the cages (see section A.7).

A criterion that (perhaps surprisingly) scores high is *water flow through the cage*. The interviews reveal that keeping the cages clean is a significant issue for off-shore fish farms (see section A.3). A high flow of fresh water greatly assists in this, as it ensures constant water circulation [15], preventing dirt from easily attaching to the cages. A clean cage contributes to *maintainability*, *the overall development of the pompano* and indirectly to *the attraction of tourists*. This makes water flow through the cages a crucial factor for the long-term success of the cages in Sisal.

Material costs are considered as 4th most important. It is the most important among the "structural criteria" (robustness & installation) Interviews reveal that nets and other small items often need to be replaced to keep the cages operational (seesection A.5). If the material costs are very high, the overall expenses increase significantly, which may result in fewer or no fishermen wanting to use the cages. Unlike installation costs and the need for structural robustness, material costs are evidently ongoing expenses that fishermen continue to incur as long as the cages are in use. The need for structural robustness refers to the fact that the cage framework must be strong enough to withstand extreme weather; once this is achieved, the costs are not felt as consistently over the long term. The need for structural robustness is considered more important than installation costs because structural robustness indirectly affects maintainability and material costs . As a result, it is viewed as more important in the long term compared to installation costs.

The criterion easiness to maintain has a score of 4, making it of average importance. This is also reflected in the interviews (seesection A.1) . Fishermen indicate that they prefer to maintain the cages themselves to keep costs low. However, this is to a certain extent; they want to replace the nets and other simple components but do not necessarily want to fix/repair the entire structure. Other factors, such as costs and revenue (fuel/material costs and capacity), are considered more important by the fishermen (see section A.3).

It is notable that the attraction of tourism scores relatively low. Although many locals express a desire to attract more tourists (see section A.1 section A.3), this is/will not the main reason for using fish farms but rather a beneficial side effect. The fish cages must first function properly before tourism can be leveraged. This explains why this criterion scores relatively low comparing them to the others. In a later stage of the implementation of fish farms in Sisal, it could play an increasingly important role.

Biochemical fish preference scores very low and is therefore not considered important. This is based on the conclusion drawn from Appendix A, which shows that distance has little impact on the Pompano fish. At various distances, the water still maintains optimal conditions for the Pompano. Additionally, research has shown that clean water is considered much more important for the well-being of the fish, particularly due to the water flow through the cage. Since this criterion is still somewhat important and will be included in further research, it cannot be assigned a value of 0 (even though the matrix suggests otherwise); therefore, a score of 1 is given to this criterion.

Now that the comparison matrix is available you can calculate the weights of each criterion. You divide each for each criterium the sum of the score by the total points that are given. This is a total of 37. For fuel consumption this means:

$$\frac{8}{37} = 0.216 \tag{E.1}$$

This is repeated for all criteria. The weights are also multiplied by 10 to show the difference better. The results are shown in Figure E.3.

Pairwise comparison matrix				
	Total score per criterion	Score/total	Weight	T c
Fuel consumption	8	0,216	**2,16**	
Easiness to maintain	4	0,108	**1,08**	
Capacity cage	7	0,189	**1,89**	
Accesibility tourism tours	1	0,027	**0,27**	
Water flow through cage	6	0,162	**1,62**	
Biochemical fish preference	1	0,027	**0,27**	
Need for structural robustness	3	0,081	**0,81**	
Material costs	5	0,135	**1,35**	
Instalation costs	2	0,054	**0,54**	
Totaal	37			

Figure E.3: AHP weight per Criterion

F
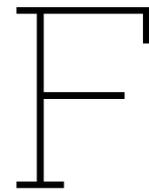
Sensitivity Analysis

The sensitivity analysis that is used in this case is the weight sensitivity analysis. This means that we will change the weights of certain criteria and see what effect is has on the end results. The weights of the criteria will be changed with -80% and +80%, in regards to the weights that were determined with the AHP method.

When the weights are being factored by +-80%, the other weights need to change as well, as the total sum of the weights need to be 10. Therefore, the change of the remaining weights has been done proportionately.

This was done through the following steps:

- W_{total}: Total sum of weights (10 in this case).
- W_1: Weight of the criterion being adjusted.
- W_{rest}: Sum of all other weights, defined as:

$$W_{\text{rest}} = 10 - W_1$$

- W_1': Adjusted weight of the criterion after the increase or decrease.
- W_i': Adjusted weight of any other criterion $i \neq 1$.

First the weight of the criterion that is going to be adjusted needs to be calculated, this is done as follows:

- For a 80% increase:
$$W_1' = W_1 \times 1.8$$

- For a 80% decrease:
$$W_1' = W_1 \times 0.2$$

Once this has been done, the remaining weight needs to be calculated in order for us to eventually redistribute them proportionally. We can use the following formula to do this.

Define W_{rest}' as the new sum of the remaining weights after adjusting W_1:

$$W_{\text{rest}}' = W_{\text{total}} - W_1'$$

To adjust the remaining weights proportionally, we have to calculate the scaling factor:

$$\text{Scaling factor} = \frac{W_{\text{rest}}'}{W_{\text{rest}}}$$

To calculate the new weights of the remaining criteria, the following formulas is used:

For each remaining weight W_i, the adjusted weight is:

$$W_i' = W_i \times \text{Scaling factor}$$

When calculating the new weight the following results arise from them.

Original weights			Rest proportion original
Fuel consumption	2,162		7,838
Easiness to maintain	1,081		8,919
Capacity cage	1,892		8,108
Accessibility tourism tours	0,270		9,730
Water flow through cage	1,622		8,378
Biochemical fish preference	0,270		9,730
Need for structural robustness	0,811		9,189
Material costs	1,351		8,649
Installation costs	0,541		9,459

Figure F.1: Original weights and rest proportion

Capacity cage (-80%/+80%)	-80%	80%	Rest proportion -80%	Rest proportion +80%
Fuel consumption	2,57	1,76	9,62	6,59
Easiness to maintain	1,28	0,88		
Capacity cage	0,38	3,41	Scaling factor -80%	Scaling factor +80%
Accessibility tourism tours	0,32	0,22	1,19	0,81
Water flow through cage	1,92	1,32		
Biochemical fish preference	0,32	0,22		
Need for structural robustness	0,96	0,66		
Material costs	1,60	1,10		
Installation costs	0,64	0,44		
Total sum	10,00	10		

Figure F.2: New weights with capacity cage change

Fuel consumption (-80%/+80%)	-80%	80%	Rest proportion -80%	Rest proportion +80%
Fuel consumption	0,43	3,89	9,57	6,11
Easiness to maintain	1,32	0,84		
Capacity cage	2,31	1,47	Scaling factor -80%	Scaling factor +80%
Accessibility tourism tours	0,33	0,21	1,22	0,78
Water flow through cage	1,98	1,26		
Biochemical fish preference	0,33	0,21		
Need for structural robustness	0,99	0,63		
Material costs	1,65	1,05		
Installation costs	0,66	0,42		
Total sum	10,00	10,00		

Figure F.3: New weights with fuel consumption change

Maintainability (-80%/+80%)	-80%	80%	Rest proportion -80%	Rest proportion +80%
Easiness to maintain	0,22	1,95	9,78	8,05
Fuel consumption	2,37	1,95		
Capacity cage	2,08	1,71	Scaling factor -80%	Scaling factor +80%
Accessibility tourism tours	0,30	0,24	1,10	0,90
Water flow through cage	1,78	1,46		
Biochemical fish preference	0,30	0,24		
Need for structural robustness	0,89	0,73		
Material costs	1,48	1,22		
Installation costs	0,59	0,49		
Total sum	10,00	10,00		

Figure F.4: New weights with Easiness to maintain change

Material costs (-80%/+80%)	-80%	80%	Rest proportion -80%	Rest proportion +80%
Fuel consumption	2,43	1,89	9,73	7,57
Easiness to maintain	1,22	0,95		
Capacity cage	2,13	1,66	Scaling factor -80%	Scaling factor +80%
Accessibility tourism tours	0,30	0,24	1,13	0,88
Water flow through cage	1,82	1,42		
Biochemical fish preference	0,30	0,24		
Need for structural robustness	0,91	0,71		
Material costs	0,27	2,43		
Installation costs	0,61	0,47		
Total sum	10,00	10		

Figure F.5: New weights with material cost change

Structural robustness (-80%/+80%)	-80%	80%	Rest proportion -80%	Rest proportion +80%
Fuel consumption	2,31	2,01	9,84	8,54
Easiness to maintain	1,16	1,00		
Capacity cage	2,03	1,76	Scaling factor -80%	Scaling factor +80%
Accessibility tourism tours	0,29	0,25	1,07	0,93
Water flow through cage	1,74	1,51		
Biochemical fish preference	0,29	0,25		
Need for structural robustness	0,16	1,46		
Material costs	1,45	1,26		
Installation costs	0,58	0,50		
Total sum	10,00	10,00		

Figure F.6: New weights with need for structural robustness change

Water flow through cage (-80%/+80%)	-80%	80%	Rest proportion -80%	Rest proportion +80%
Fuel consumption	2,50	1,83	9,68	7,08
Easiness to maintain	1,25	0,91		
Capacity cage	2,18	1,60	Scaling factor -80%	Scaling factor +80%
Accessibility tourism tours	0,31	0,23	1,15	0,85
Water flow through cage	0,32	2,92		
Biochemical fish preference	0,31	0,23		
Need for structural robustness	0,94	0,69		
Material costs	1,56	1,14		
Installation costs	0,62	0,46		
Total sum	10,00	10,00		

Figure F.7: New weights with water flow through change

Now the new weights have been calculated, the sensitivity analysis scores can be determined. This is done by multiplying the newly determined weights with the scores assigned during the first step of the MCA. All the tables with the results can be seen below.

Capacity cage (-80%)	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	12,83	10,26	7,70	7,70	5,13	2,57	2,57
Maintainibility	6,41	5,13	5,13	3,85	3,85	1,28	1,28
Size	0,38	0,76	1,51	1,89	1,89	1,89	1,89
Accesible tourism tours	0,32	0,64	1,28	1,28	0,96	0,64	0,32
Water flow	1,92	1,92	5,77	7,70	9,62	9,62	9,62
Fish	0,32	0,64	0,64	0,96	0,96	1,28	1,60
Structural robustness	4,81	4,81	3,85	3,85	3,85	2,89	2,89
Material costs	6,41	6,41	4,81	4,81	4,81	3,21	3,21
Instalation costs	3,21	3,21	2,57	2,57	1,92	1,28	0,64
Total score	36,62	33,79	33,26	34,61	33,00	24,66	24,02

Figure F.8: Total scores capacity cage -80%

Capacity cage (+80%)	Weights	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	1,76	8,79	7,03	5,28	5,28	3,52	1,76	1,76
Maintainibility	0,88	4,40	3,52	3,52	2,64	2,64	0,88	0,88
Size	3,41	3,41	6,81	13,62	17,03	17,03	17,03	17,03
Accesible tourism tours	0,22	0,22	0,44	0,88	0,88	0,66	0,44	0,22
Water flow	1,32	1,32	1,32	3,96	5,28	6,59	6,59	6,59
Fish	0,22	0,22	0,44	0,44	0,66	0,66	0,88	1,10
Structural robustness	0,66	3,30	3,30	2,64	2,64	2,64	1,98	1,98
Material costs	1,10	4,40	4,40	3,30	3,30	3,30	2,20	2,20
Instalation costs	0,44	2,20	2,20	1,76	1,76	1,32	0,88	0,44
Total score	1,00	28,25	29,45	35,38	39,45	38,35	32,63	32,19

Figure F.9: Total scores capacity cage +80%

Fuel consumption (+80%)	Weights	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	3,89	19,46	15,57	11,68	11,68	7,78	3,89	3,89
Easiness to maintain	0,84	4,21	3,37	3,37	2,53	2,53	0,84	0,84
Capacity cage	1,47	1,47	2,95	5,90	7,37	7,37	7,37	7,37
Accessibility tourism tours	0,21	0,21	0,42	0,84	0,84	0,63	0,42	0,21
Water flow through cage	1,26	1,26	1,26	3,79	5,05	6,32	6,32	6,32
Biochemical fish preference	0,21	0,21	0,42	0,42	0,63	0,63	0,84	1,05
Need for structural robustness	0,63	3,16	3,16	2,53	2,53	2,53	1,90	1,90
Material costs	1,05	4,21	4,21	3,16	3,16	3,16	2,11	2,11
Installation costs	0,42	2,11	2,11	1,68	1,68	1,26	0,84	0,42
Total score	1,00	36,31	33,47	33,37	35,48	32,22	24,53	24,11

Figure F.11: Total scores fuel consumption +80%

Fuel consumption (-80%)	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	2,16	1,73	1,30	1,30	0,86	0,43	0,43
Easiness to maintain	6,60	5,28	5,28	3,96	3,96	1,32	1,32
Capacity cage	2,31	4,62	9,24	11,55	11,55	11,55	11,55
Accessibility tourism tours	0,33	0,66	1,32	1,32	0,99	0,66	0,33
Water flow	1,98	1,98	5,94	7,92	9,90	9,90	9,90
Biochemical fish preference	0,33	0,66	0,66	0,99	0,99	1,32	1,65
Need for structural robustness	4,95	4,95	3,96	3,96	3,96	2,97	2,97
Material costs	6,60	6,60	4,95	4,95	4,95	3,30	3,30
Installation costs	3,30	3,30	2,64	2,64	1,98	1,32	0,66
Total score	28,56	29,77	35,28	38,58	39,14	32,76	32,10

Figure F.10: Total scores fuel consumption -80%

Maintainability (-80%)	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	11,86	9,49	7,12	7,12	4,74	2,37	2,37
Easiness to maintain	1,08	0,86	0,86	0,65	0,65	0,22	0,22
Capacity cage	2,08	4,15	8,30	10,38	10,38	10,38	10,38
Accessibility tourism tours	0,30	0,59	1,19	1,19	0,89	0,59	0,30
Water flow through cage	1,78	1,78	5,34	7,12	8,89	8,89	8,89
Biochemical fish preference	0,30	0,59	0,59	0,89	0,89	1,19	1,48
Need for structural robustness	4,45	4,45	3,56	3,56	3,56	2,67	2,67
Material costs	5,93	5,93	4,45	4,45	4,45	2,96	2,96
Installation costs	2,96	2,96	2,37	2,37	1,78	1,19	0,59
Total score	30,73	30,81	33,77	37,71	36,23	30,46	29,86

Figure F.12: Total scores easiness to maintain -80%

Maintainability (+80%)	Weights	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	1,95	9,76	7,81	5,86	5,86	3,90	1,95	1,95
Easiness to maintain	1,95	9,73	7,78	7,78	5,84	5,84	1,95	1,95
Capacity cage	1,71	1,71	3,42	6,83	8,54	8,54	8,54	8,54
Accessibility tourism tours	1,71	1,71	3,42	6,83	6,83	5,13	3,42	1,71
Water flow through cage	0,24	0,24	0,24	0,73	0,98	1,22	1,22	1,22
Biochemical fish preference	1,46	1,46	2,93	2,93	4,39	4,39	5,86	7,32
Need for structural robustness	0,24	1,22	1,22	0,98	0,98	0,98	0,73	0,73
Material costs	0,73	2,93	2,93	2,20	2,20	2,20	1,46	1,46
Installation costs	1,22	6,10	6,10	4,88	4,88	3,66	2,44	1,22
Total score	1,00	34,87	35,85	39,02	40,49	35,86	27,57	26,11

Figure F.13: Total scores easiness to maintain +80%

Material costs (-80%)	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	12,16	9,73	7,30	7,30	4,86	2,43	2,43
Easiness to maintain	6,08	4,86	4,86	3,65	3,65	1,22	1,22
Capacity cage	2,13	4,26	8,51	10,64	10,64	10,64	10,64
Accessibility tourism tours	0,30	0,61	1,22	1,22	0,91	0,61	0,30
Water flow through cage	1,82	1,82	5,47	7,30	9,12	9,12	9,12
Biochemical fish preference	0,30	0,61	0,61	0,91	0,91	1,22	1,52
Need for structural robustness	4,56	4,56	3,65	3,65	3,65	2,74	2,74
Material costs	1,08	1,08	0,81	0,81	0,81	0,54	0,54
Installation costs	3,04	3,04	2,43	2,43	1,82	1,22	0,61
Total score	31,49	30,57	34,86	37,91	36,39	29,73	29,12

Figure F.14: Total scores material costs -80%

Material costs (+80%)	Weights	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	1,89	9,46	7,57	5,68	5,68	3,78	1,89	1,89
Easiness to maintain	0,95	4,73	3,78	3,78	2,84	2,84	0,95	0,95
Capacity cage	1,66	1,66	3,31	6,62	8,28	8,28	8,28	8,28
Accessibility tourism tours	0,24	0,24	0,47	0,95	0,95	0,71	0,47	0,24
Water flow through cage	1,42	1,42	1,42	4,26	5,68	7,09	7,09	7,09
Biochemical fish preference	0,24	0,24	0,47	0,47	0,71	0,71	0,95	1,18
Need for structural robustness	0,71	3,55	3,55	2,84	2,84	2,84	2,13	2,13
Material costs	2,43	9,73	9,73	7,30	7,30	7,30	4,86	4,86
Installation costs	0,47	2,36	2,36	1,89	1,89	1,42	0,95	0,47
Total score	1,00	33,38	32,67	33,78	36,15	34,97	27,57	27,09

Figure F.15: Total scores material costs +80%

Structural robustness (-80%)	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	11,57	9,26	6,94	6,94	4,63	2,31	2,31
Easiness to maintain	5,79	4,63	4,63	3,47	3,47	1,16	1,16
Capacity cage	2,03	4,05	8,10	10,13	10,13	10,13	10,13
Accessibility tourism tours	0,29	0,58	1,16	1,16	0,87	0,58	0,29
Water flow through cage	1,74	1,74	5,21	6,94	8,68	8,68	8,68
Biochemical fish preference	0,29	0,58	0,58	0,87	0,87	1,16	1,45
Need for structural robustness	0,81	0,81	0,65	0,65	0,65	0,49	0,49
Material costs	5,79	5,79	4,34	4,34	4,34	2,89	2,89
Installation costs	2,89	2,89	2,31	2,31	1,74	1,16	0,58
Total score	31,19	30,32	33,92	36,82	35,37	28,55	27,97

Figure F.16: Total scores need for structural robustness -80%

Structural robustness (+80%)	Weights	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	2,01	10,05	8,04	6,03	6,03	4,02	2,01	2,01
Easiness to maintain	1,00	5,02	4,02	4,02	3,01	3,01	1,00	1,00
Capacity cage	1,76	1,76	3,52	7,03	8,79	8,79	8,79	8,79
Accessibility tourism tours	0,25	0,25	0,50	1,00	1,00	0,75	0,50	0,25
Water flow through cage	1,51	1,51	1,51	4,52	6,03	7,54	7,54	7,54
Biochemical fish preference	0,25	0,25	0,50	0,50	0,75	0,75	1,00	1,26
Need for structural robustness	1,46	7,30	7,30	5,84	5,84	5,84	4,38	4,38
Material costs	1,26	5,02	5,02	3,77	3,77	3,77	2,51	2,51
Installation costs	0,50	2,51	2,51	2,01	2,01	1,51	1,00	0,50
Total score	1,00	33,67	32,92	34,72	37,24	35,98	28,74	28,24

Figure F.17: Total scores need for structural robustness +80%

Water flow through cage (-80%)	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	12,48	9,99	7,49	7,49	4,99	2,50	2,50
Easiness to maintain	6,24	4,99	4,99	3,75	3,75	1,25	1,25
Capacity cage	2,18	4,37	8,74	10,92	10,92	10,92	10,92
Accessibility tourism tours	0,31	0,62	1,25	1,25	0,94	0,62	0,31
Water flow through cage	0,32	0,32	0,97	1,30	1,62	1,62	1,62
Biochemical fish preference	0,31	0,62	0,62	0,94	0,94	1,25	1,56
Need for structural robustness	4,68	4,68	3,75	3,75	3,75	2,81	2,81
Material costs	6,24	6,24	4,68	4,68	4,68	3,12	3,12
Installation costs	3,12	3,12	2,50	2,50	1,87	1,25	0,62
Total score	35,91	34,97	34,99	36,57	33,46	25,34	24,72

Figure F.18: Total scores water flow through cage -80%

Water flow through cage (+80%)	Weights	2 km (weighted)	4 km (weighted)	6 km (weighted)	8 km (weighted)	10 km (weighted)	15 km (weighted)	20 km (weighted)
Fuel consumption	1,83	9,14	7,31	5,48	5,48	3,65	1,83	1,83
Easiness to maintain	0,91	4,57	3,65	3,65	2,74	2,74	0,91	0,91
Capacity cage	1,60	1,60	3,20	6,40	7,99	7,99	7,99	7,99
Accessibility tourism tours	0,23	0,23	0,46	0,91	0,91	0,69	0,46	0,23
Water flow through cage	2,92	2,92	2,92	8,76	11,68	14,59	14,59	14,59
Biochemical fish preference	0,23	0,23	0,46	0,46	0,69	0,69	0,91	1,14
Need for structural robustness	0,69	3,43	3,43	2,74	2,74	2,74	2,06	2,06
Material costs	1,14	4,57	4,57	3,43	3,43	3,43	2,28	2,28
Installation costs	0,46	2,28	2,28	1,83	1,83	1,37	0,91	0,46
Total score	1,00	28,96	28,27	33,65	37,49	37,89	31,95	31,50

Figure F.19: Total scores water flow through cage +80%

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Environmental Forcing Conditions

The data analysis presented in this Appendix consists of three primary components: wave analysis, current analysis and direction analysis. Each step is crucial to understanding the environmental conditions to which offshore fish cages will be subjected. The objective of the analyses is to determine a design value for wave height, period and direction, as well as a design value for current speed across depth and direction.. Although the location of the fish cage is determined to be 8 km offshore, the design values are based on the data collected from the position 12 km offshore to minimise extrapolation error and effectively incorporate a safety factor. This Appendix will provide a detailed methodology and the results of each analysis, supported by relevant figures and results. The complete analysis is provided in the detailed process of data cleaning, statistical analysis and extreme value analysis (EVA). The following sections will outline each component of the data analysis.

G.1. Wave Data Analysis

The wave data analysis compares the wave conditions between two locations near Sisal: the local data, collected over the past 10 years, and the offshore ERA5 data, which provides a longer historical record. The analysis was conducted with the goal of ensuring that the fish cages can withstand the wave conditions of the nearest location. The further offshore location was used to clean the data and conduct the extreme value analysis (EVA).

The datasets considered in this analysis are as follows:

- **Local Data**: This dataset contains wave height (H_s) in metres, wave period (T_p) in seconds and wave direction (D_p) in degrees, information from a site 12.2 km offshore from Sisal. The RDI ADCP (Acoustic Doppler Current Profiler, Sentinel V and Workhorse, were primarily positioned at a depth of approximately 10.4 meters. The range of the dataset is from the end of March 2014 to the end of April 2023 with spaces of missing data in between.

- **ERA5 Data**: ERA5 reanalysis dataset provides hourly estimates of atmospheric and oceanic conditions. The dataset also contains wave height, period and direction. The ERA5 dataset was used as the primary reference for the extreme value analysis due to its long-term historical record. The range of the dataset is from the beginning of 1985 until the end of February 2024.

The steps for wave analysis are outlined below:

- **Data Cleaning:** Cleaning was performed to remove erroneous values from the local dataset, based on a comparison with the ERA5 dataset. A 4x standard deviation filter was applied to exclude outliers.

- **Historical Data Comparison:** A comparison factor was calculated to adjust the design values from the ERA5 dataset to the local data. This adjustment ensures that the design values reflect the specific conditions at the local site.

- **Design Wave Height** Using extreme value analysis (EVA), the design wave height was estimated from the ERA5 dataset, which was then adjusted to the local site using the comparison factor.

- **Wave Height and Period Relationship:** A correlation analysis was conducted to explore the relationship between wave height (H_s) and wave period (T_p). This included calculating the correlation coefficient and generating scatter plots.

- **Design Wave Period:** Power law regression was applied to determine the relationship between wave height and period. This regression allowed for estimating the dominant period corresponding to the design wave height.

G.1.1. Data Cleaning

The data cleaning process is crucial to ensuring that only reliable data are used in the subsequent analysis. Given the proximity of the two sites (approximately 25 km), it was assumed that the wave conditions at both locations would be similar. Therefore, discrepancies between the local data and the ERA5 data were used to identify and remove measurement errors in the local dataset.

The datasets were pre-processed as follows:

1. **Resampling**: Both datasets were resampled to hourly intervals for consistency in time steps.

2. **Outlier Removal**: Outliers were identified by comparing the wave height (H_s) and wave period (T_p) values between the local and ERA5 datasets. A threshold of 4 standard deviations was used to remove erroneous data points. Outliers were flagged if the difference between the two datasets exceeded ± 4 standard deviations.

The choice of 4 standard deviations as the threshold for outlier removal is based on the assumption that any differences exceeding this limit are likely due to measurement errors. In a normal distribution, about 99.99% of the data points lie within ± 4 standard deviations from the mean. Therefore, setting the threshold at this level ensures that only extreme outliers, which are unlikely to reflect the natural wave conditions, are removed from the dataset.

Figures G.2 and G.3 show the difference plots for H_s and T_p, with outliers identified using the 4 times standard deviation threshold.
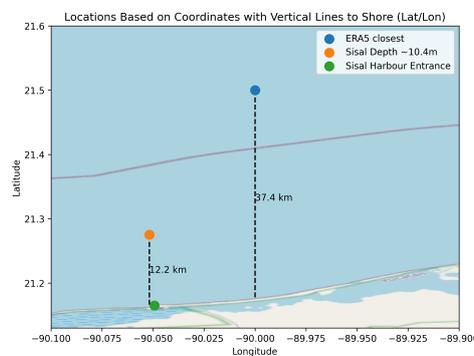
Figure G.1: Locations Based on Coordinates with Vertical Lines to Shore (Lat/Lon). This map shows the positions of the Sisal wave height measurement site, the Sisal harbor, and the closest ERA5 offshore location.
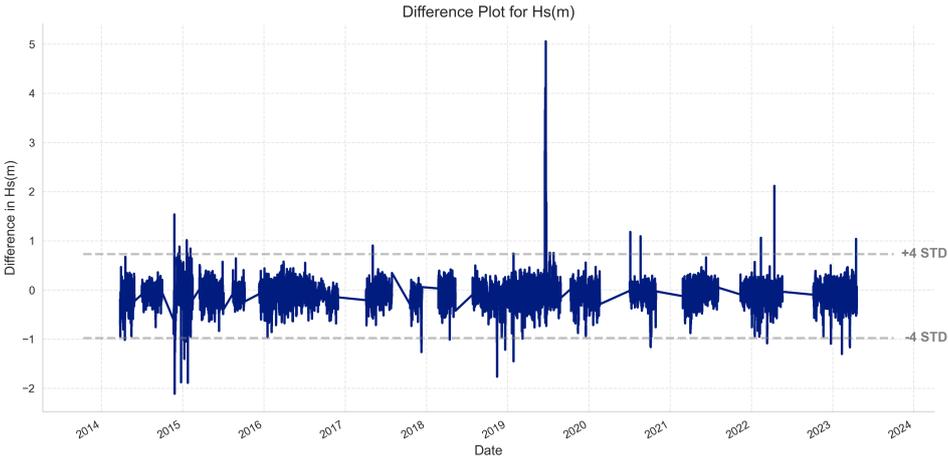
Figure G.2: Difference Plot for Wave Height (H_s) with ± 4 Standard Deviation Thresholds.
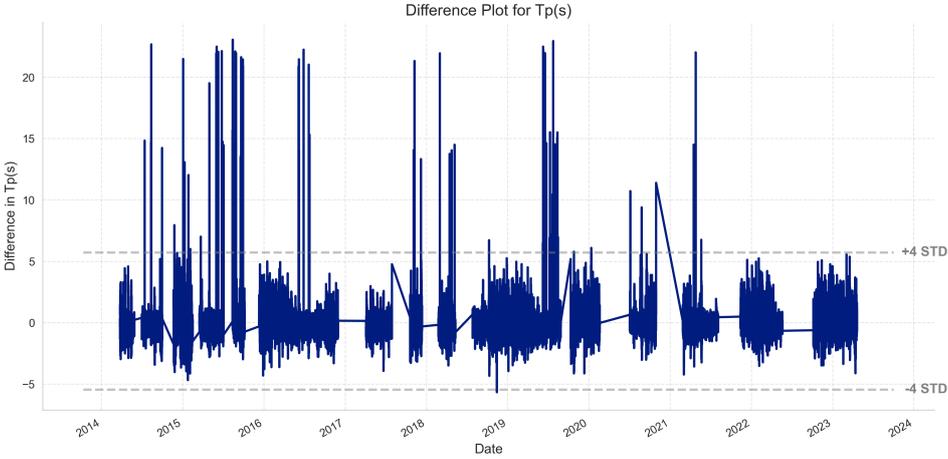
Figure G.3: Difference Plot for Wave Period (T_p) with ± 4 Standard Deviation Thresholds.

Figure G.4 shows a comparison of the cleaned wave height and period data, highlighting the impact of the data cleaning process on the local dataset. Furthermore, it can be seen that there are some periods in which no data was available. The reason for these gaps in the dataset is unknown, but they may be due to instrument malfunction or periods where data collection was interrupted.

Hs(m) Comparison: Given Sisal Data vs Cleaned Hs(m) Sisal vs Cleaned Hs(m) and Tp(s) Sisal
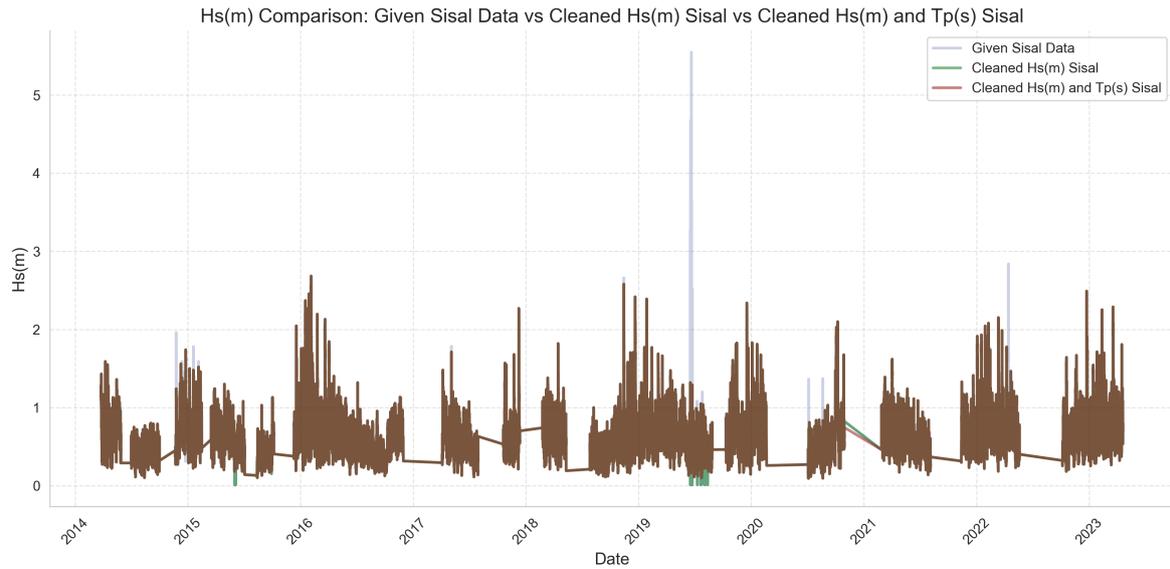
Figure G.4: Wave Height Comparison: Sisal Given vs Cleaned using $H_s(m)$ and $T_p(s)$.

G.1.2. Historical Data Comparison

The goal of this comparison is to determine a factor that can be used to adjust the design wave height from the offshore location (ERA5) to the more relevant inshore location (Sisal Cleaned). In Figure G.5, the wave height time series from both datasets is plotted. The key observation here is the general similarity in the trend and distribution of wave heights between the two datasets, although the wave heights in the ERA5 dataset tend to be higher. This is expected, given that the wave conditions in more offshore locations are generally rougher than those closer to shore. This figure shows the general agreement between the two datasets, which justifies the comparison and adjustment of the design values based on the ERA5 data.
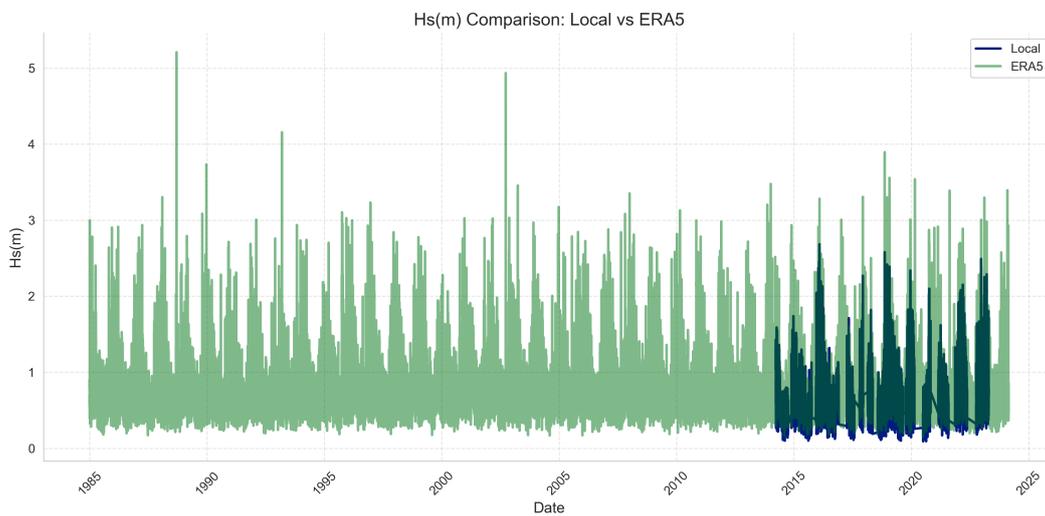
Figure G.5: Wave Height Comparison: Sisal Cleaned vs Sisal ERA5. This figure shows the time series of wave heights from both datasets.
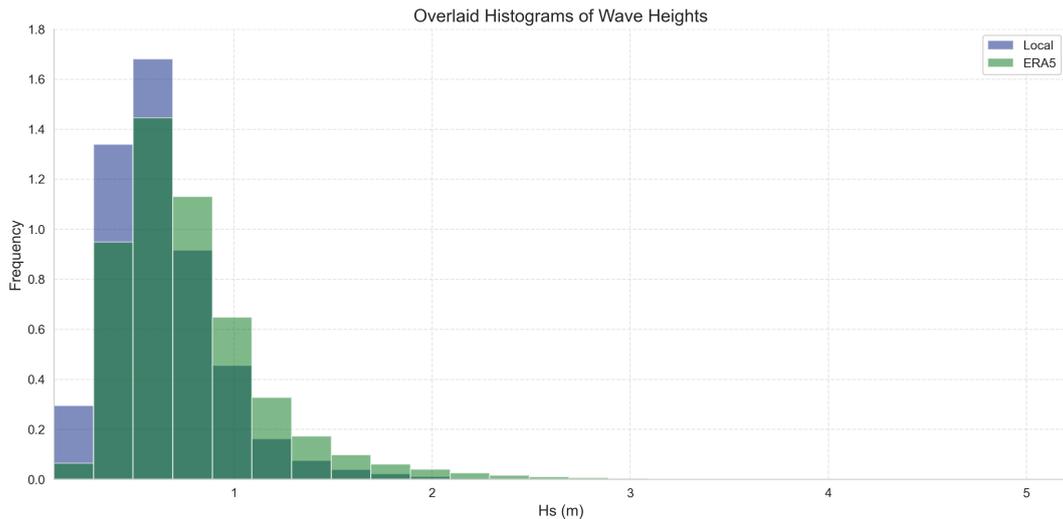
Figure G.6: Histogram of Wave Heights for Sisal Cleaned and Sisal ERA5. This figure shows the distribution of wave heights for both datasets.

In Figure G.6, the wave height histograms are displayed for both datasets. The histograms provide a clear indication of the frequency distribution of the wave heights at each location. The majority of wave heights for both datasets are below 1 metre, but the EVA5 dataset exhibits a longer tail, indicating the presence of higher wave heights offshore. This reinforces the idea that the offshore wave conditions are generally rougher, which is why it is necessary to adjust the design values derived from the ERA5 data to better match the conditions near Sisal.
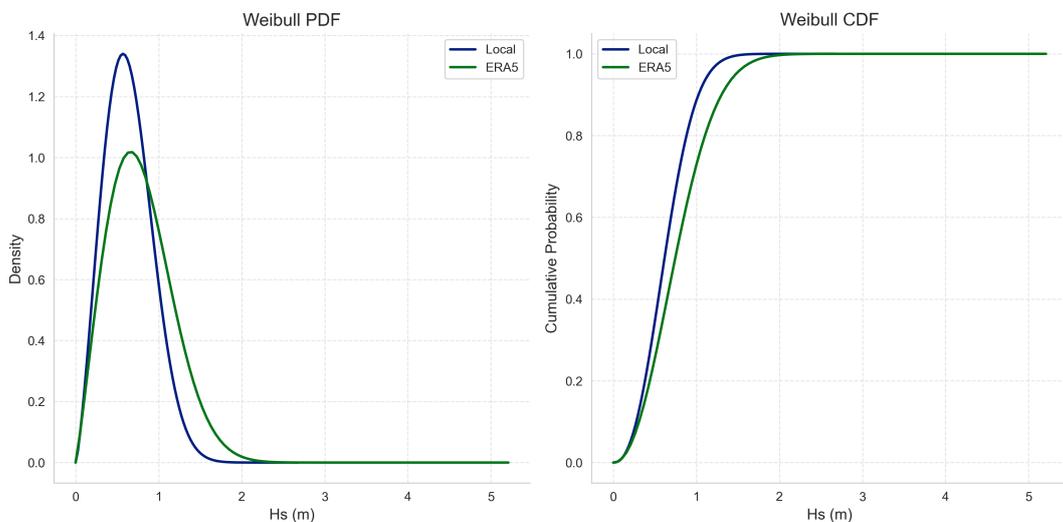
Figure G.7: Weibull Probability Density Function (PDF) and Cumulative Distribution Function (CDF) for Sisal Cleaned and Sisal ERA5 datasets.

The Weibull distribution was fitted to the wave height data from both datasets, as shown in Figure G.7. This distribution is commonly used in modelling natural phenomena such as wave heights because it effectively represents skewed distributions where extreme values, such as high waves, occur with decreasing frequency, as shown in Figure G.6.

In this analysis, the key focus is on the scale parameter of the Weibull distribution, which defines the spread of the data. Since the wave height data from both the ERA5 and local datasets follow a similar distribution, the scale parameter is used to calculate a factor. The scale parameter for the ERA5 data

is 0.88, while for the local data, it is 0.72. The ratio of these scale parameters provides a factor k by which the design value of the EVA will be adjusted:

$$\text{Adjusted Design Value} = \text{Design Value}_{\text{ERA5}} \times \text{k} \tag{G.1}$$

The scale ratio is calculated as:

$$\text{k} = \frac{\text{Scale}_{\text{Sisal Cleaned}}}{\text{Scale}_{\text{ERA5}}} = \frac{0.720882}{0.884745} = 0.815 \tag{G.2}$$

This factor will be applied in the next section during the extreme value analysis to ensure that the design wave height reflects local conditions at Sisal, although the longer ERA5 dataset is used for the initial analysis.

G.1.3. Design Wave Height

The design wave height is one of the most critical parameters for ensuring the structural integrity of offshore installations, such as fish cages. To accurately estimate this value, an extreme value analysis (EVA) was performed using the Peaks Over Threshold (POT) method. The goal of this analysis is to identify the most extreme wave events from the historical wave height data, specifically focussing on the ERA5 dataset, and use this information to estimate a reliable design wave height.

The Peaks Over Threshold (POT) method is a widely used approach in extreme value analysis. It focuses on identifying only those observations that exceed a specified threshold, capturing the most significant events in the dataset, which are critical for structural design.

By focusing on the tail of the distribution, the POT method enables the analysis of the most impactful wave heights, ensuring that the fish cages can withstand rare but extreme environmental conditions. Once the exceedances over the threshold are identified, these peaks are then fitted to a Generalised Pareto Distribution (GPD) to estimate return levels for specified return periods, which correspond to the design wave height.

Threshold and De-clustering Time Selection

One of the key steps in the POT method is selecting an appropriate threshold. The threshold must be high enough to capture extreme events, but not so high that it results in too few data points for reliable analysis. To determine the most suitable threshold, an analysis was performed using various thresholds ranging from 2.45 to 3.10 metres. The objective was to determine a threshold that effectively captured extreme events while striking a balance between the goodness-of-fit of the GPD and the inclusion of a sufficient number of peaks in the analysis.

The following three key factors were taken into account:

1. **Chi-square Statistic**: Measures how well the Poisson model fits the data. A lower chi-square statistic indicates a better fit.

2. **p-value:** Indicates the statistical significance of the fit. A p-value greater than 0.05 suggests that the Poisson model fits the data well.

3. **Number of peaks:** Represents the number of extreme events identified above the threshold. A sufficient number of peaks is necessary for a robust analyses, but too many may dilute the focus on truly extreme events.

Threshold	2.45	2.50	2.55	2.60	2.65	2.70	2.75	2.80	2.85	2.90	2.95	3.00	3.05	3.10
Number of Peaks	135	125	115	99	91	84	75	63	57	41	32	27	24	22

Table G.1: Number of Peaks for Various Thresholds
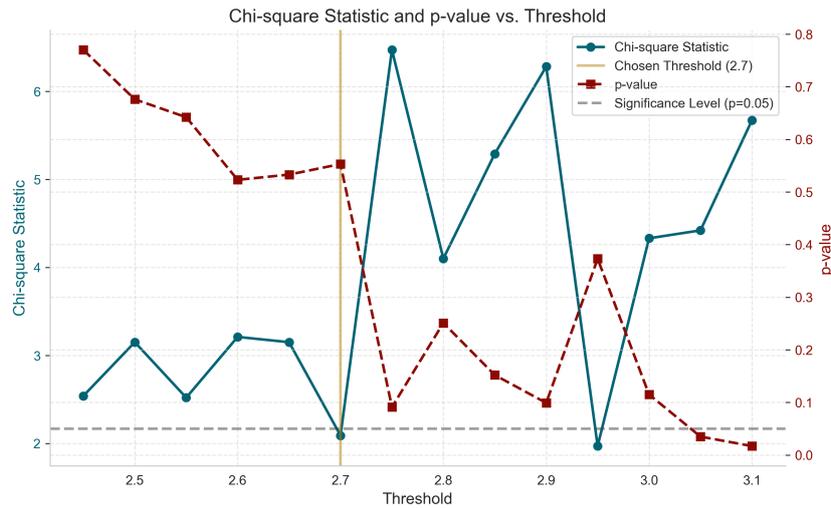
Figure G.8: Plot of Chi-square Statistic and p-value versus Threshold values, highlighting the chosen threshold and significance level in the Extreme Value Analysis of wave heights

Based on Table G.1 and Figure G.8 the threshold of 2.70 metres was chosen as the most appropriate threshold for the following reasons. Firstly, the threshold yields the lowest chi-square statistic 2.09, besides 2.95 metres (1.97), indicating the second best fit to the GPD compared to the other thresholds. The p-value at the 2.70-meter threshold is 0.553, which is well above the significance level of 0.05. This suggests that the differences between the observed and expected exceedances are not statistically significant, reinforcing the appropriateness of this threshold for modelling extreme wave heights. At the 2.70-meter threshold, the number of peaks identified is 84, which strikes a balance between capturing enough extreme events for robust analysis and avoiding the inclusion of too many non-extreme events. Lower thresholds, such as 2.50 metres, capture more peaks (e.g. 125 peaks), but this can include less extreme wave events, potentially skewing the analysis. Conversely, higher thresholds (e.g. 2.95 metres) result in fewer peaks (41 peaks), which does not provide enough data for a reliable analysis.

Once the threshold is set, a declustering time is applied to avoid counting multiple observations from the same storm event. A declustering time of 4 days was selected, meaning that any peak within 4 days of a previous peak is considered part of the same event. This step ensures that only independent extreme wave events are included in the analysis. Declustering is crucial to avoid artificially inflating the number of extreme events, which could lead to an overestimation of return levels. It ensures that the peaks used in the analysis represent distinct, independent events.
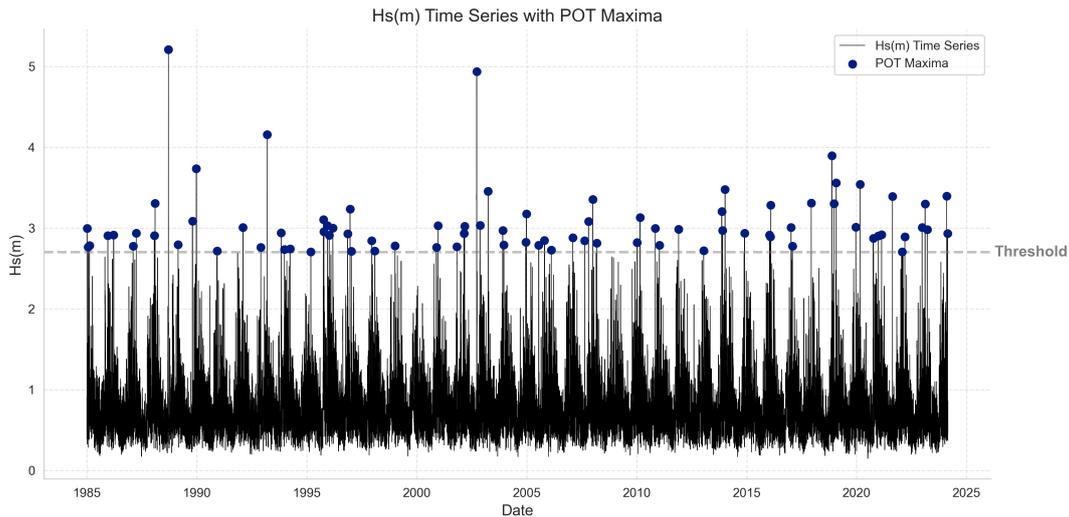
Figure G.9: Hs(m) Time Series with POT Maxima with a Threshold of 2.7 and a De-clustering Time of 4 days

Figure G.10 highlights the frequency of extreme wave events exceeding the selected threshold. The Probability Mass Function (PMF) shows that the majority of years experience 2 to 3 extreme wave events. This aligns with the expected occurrence of rare extreme events, such as hurricanes, which drive wave heights significantly higher.

The Cumulative Distribution Function (CDF) complements this by showing that nearly 90% of the years see 3 or fewer extreme events. The relative rarity of years with higher exceedances suggests that the selected threshold and the 4-day de-clustering time are appropriate. These settings ensure that only significant, independent wave events are captured, avoiding overcounting events from the same storm system. The distribution reflects a realistic scenario where extreme wave events are infrequent but important for design considerations, further validating the choices made for threshold and de-clustering time.
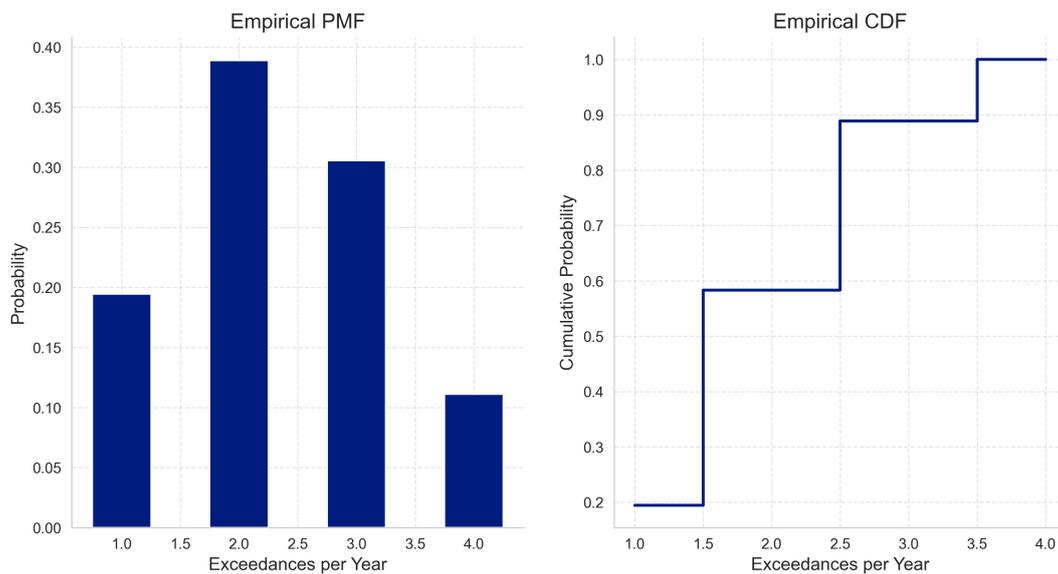
Figure G.10: Empirical Probability Mass Function (PMF) and Cumulative Distribution Function (CDF) of exceedances per year. The PMF shows the probability of a given number of exceedances, while the CDF shows the cumulative probability.

As said before, the occurrence of extreme events (exceedances) is expected to follow a GPD, as extreme events are generally rare and random. A Poisson model was fitted to the empirical data and

the results are compared in Figure G.11. The close alignment of the empirical CDF and the Poisson CDF visually confirms the conclusion that the Poisson model accurately describes the frequency of exceedances.
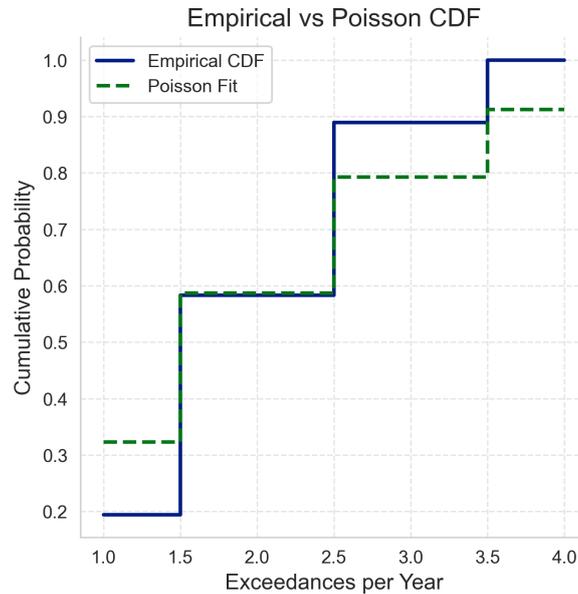
Figure G.11: Comparison of Empirical and Poisson CDF. The close alignment of the curves indicates a good fit, confirming that the Poisson model accurately describes the frequency of exceedances.

G.1.4. Return Levels and Design Wave Height

To continue the analysis , the focus now is on determining the height of the design wave, which is crucial to ensure that fish cages can withstand the extreme conditions that are expected during their design life. In this case, a 20-year return period was chosen, as it aligns with the typical design life of fish cages. To calculate the design wave height, use the parameters obtained from the GPD.

GPD Fit and Return Level Estimation

In Figure G.12) the histogram of the exceedances is shown along with the fitted GPD Probability Density Function (PDF). The close alignment of the empirical data and the GPD PDF validates the use of this model for estimating extreme wave heights. The GPD fit captures the tail behavior well, reinforcing the robustness of the design value.

The right-hand side of the figure shows the exceedance probability plot, which illustrates the probability that a wave height exceeds a certain value. The good alignment between the empirical data and the GPD model further confirms the suitability of the GPD for predicting extreme wave heights.

Design Wave Height

The Return Level (RL) for a given return period N can be calculated using the following formula for a GPD:

$$\text{RL}_T = \text{th} + \frac{\sigma_{th}}{\xi} \left(\left(\frac{n_{th} \cdot N}{M} \right)^{\xi} - 1 \right)$$

Where:

- th is the threshold (2.7 meters),
- σ is the scale parameter of the GPD (0.3155),
- ξ is the shape parameter of the GPD (0.1166),
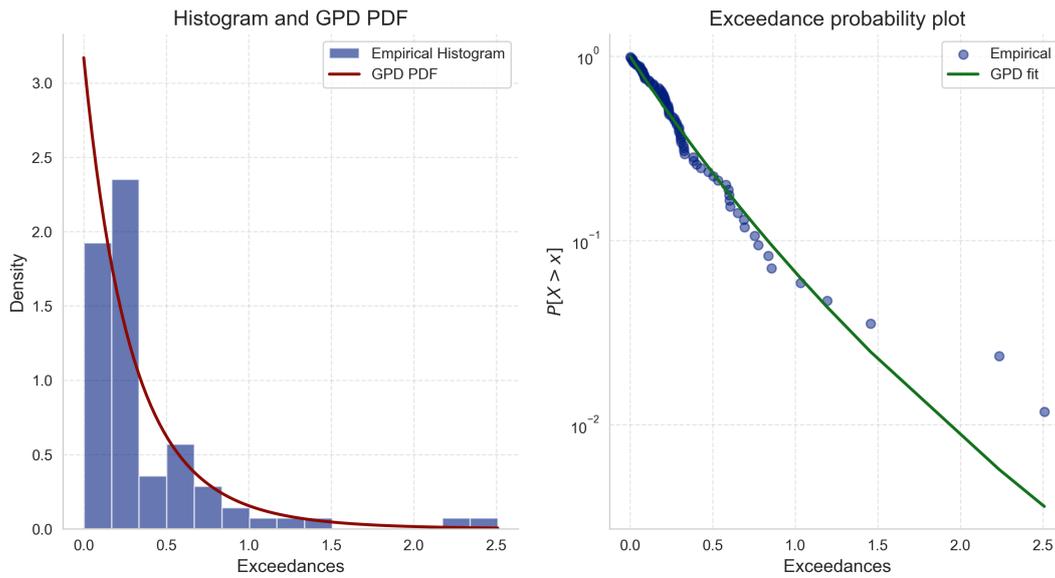
Figure G.12: Left: Histogram of Exceedances with Fitted GPD PDF. Right: Exceedance Probability Plot with GPD Fit. These plots show the GPD fitting process and highlight the predicted return levels for different exceedances.

- n_{th} is the total number of sampled exceedances (84),
- M is the total number of years in the data set (39 years).

In Figure G.13 are shown using Figure G.1.4 over for Return Periods. For designing the fish cage, a Return Period of 20 years was chosen. As marine environments, especially hurricane-prone areas, are subject to periodic extreme weather conditions. Designing for a 20-year return period ensures that the fish cage is robust enough to handle the type of extreme wave height that might occur. In addition to that designing for a longer return period, such as 50 or 100 years, would result in unreasonable material costs.
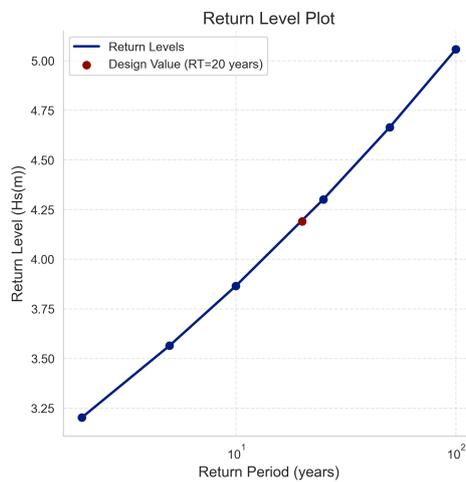
Figure G.13: Return Level over different Return Periods

For our dataset, with a return period of 20 years, the estimated return level, or the **design wave height,** is approximately 4.19 meters. This value corresponds to the location where the ERA5 data was collected. However, to adjust this design wave height for the local site, we apply the previously calculated adjustment factor, $k = 0.815$, as discussed in the earlier section. The design wave height for the local location is then given by:

$$W_h = k \times RL_T = 0.815 \times 4.19 = 3.40\text{m} \tag{G.3}$$

Thus, the adjusted design wave height for the local site is **3.42 meters**.

G.1.5. Wave Height and Period

In this subsection, the relationship between wave height and wave period is explored through analyses and visual representation. The goal is to understand how these parameters interact, especially for extreme wave events that are relevant for the design of offshore fish cages.

The scatterplots in Figure G.14a and G.14b provide a detailed look at the relationship between wave height and wave period for both datasets.

(a) ERA5 data

(b) Local data
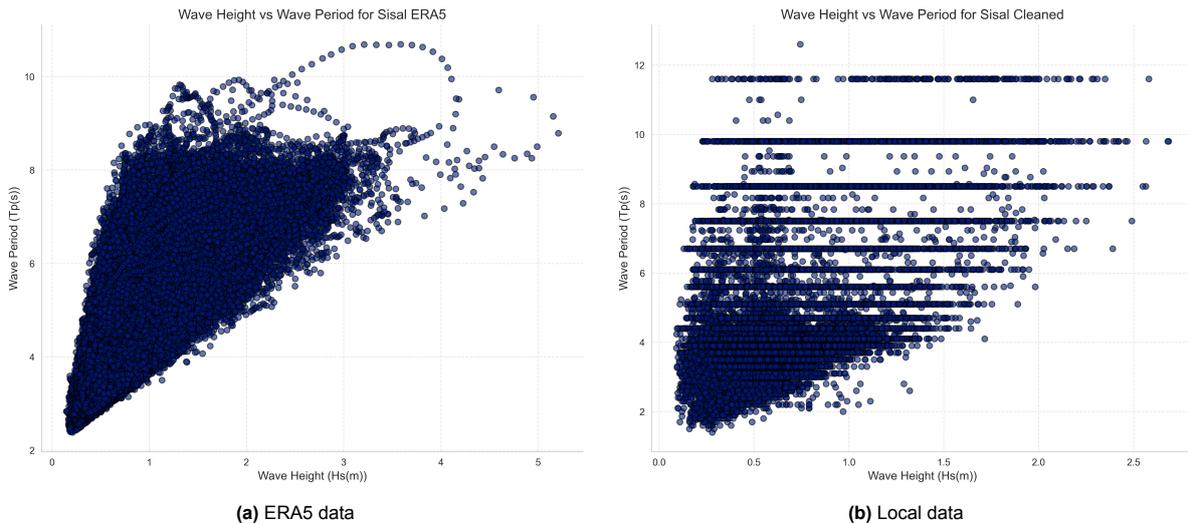
Figure G.14: Comparison of Wave Height vs. Wave Period

The ERA5 scatter plot reveals a clear, continuous relationship between wave height and wave period, where higher wave heights correspond with longer wave periods. This level of precision makes the dataset highly reliable for wave period estimation. The covariance between wave height and wave period is 0.298 and the Pearson correlation coefficient is a strong 0.753. These values indicate a robust linear relationship, which means that as the wave height increases, the wave period also consistently increases. The strong correlation further suggests that the ERA5 dataset provides valuable and reliable insight into the wave height-period relationship, making it particularly well suited for predictive and design applications.

In contrast, the local dataset appears to be less precise, as seen in the horizontal lines of the scatter plot, likely caused by 'binned' or rounded values for wave periods. This suggests that instead of continuous, precise measurements, the wave period values are grouped into specific categories or intervals, which is a result of the ADCP's limited precision in measuring frequency. The local dataset shows a covariance of 0.225 and a moderate Pearson correlation coefficient of 0.475. Although there remains a positive relationship between wave height and wave period, it is weaker and less consistent compared to the ERA5 dataset. The reduced correlation is likely due to the binned wave period values, making the Sisal Cleaned dataset less reliable for detailed wave period analysis.

Given the stronger correlation and continuous data in the ERA5 dataset, it provides a more reliable basis for analyzing the relationship between wave height and wave period. In contrast, the local dataset's binned values and weaker correlation make it less suitable for detailed analysis. Therefore, the ERA5 dataset will be used for further wave period estimation and design considerations.

Power-Law Regression for Design Wave Period

A power-law regression was applied to the ERA5 dataset to predict the wave period corresponding to the design wave height. Power-law regression is commonly used when a non-linear relationship is expected between two variables, in this case, wave height and wave period.

$$T_p = a \times H_s^b \tag{G.4}$$

The regression model produced the following results:

- **Power-law parameters**: $a = 4.8522$, $b = 0.4096$

- **R-squared value**: $R^2 = 0.564$, indicating that the model explains about 56.4% of the variance in wave period based on wave height.

- **Design Wave Period**: For the design wave height of 3.4026 m, the predicted wave period is 8.012 seconds, with a 95% confidence interval of $[6.671, 9.353]$ seconds.

This regression result provides a solid estimate for the design wave period, which is a key factor in determining the forces acting on the fish cages during extreme wave events. Figure G.15 shows the power-law regression curve, with the design wave height and confidence interval marked.
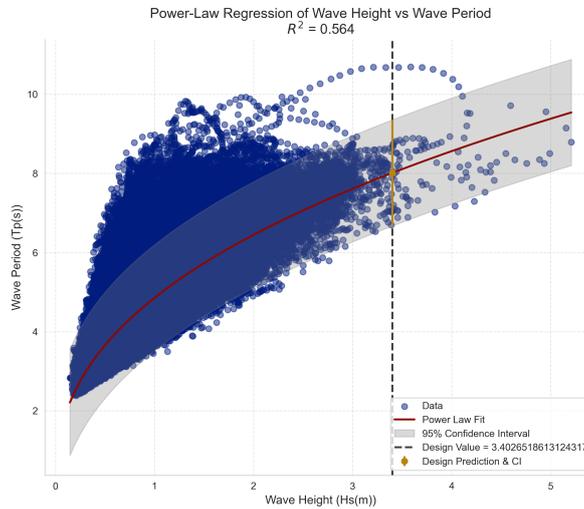
Figure G.15: Power-law Regression of Wave Height vs. Wave Period. The design wave height and its predicted wave period are marked, with a 95% confidence interval shown.

G.2. Current Data Analysis

The current data was obtained from an Acoustic Doppler Current Profiler (ADCP) over various depths, ranging from $-8.8\,m$ to $-1.1\,m$ with an interval as shown in Table G.2. The location of the ADCP is the same as the ADCP used in section G.1. The ADCP measures water velocity in two horizontal directions: the U component, which represents the East-West flow, and the V component, which represents the North-South flow. A positive value in the U component indicates a current flowing towards the East, while a negative value indicates a current flowing towards the West. Similarly, for the V component, a positive value signifies a current flowing towards the North, and a negative value represents a current flowing towards the South. These directional components are essential for understanding the flow dynamics at various depths, providing a comprehensive picture of water movement in the study area.

-8.8	-8.5	-8.1	-7.8	-7.5	-7.1	-6.8	-6.5	-6.1	-5.8	-5.5	-5.1

Table G.2: Depth intervals in meters for current measurements.

G.2.1. Data Cleaning

Before any analysis, outliers were removed from the data. This was done by applying a threshold of 4 times the standard deviation ($4 \times \sigma$) to each component (U and V). Any values that exceeded this threshold were flagged as outliers and removed to ensure that the dataset was free of erroneous values. The process was repeated twice to ensure all measurement errors were eliminated from the data.

G.2.2. Extrapolation of U and V Components

Since the ADCP does not provide direct measurements for depths shallower than $-1.1\,m$, the U and V components were extrapolated using polynomial regression. A 3rd-degree polynomial was fitted for each time step to the available U and V components, allowing for the prediction of the velocities at shallower depths $-0.8\,m$ and $-0.5\,m$.
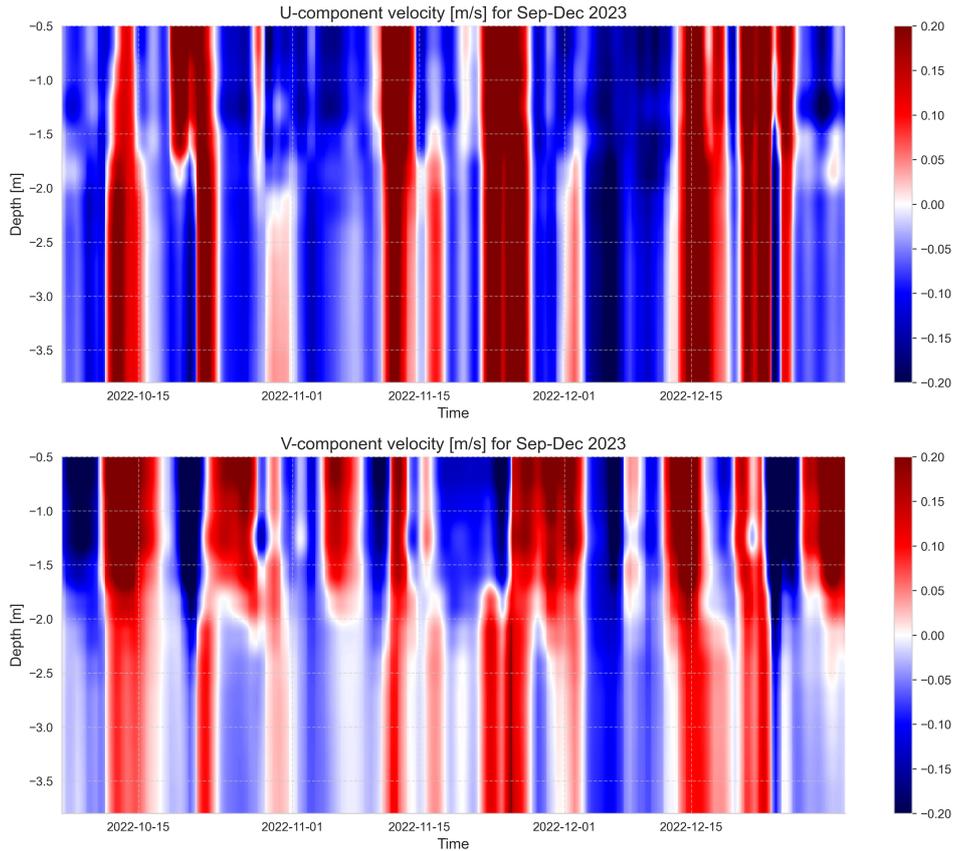
Figure G.16: Heatmaps of U and V components for September-December 2023 at various depths.

Figure G.16 shows the heatmaps for U and V components a short period of time. These heat maps demonstrate that the extrapolation performed at the shallower depths was successful, as the dynamic nature of the currents is clearly visible at all depths, including the extrapolated regions. The continuity of the patterns at shallower depths aligns well with the deeper measured data, indicating that the polynomial fitting effectively captured the underlying current behaviour.

From the heatmaps, it is evident that the currents fluctuate significantly over time and depth, with alternating positive and negative velocities. These alternating red (positive) and blue (negative) bands indicate changes in the flow direction, likely driven by tidal forces or other environmental factors. The change in flow direction will be discussed in section G.3.

G.2.3. Current Speed Calculation

The current speed S is calculated from the U and V components using the following equation:

$$S = \sqrt{U^2 + V^2}$$

Where:

- U is the east-west velocity component (m/s),
- V is the north-south velocity component (m/s),
- S is the current speed (m/s).

The speed was calculated for both the available and extrapolated depths. After obtaining the speed, the next step was to create a boxplot to better understand the distribution of the current speeds at various depths.
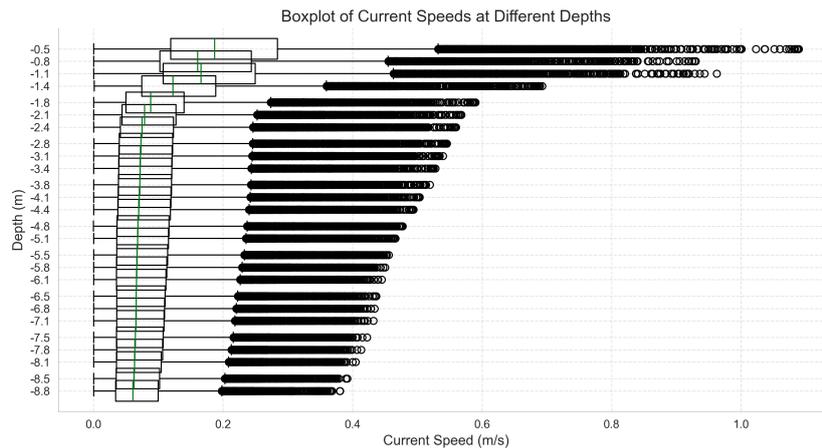
Figure G.17: Boxplot of Current Speeds over Depth

In **??**, the majority of current speeds fall between $0.2\,m/s$ and $0.4\,m/s$, with only a few instances exceeding $0.5\,m/s$. This distribution illustrates that moderate current speeds dominate the dataset, while higher speeds are relatively rare. The boxplot provides a clear indication of the overall current behaviour, showing that extreme current speeds occur infrequently, reflecting the general stability of the current conditions in the area.

The plot reveals that current speeds tend to decrease with increasing depth. Near the surface, the currents are more variable, displaying a broader range of speeds, as evidenced by the wider interquartile range and the presence of outliers. This can be attributed to the fact that the ADCP is sometimes located near the sea surface. This exposes it to the effects of wind-driven surface currents, waves and turbulence. Additionally, proximity to the sea surface introduces noise and instability due to surface interactions, further contributing to the observed variability. As we move to greater depths, the current speeds become more consistent, with a narrower distribution and fewer outliers, indicating that the influence of surface forces diminishes with depth. This trend highlights the dynamic nature of shallower currents compared to the more stable, deeper currents.

In further analysis, the depth of $-1.1\,$m is removed, despite being directly measured and not extrapolated. This decision was made because the depth of $-1.1\,$m shows higher speeds than $-0.8\,$m, its removal therefore helps smooth the velocity profile as the depth increases. By excluding this depth, the progression of current speed with increasing depth becomes more consistent and realistic.

G.2.4. Design Current Speed

The dataset, spanning only 10 years, is too short for a reliable Extreme Value Analysis (EVA). EVA typically requires longer datasets, ideally spanning multiple decades, to accurately model rare and extreme events, such as unusually strong currents. With only 10 years of data, the statistical significance of the extreme value predictions would be limited, making it unsuitable for confidently estimating return periods for extreme currents. Therefore, alternative approaches must be used for assessing design currents.

The design current speed, with the depth -1.1 removed, is therefore determined by the 95th percentile of the current-speed distribution. This means that 95% of the observed current speeds are lower than the design current speed, which ensures that the fish cage is designed to withstand the most extreme currents without over-designing the structure for extremely rare events. In Figure G.18, the design current speed is plotted against the depth. As seen in the boxplot (Figure G.17), the majority of current speeds are moderate, particularly at deeper depths, where the range of current speeds is smaller and more uniform. Using the 95th percentile strikes a balance between capturing the significant current forces and avoiding overly conservative designs that could lead to unnecessary material and cost increases. This approach ensures that the fish cages are robust enough to handle the majority of extreme conditions without being overengineered for highly unlikely events. Additionally, by using the 95th percentile, we exclude the varying measurement precision at the top of the surface, where data tends to be less reliable due to factors such as instrument exposure and surface turbulence.
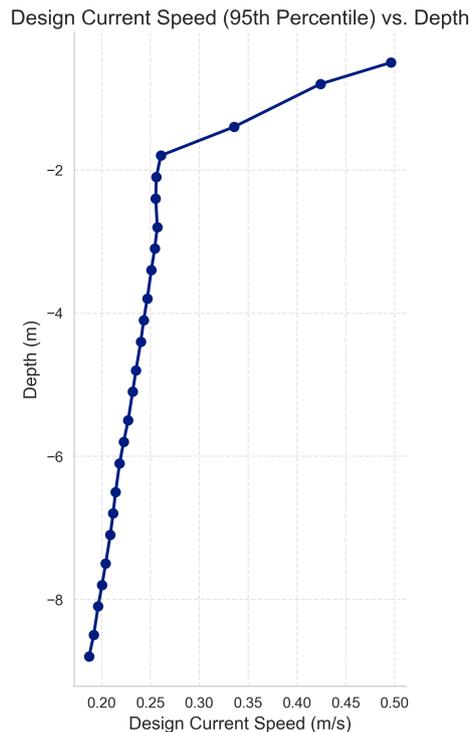
Figure G.18: Design current speed (95th percentile) vs. depth.

G.3. The Relationship Between Wave and Current Directions

In this section, we analyse the relationship between wave and current directions, focussing specifically on the overlap between the 95th percentile for wave height and current speed. This provides a concentrated view of the conditions when both the waves and currents are at their most extreme, occurring simultaneously. By examining histograms and scatter plots, we can derive critical insights into the interaction between these environmental forces during extreme events.

G.3.1. Wave Direction Analysis

The analysis of wave directions provide a clear understanding of how the waves behave around the site. The wind rose diagrams for the wave direction, Figure G.19, show both local data and ERA5 data, covering all wave height conditions and the top 5% of the wave heights. The predominant direction for the local data is from the *northeast* (NE), while for the ERA5 data, it is from the *northeast-east* (NE-E). These directions are crucial for the fatigue assessment of the structure. The slight variation in angles can be attributed to the difference in the distance from the shore between the two data sources.

A change is seen in the top 5% of the wave heights. The local data indicate that the most significant wave events primarily originate from the *northeast-northeast* (NNE) and *northeast* (N). The ERA 5

data is slightly more centred around the *north* (N), which is consistent with the overall data.

Figure G.19: Top 5% current speeds, predominantly eastward, at -1.1 m, -4.8 m, and -8.8 m depths.

G.3.2. Current Direction Analysis

In terms of currents, the current rose diagrams, Figure G.20, show the current directions and speeds at three different depths. At a depth of *1.1 m*, the top 5% of current speeds are largely concentrated from the *east* (E) to *east-southeast* (ESE). As the depth increases to *4.8 m* and *8.8 m*, the predominant current direction remains *east*, with a slight change toward *east-northeast* (ENE) at deeper levels. As said before the ADCP exhibits more variability at shallower depths, which can be partially attributed to its occasional exposure to sea level conditions. Other contributing factors might include varying flow dynamics or measurement precision near the surface.
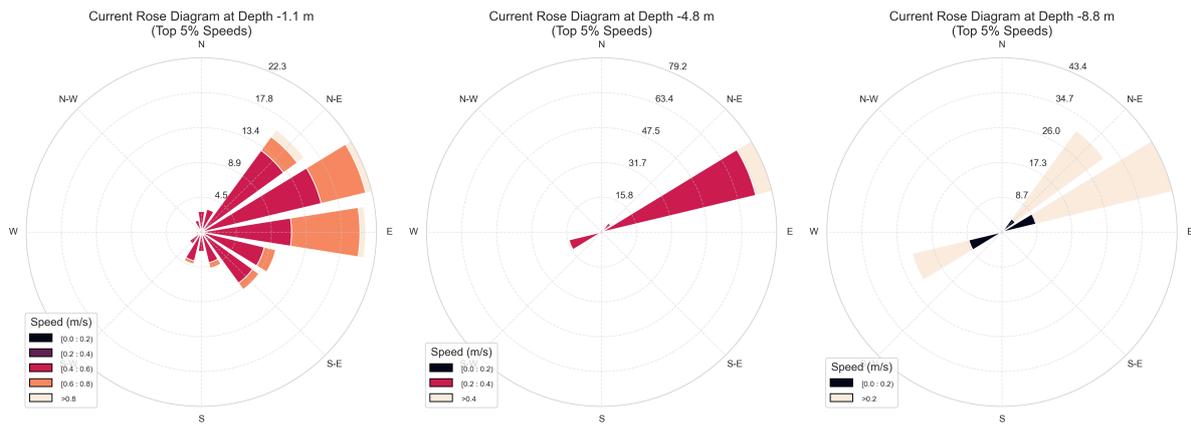
Figure G.20: Wave directions from local and ERA5 data, mainly from NE and N

G.3.3. Wave and Current Interaction at the 95th Percentile

To examine the relationship between the directions of the highest wave heights and the strongest current speeds, the 95th percentile for both variables was taken into account. Only the moments where both the wave height and current speed exceeded this threshold were analyzed. A current depth of 2.1 meters was chosen for this analysis, as it closely corresponds to the mid-depth of the fish cage.

The scatter plot provides valuable insights into the interaction between these extreme events. While there is no strong correlation between wave and current directions, the directions of the strongest currents and highest waves are clearly discernible. The distribution of wave directions shows a distinct concentration around one main cluster, between approximately 340° and 20°. This indicates that waves arrive predominantly from a limited range of directions. Similarly, the current directions cluster primarily around 50° and 250°, which aligns with the findings of the windrose at a depth of -4.1 metres. Although the relationship is not linear, these clusters suggest that under certain conditions, waves and currents are more likely to follow predictable patterns or align in specific directions.
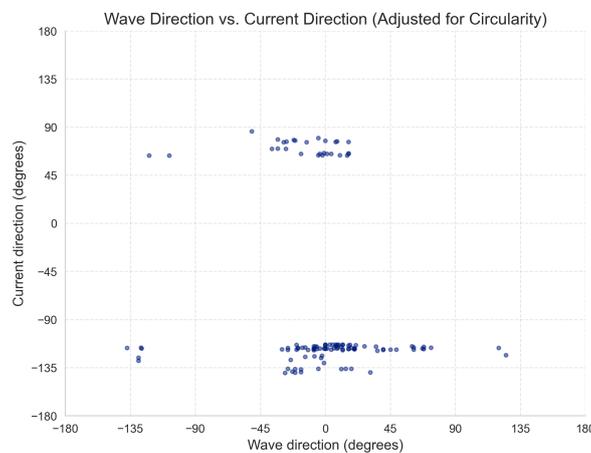
Figure G.21: Relationship of 95th percentile current direction and wave direction

?? illustrates the distribution of current directions, highlighting the contrast between all current directions and those within the 95th percentile for wave height, current speed, and the combination of both. The overall distribution shows two prominent peaks at approximately 50° and 250°, indicating that currents predominantly flow in these directions. While other current directions exist, they occur with significantly lower frequency.

When analyzing the 95th percentile for wave height, it becomes evident that the highest wave events are most frequently associated with currents flowing toward 250°, with a much smaller occurrence near

70°. This suggests a strong correlation between significant wave events and currents moving in the 250° direction. On the other hand, the 95th percentile for current speed reveals that the strongest currents are concentrated around 70°, with a smaller peak at 250°. This indicates that the highest current speeds typically flow toward 70°, with moderately strong currents also present at 250°.
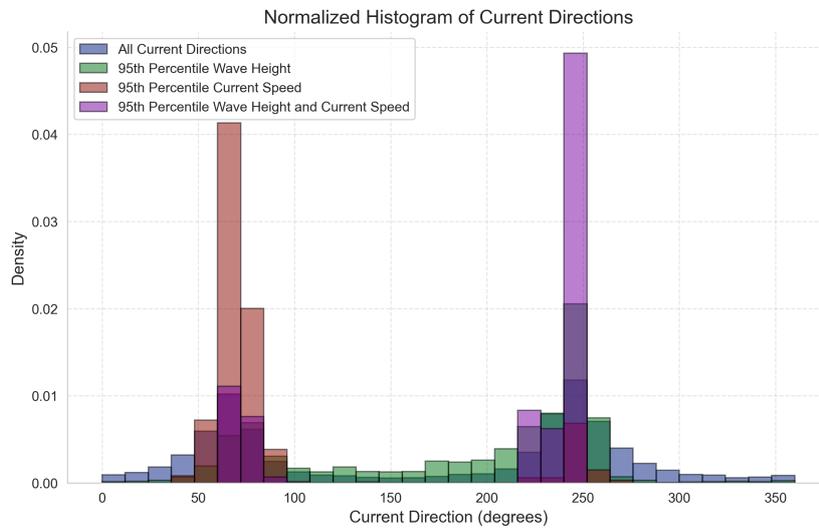

Figure G.22: Normalized Histogram of Current Directions and the 95th Percentile

?? shows the distribution of wave directions, comparing all wave directions with those within the 95th percentile for wave height, current speed, and their combination. The overall wave direction distribution reveals a dominant cluster between 0° and 50°, indicating that the majority of waves come from these directions. Waves from other directions are much less frequent. The 95th percentile wave height is primarily clustered between 320° and 40°, which suggests that significant wave events follow the general directional patterns observed for all waves. When considering both high wave height and high current speed together, the most extreme conditions tend to concentrate between 0° and 350°. This indicates that severe marine conditions, characterized by both strong waves and fast currents, predominantly occur within this directional range, reinforcing the importance of these directions for understanding wave-current interactions.
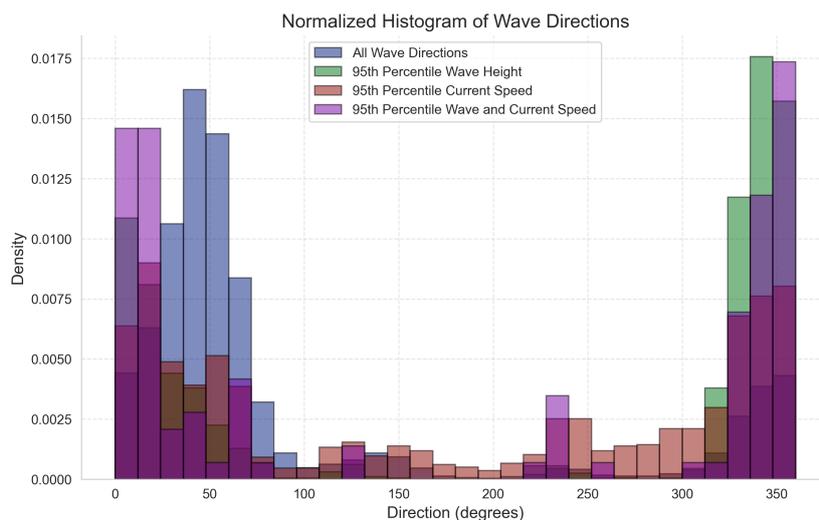
Figure G.23: Normalized Histogram of Wave Directions and the 95th Percentile

In conclusion, the windroses and histograms provide key insights into the interaction between wave

and current directions. Current directions are mainly clustered around 70° and 250°, while wave directions are concentrated between 350° and 20°. The 95th percentile events—whether for wave height, current speed, or both—highlight critical directions where extreme conditions are most likely to occur, particularly around 250° for currents and between 0° and 20° for waves. These directional patterns are essential for informing design considerations, as they help to identify the conditions under which extreme forces may act on structures, ensuring that the design can adequately withstand these forces for optimal stability and safety.

G.4. Concluding Design Values

The data analysis conducted in this study has provided a comprehensive understanding of the environmental conditions offshore near Sisal, specifically focussing on wave and current behaviour. These findings are crucial for determining the design parameters necessary to ensure the structural integrity and longevity of offshore fish cages.

Design Wave Height

Using extreme value analysis (EVA) based on the ERA5 dataset, the 20-year return level for wave height was calculated to be approximately 4.19 metres. To account for local conditions, this design wave height was adjusted using a comparison factor derived from the difference between the local Sisal data and the ERA5 data, resulting in an adjusted design wave height of **3.40 meters**. This value reflects the most extreme wave conditions expected at the fish cage location over the design life of the structure.

Design Wave Period

The relationship between wave height and period was explored using power-law regression on the ERA5 dataset. For the calculated design wave height of 3.40 meters, the corresponding design wave period was estimated to be approximately **8.01 seconds**, with a 95% confidence interval ranging from 6.67 to 9.35 seconds. This period is essential for determining the dynamic response of the fish cages to wave forces.

Design Current Speed

The current data was analysed to determine the 95th percentile of current speeds at various depths, representing the extreme current conditions that the structure will face. Based on the analysis, the design current speeds vary with depth, with the highest current speeds near the surface. The 95th percentile design current speed at the surface was found to be **0.50 m/s**, while deeper depths exhibit slightly lower current speeds. This information, summarised in the current design values figure, ensures that the cages are designed to withstand the most extreme currents in the area.

Depth (m)	Speed (m/s)
-0.50	0.50
-0.80	0.42
-1.40	0.34
-1.80	0.26
-2.10	0.26
-2.40	0.26
-2.80	0.26
-3.10	0.25
-3.40	0.25
-3.80	0.25
-4.10	0.24
-4.40	0.24
-4.80	0.24
-5.10	0.23
-5.50	0.23
-5.80	0.22
-6.10	0.22
-6.50	0.21
-6.80	0.21
-7.10	0.21
-7.50	0.20
-7.80	0.20
-8.10	0.20
-8.50	0.19
-8.80	0.19

Table G.3: Depth and corresponding current speed.

G.4.1. Wave and Current Interaction

The interaction between wave and current directions was also analysed, focussing on the 95th percentile events for both wave height and current speed. The analysis showed that the most extreme wave and current conditions tend to align in specific directional clusters, with waves predominantly arriving from **340° to 20°**, and currents clustering around **70° and 250°**. These insights are critical for understanding how waves and current forces will combine during extreme events and for designing the structure accordingly to handle these forces in the critical directions.

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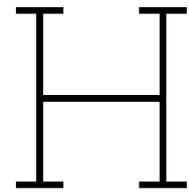
Design process

</div>

H.1. ProteusDS

ProteusDS is marine dynamic analysis software. It is designed to calculate what happens to equipment in a marine environment when there's wind, currents, and waves. Purpose-built tool-sets make it easy to use and learn to solve common problems, like oceanographic mooring design [14]. The tool-sets interesting for obtaining results in this particular project are the Proteus Simulation Toolbox (PST), the fish farm report tool and the Oceanographic Designer.

H.1.1. Installation summary

In this project, a 7-day demo version of the software was used, after finding out that the software was useful, a request to get an extension of the software in exchange for promoting it was presented and accepted. The installation process for ProteusDS involved the following steps, based on the software documentation:

1. Download the Installation Package
   The ProteusDS software package can be downloaded from the Dynamic Systems Analysis Ltd. (DSA) website. [13].

2. License Activation
   ProteusDS operates under a Software-as-a-Service model, and a valid license key is required to run the software. The license key is obtained through a two-step process:

   (a) A License Request Utility was downloaded.

   (b) The request file is sent to DSA, who then provides the appropriate license key, which can be activated via the PTS [13].

3. Running the software
   After installation and licensing, the PTS is used to set up the simulations.

4. Download LiverpoolSetup
   From the the DSA installation website a system designer file named LiverpoolSetup is downloaded. This designer creates fish farms designs fit for the ProteusDS simulation.

H.1.2. Data input

After installing the demo structural and environmental data need to be implemented into the program. The structural concept parameters are determined in chapter 7 and the environmental conditions are determined in Appendix G. Table H.1 illustrates the environmental input to do checks on the systems in the software. Later some of these values change for design purposes.

Environmental Conditions

Value		Unit
Air density	1,29	kg/m^3
Air Kinematic viscosity	1,67E-05	m^2/s
Current	0,5	m/s
Current heading	43	degrees
Waterdepth	8	m
Waterdensity	1025	kg/m^3
Water Kinematic Viscosity	1,80E-06	m^2/s
Wavetype	Airy	
Waveheading	43	degrees
Waveheight	0,8	m
Waveperiod	9	s

Table H.1: Environmental input date used in ProteusDS software for concept 1 testing

Structural dimensions

The structural dimensions when creating a basic fish farm according the software are illustrated in Figure H.1. Table C.1 shows most of the parameters used, because this project contains a cylinder shaped cage the cone height is set to zero and the bottom diameter is equal to the top diameter.
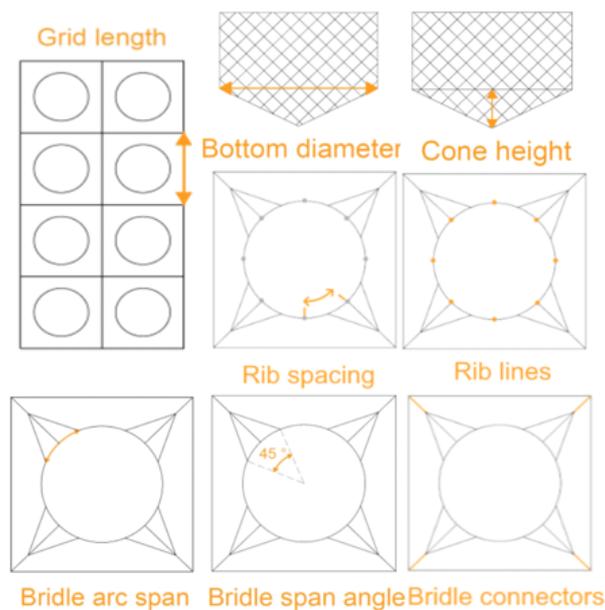
Figure H.1: Dimensions cage according LiverPool set-up

H.1.3. Concept 1a, 1b and 1c development

This section details the development of concept 1a, 1b and 1c, aimed to determine the most suitable diameter-depth ratio for the fish farm design.

1. Development of Concept 1 involved creating a three different fish farm model using the Liverpool Setup Designers (see Figure H.1).

2. The model integrated structural inputs from the three sub-concepts, each representing different diameters and depths.

3. Unnecessary elements, such as grid lines and the fourth mooring system, were removed to simplify visualization and focus on relevant components.

4. Mooring lines were created with dimensions matching those used in the Celestún case to ensure consistency.

5. Extreme environmental conditions anticipated for the site were input into the model set to be maximal on one mooring system.

6. The model was rendered for 30 seconds with half-second time steps to allow for detailed analysis of system behaviour under simulated conditions.

7. An example of the rendered system is illustrated in Figure H.2, showcasing the fish farm design and its mooring setup.

8. Tension in the mooring lines was calculated at each time step during the rendering process, providing essential data for evaluating stability and performance under varying environmental forces.
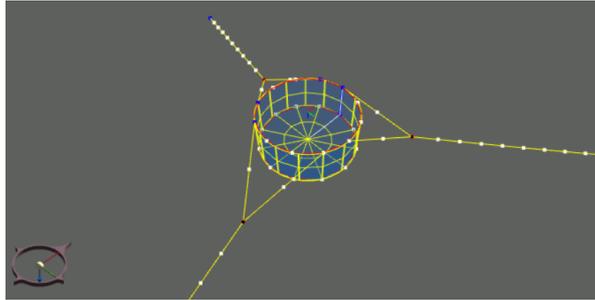
Figure H.2: Visualizer ProteusDS concept 1B

H.1.4. Concept 2 and 3 Development

This section outlines the development of Concepts 2 and 3, where ProteusDS was employed to simulate fish farm configurations with two and three cages, respectively. These concepts aim to explore the stability, mooring tension, and structural integrity under environmental forces.

Concept 2: Two-Cage Fish Farm

For Concept 2, ProteusDS was used to model a fish farm setup with two cages, increasing the complexity of the mooring system compared to Concept 1. The following steps were taken:

1. A copy of Concept 1B was made, and an additional cage was added to the model, creating a two-cage system.

2. Both cages were equipped with just two set of brittle lines and a mooring line.

3. To connect the cages, a RigidBody in the form of a 5 meter long cylinder was placed between the two float collars.

4. A 'Tensionerconnection' was introduced between the rigid body and the cages to allow sufficient degrees of freedom for movement while maintaining a minimum distance of 1 meter between the cages. This setup ensures that the cages can move independently but remain tethered close enough to each other for structural support.
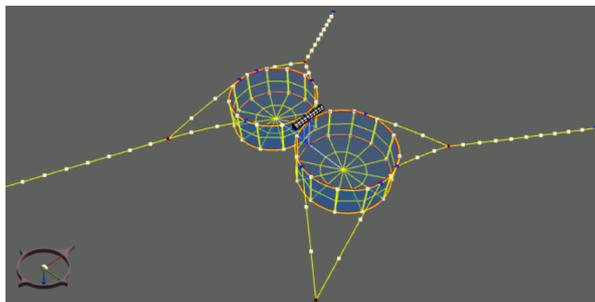

Figure H.3: Visualizer ProteusDS concept 2

Concept 3: Three-Cage Fish Farm

For Concept 3, the design was extended to a three-cage fish farm to further explore structural dynamics and mooring tensions. ProteusDS was again used, with the following steps:

1. The same approach from concept 2 was applied, but this time three cages were modeled. Each cage was outfitted with one pair of brittle lines and a mooring system.

2. A triangular setup was formed between the cages, using three rigid bodies. These rigid bodies were connected to the cages using 'RigidBodyRigidBodyABA' connections with revolute joints, allowing for rotational freedom while maintaining structural integrity (see Figure H.4.

3. To ensure the rigid bodies were attached securely to the float collars of the cages, 'RigidBody-ForceDCableForce' connections were employed. These connections provided the necessary force distribution to handle the environmental stresses on the system.

4. Again, the tension in the mooring lines was calculated at each time step during the rendering process.

This setup enabled the analysis of how the three-cage system, configured in a triangular formation, responded to the environmental forces.
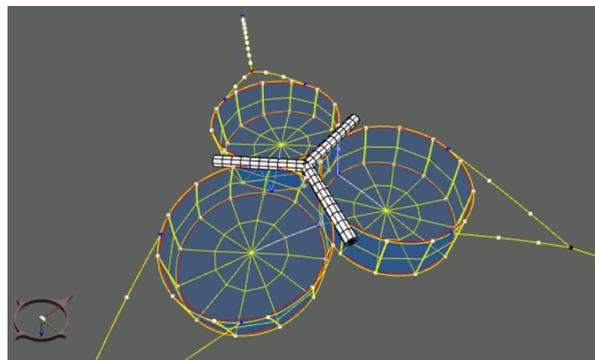
Figure H.4: Visualizer ProteusDS concept 3

H.2. Simulation and Render results

After designing the concepts in the software, the simulation toolbox generates high-quality renders of the structure, illustrating the dynamic behaviour of the offshore cage. These renders enable time-based simulations of mooring line tension. All files associated with the software, including the simulation models and environmental data, are available for download at:
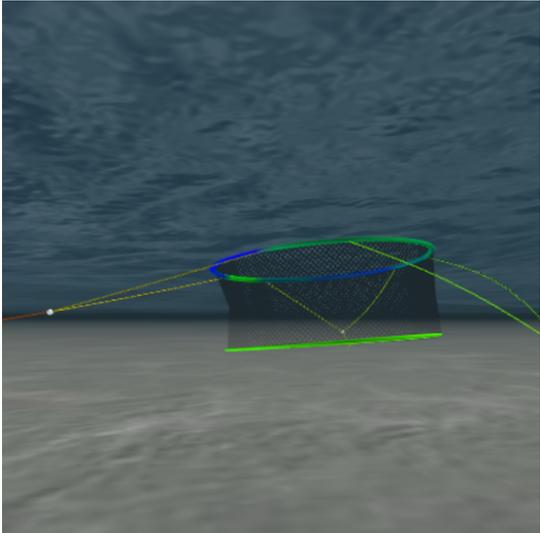
Google Drive folder with all files

This link provides access to every component necessary for replicating the simulation setup, enabling further analysis or customization
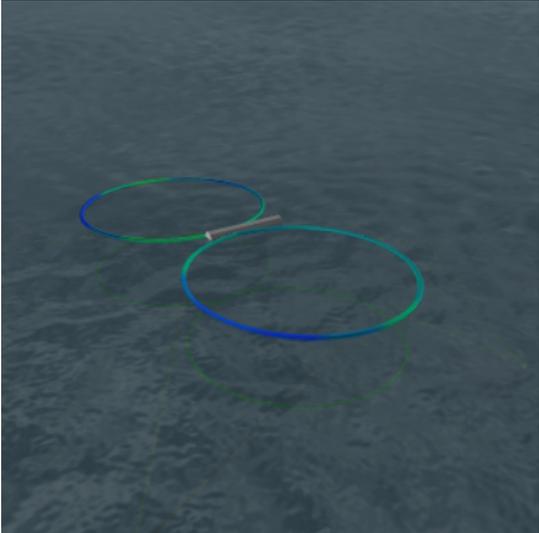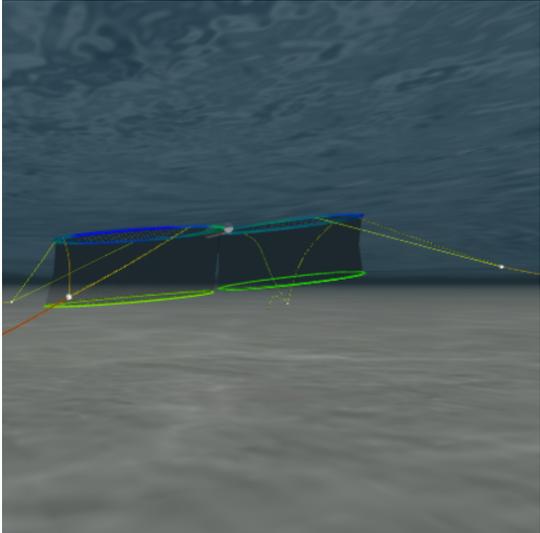
Time based render results
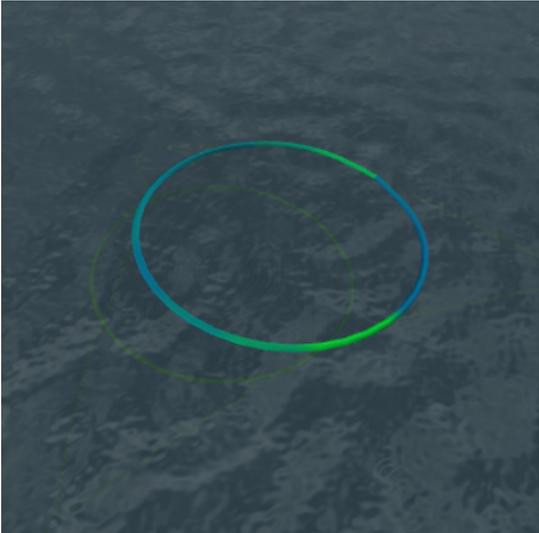
(a) Top View Render Result

(b) Side View Render Result

Figure H.5: Concept 1 Render Results: Tension illustrated in the object.

(a) Top View Render Result

(b) Side View Render Result

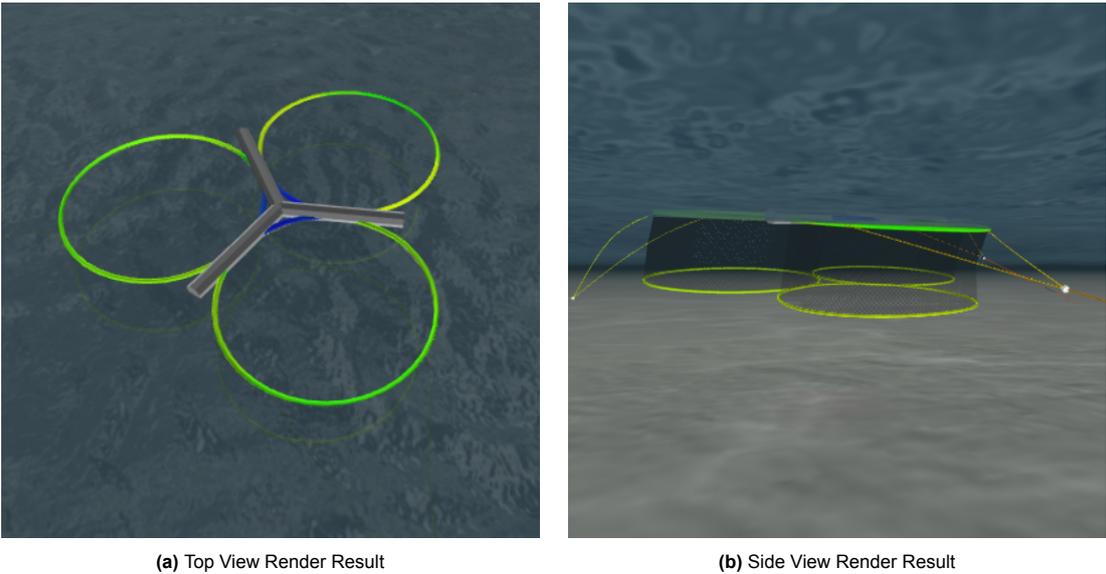**Figure H.6:** Concept 2 Render Results: Tension illustrated in the object.

(a) Top View Render Result

(b) Side View Render Result

Figure H.7: Concept 3 Render Results: Tension illustrated in the object.

Simulations mooring line tension
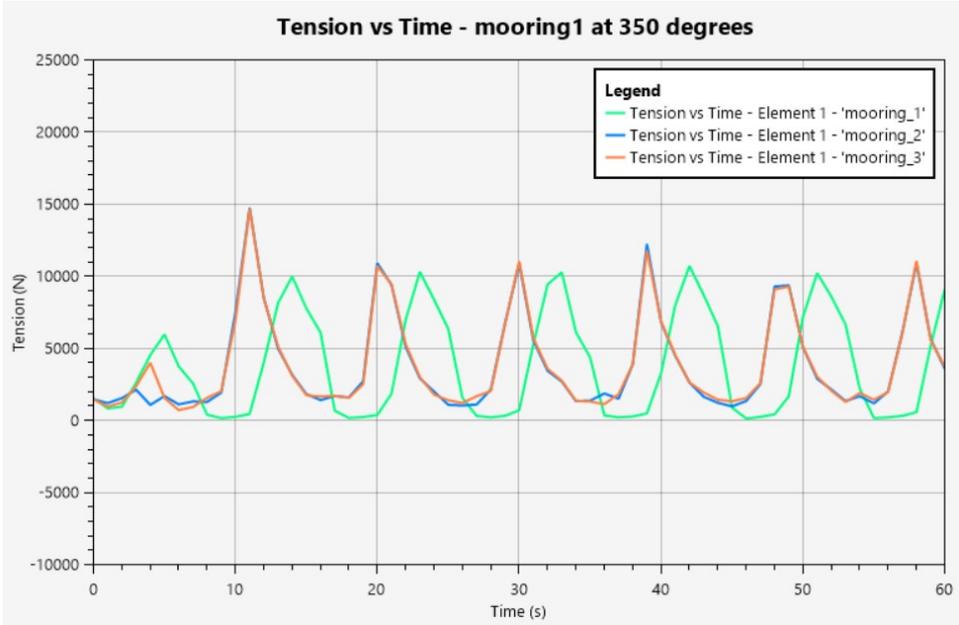
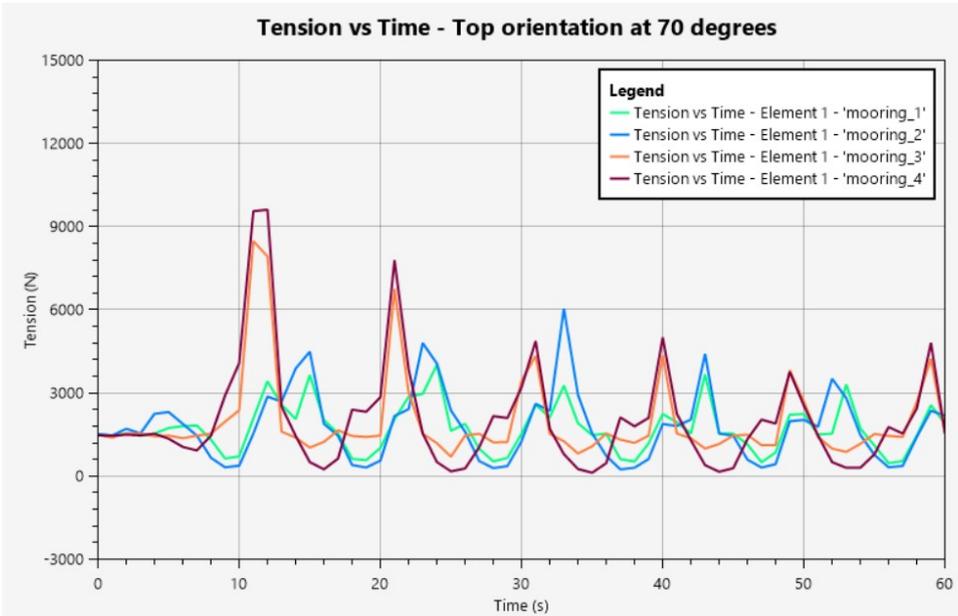**Figure H.8:** Full simulation results of Concept 1 with mooring line 1 pointing at 350 degrees

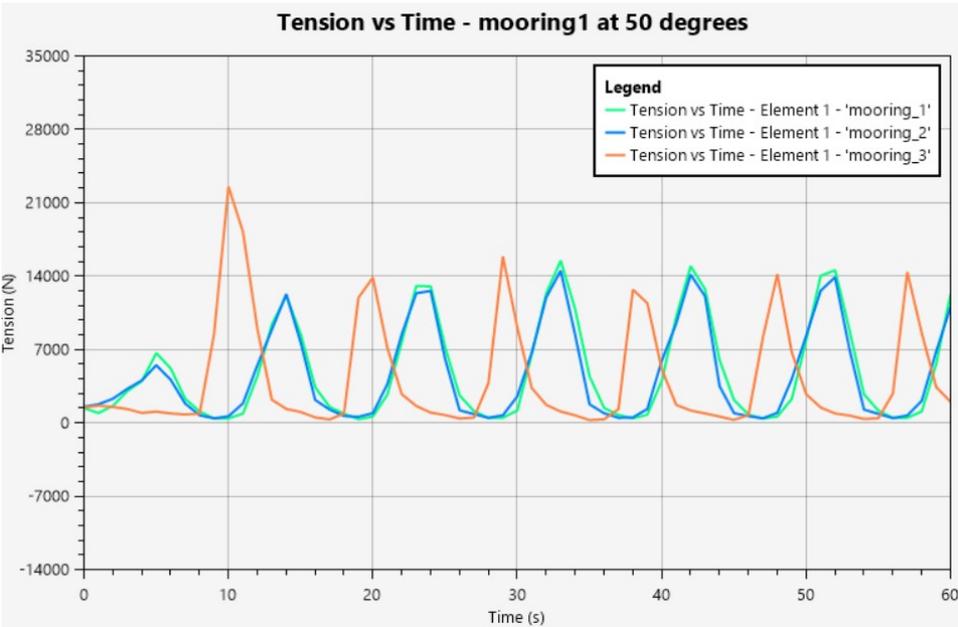**Figure H.9:** Full simulation results of Concept 2 with the top orientation pointing at 70 degrees

Figure H.10: Full simulation results of Concept 3 with mooring line 1 pointing at 50 degrees
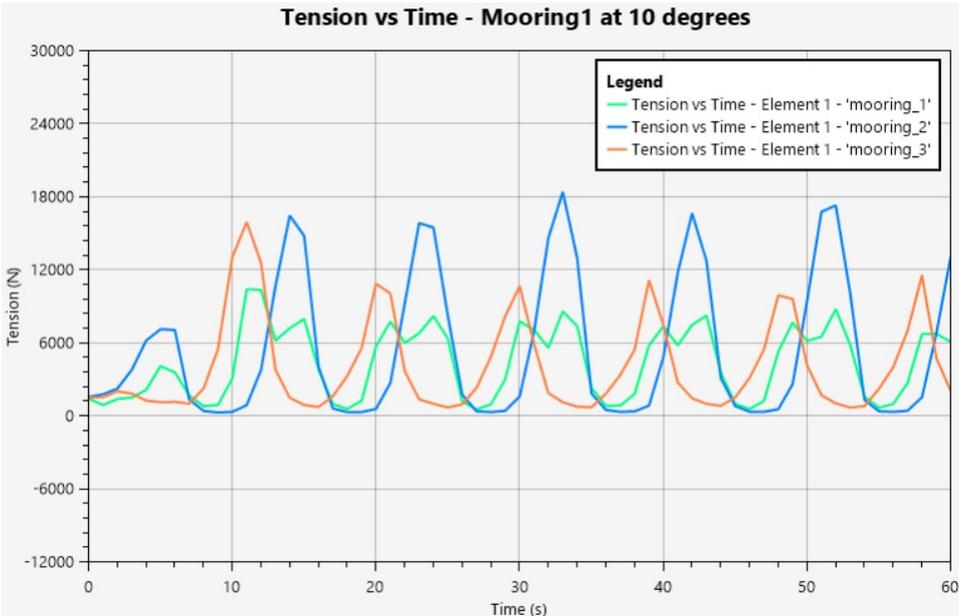
Figure H.11: Full simulation results of Concept 3 with mooring line 1 pointing at 10 degrees
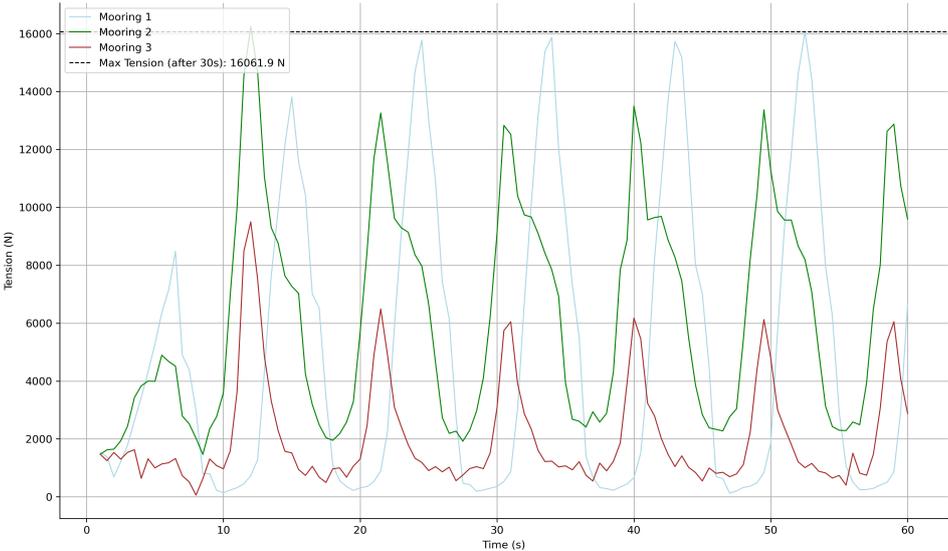
Optimized simulations

Figure H.12: Resulting tension in mooring lines of Concept 1, at optimal Load Orientation
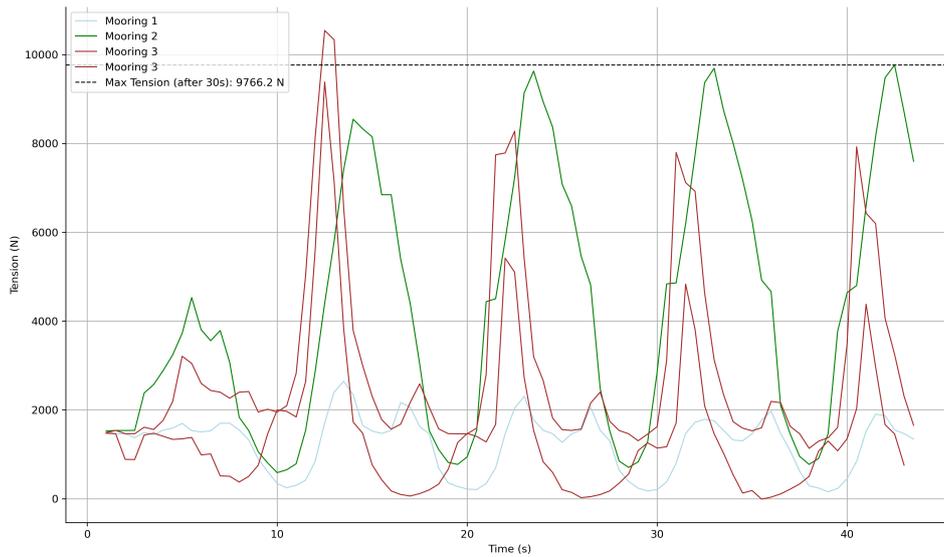
Figure H.13: Resulting tension in mooring lines of Concept 2, at optimal Load Orientation
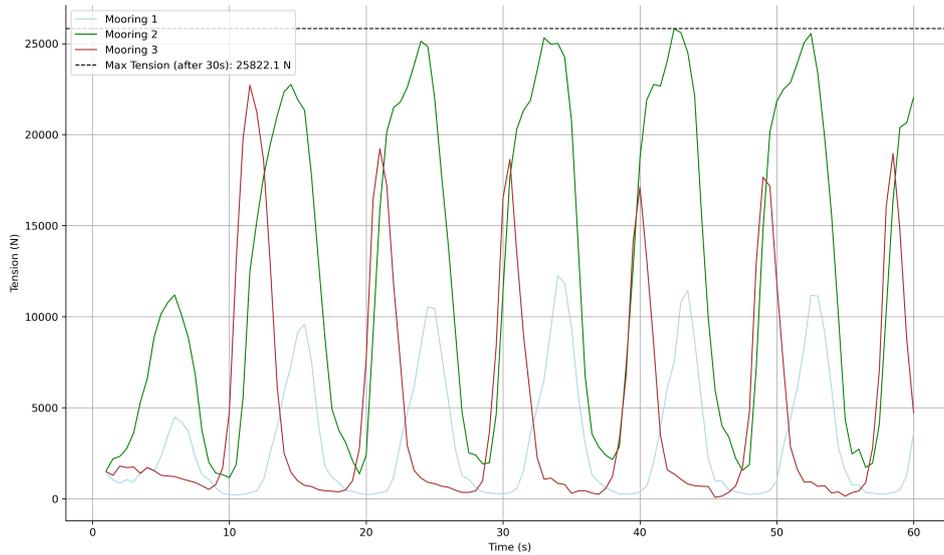

Figure H.14: Resulting tension in mooring lines of Concept 3, at optimal Load Orientation

H.3. Anchor design procedure

H.3.1. Ultimate Limit State (ULS) Design

Preliminary Design

Initial parameters & structural analysis

For the preliminary design, standard mechanical properties of concrete are used and the obtained mechanical elements from the system are: axial force, shear force, overturning moment and displacements.

Anchor weight

The initial anchor weight can be determined by formula **??** [56]:

$$W_{\mathsf{DWA}} = \frac{H_d}{\tan(\phi - 5°)} + V_d \qquad (\mathsf{H.1})$$

where:

- W_{DWA} is the anchor weight [kN]
- H_d is the design horizontal load [kN], is equal to $F_A \cos(\zeta)$
  - ζ is the angle between the anchor loading and a horizontal line.
- ϕ is the friction angle of the seabed [degrees]
- V_d is the design vertical load [kN], is equal to $F_A \sin(\zeta)$

Anchor width
If a square anchor without shear keys is assumed, the minimum width can be determined with:

$$B = \left[\frac{6W_{\text{DWA}}H_d}{\gamma_c(W_{\text{DWA}} - V_d)} \right]^{\frac{1}{3}} \tag{H.2}$$

where:

- B is the width of the anchor [m]
- γ_c is the concrete density [kN/m^3]

The maximum height, H_m, for the connection of the mooring line above the base of the anchor can be determined by [47]:

$$H_m = \frac{B(W_{\text{DWA}} - V_d)}{6H_d} \tag{H.3}$$

where:

- H_m is the maximum height of the mooring line connection [m]

The length of the cubical anchor required to achieve the specified weight can be calculated as:

$$L_{\text{DWA}} = \frac{W_{\text{DWA}}}{\gamma_c H_m B}$$

where:

- L_{DWA} is the length of the cubical anchor,

Overturning moment
The overturning moment of the structure, M_d, is determined based on the following equation [4]:

$$M_d = W_{\text{DWA}} \left(\frac{B}{2} \right) - V_d \left(\frac{B}{2} \right) - H_d H_{\text{DWA}} \tag{H.4}$$

Where:

- M_d is the overturning moment [kNm]

The load eccentricity, e, is determined using:

$$e = \frac{M_d}{V_d} \tag{H.5}$$

Where:

- e is the load eccentricity [m]

Geotechnical capacity
Bearing capacity
The geotechnical capacity of the structure can be determined using the DNV-OS-J101 offshore standard from [12]. The bearing capacity for drained conditions, because of the sandy seabed and we're considering long-term consolidated applications, can be obtained by:

$$Q_{\mathsf{RAGD}} = \frac{1}{2}\gamma_{\mathsf{soil}}b_{\mathsf{eff}}N_\gamma s_\gamma i_\gamma + p'N_q s_q i_q + c_d N_c s_c i_c \tag{H.6}$$

Where:

- Q_{RAGD} is the bearing capacity [kN]
- γ_{soil} is the soil unit weight [kN/m^3]
- b_{eff} is the effective width [m]
- N_γ, N_q, N_c are bearing capacity factors
- s_γ, s_q, s_c are shape factors
- i_γ, i_q, i_c are inclination factors
- p' is the effective overburden pressure at the level of the foundation-soil interface [kN/m^2]
- c_d is the design cohesion [kPa]

To determine the parameters needed for the bearing capacity, the effective width b_{eff} and the effective length l_{eff} must be calculated. The effective area is defined as:

$$A_{\mathsf{eff}} = b_{\mathsf{eff}} \cdot l_{\mathsf{eff}}$$

Depending on the eccentricity of the vertical load, two scenarios can be considered:

Scenario 1: Eccentricity with Respect to One Symmetry Axis
In this scenario, the load eccentricity is determined with respect to only one of the two symmetry axes of the foundation. The effective dimensions are calculated using the following expressions:

$$b_{\mathsf{eff}} = B - 2e$$
$$l_{\mathsf{eff}} = B$$

where B is the width of the anchor and e is the eccentricity of the vertical force. This scenario is applicable when the load is displaced along only one axis of the foundation, resulting in a rectangular effective area.

Scenario 2: Eccentricity with Respect to Both Symmetry Axes
In this scenario, the load eccentricity is determined with respect to both symmetry axes of the foundation. The effective dimensions are calculated using:

$$b_{\mathsf{eff}} = l_{\mathsf{eff}} = B - \sqrt{2}e$$

This scenario applies when the load is displaced diagonally from the center of the foundation, affecting both dimensions equally.

Additional Parameters for Bearing Capacity

After determining the effective area, the following parameters are needed to complete the bearing capacity formula. These parameters include design cohesion, load factors, shape factors, and inclination factors.

1. Design Cohesion: The design cohesion c_d is calculated as:

$$c_d = \frac{c}{\gamma_c}$$

2. Friction Angle for Drained Conditions: The friction angle ϕ_d for fully drained conditions is calculated by:

$$\phi_d = \arctan\left(\frac{\tan(\phi)}{\gamma_\phi}\right)$$

3. Load Factors: The load factors are determined by the following expressions:

$$N_q = \exp(\pi \tan \phi_d) \left[\frac{1 + \sin \phi_d}{1 - \sin \phi_d}\right]$$

$$N_c = (N_q - 1) \cot \phi_d$$

$$N_\gamma = \frac{3}{2}(N_q - 1) \tan \phi_d$$

4. Shape Factors: Shape factors account for the geometry of the anchor and are given by:

$$s_q = s_c = 1 - 0.2\frac{b_{\text{eff}}}{l_{\text{eff}}}$$

$$s_\gamma = 1 - 0.4\frac{b_{\text{eff}}}{l_{\text{eff}}}$$

5. Inclination Factors: Inclination factors account for the inclination of the applied load and are calculated as:

$$i_q = i_c = \left[1 - \frac{H_d}{V_d + A_{\text{eff}}c_d \cot \phi_d}\right]^2$$

$$i_\gamma = i_q^2$$

These parameters are necessary for completing the calculation of the bearing capacity in fully drained conditions, ensuring the anchor design is robust and capable of handling the applied loads.

Sliding capacity

The sliding capacity in drained conditions can be determined by:

$$Q_{\text{RLGD}} = (c_d A_{\text{eff}} + V_d \tan(\phi))\, \mu \tag{H.7}$$

Where:

- Q_{RLGD} is the sliding capacity [kN]
- A_{eff} is the effective area of the anchor base [m^2]
- μ is the friction coefficient

Design revision

The acting forces (V_d, H_d) must be less than the resistant axial and sliding forces (Q_{RAGD}, Q_{RLGD}). If not, the preliminary design is revised, and the design process is repeated.

Structural capacity

The structural capacity checks come from the ACI-standard for structural concrete [1], and can be determined by:

Axial capacity (structural)

$$Q_{\mathsf{RASD}} = 0.8 \left(\vartheta \sqrt{f_c'} \right) A_P \tag{H.8}$$

Where:

- Q_{RASD} is the axial capacity [kN]
- ϑ is a strength reduction factor, based on the type of concrete [1]
- f_c' is the concrete compressive strength [MPa]
- A_P is the cross-sectional area of the anchor (DWA) [m^2]

Sliding capacity

$$Q_{\mathsf{RSSD}} = \mu N_f = \mu \left[W_{\mathsf{DWA}} - V_d \right] \tag{H.9}$$

Where:

- Q_{RSSD} is the sliding capacity [kN]
- N_f is the normal force [kN]

Design revision

The resistant axial (Q_{RASD}) and lateral capacities (Q_{RLSD}) must not be exceeded by the design loads (V_d, H_d). If these conditions are not met, the structure's geometry must be revised, and the design process repeated. Additionally, sliding capacity should be checked ($Q_{\mathsf{RSSD}} \geq H_d$).

H.3.2. Application of Design Procedure

For each cage concept, analyze key results like total forces and anchor designs. Determine final design parameters, including anchor weight and dimensions. Balance cost, durability, and maintenance to meet environmental and operational requirements in Sisal. Select final designs for long-term stability and durability.

Results

Geotechnical and Structural Capacities						
Capacity Type	**Symbol**	**Concept 1**	**Concept 2**	**Concept 3**	**Unit**	**Formula**
Overturning moment	M_d	21,29	14,60	35,80	kNm	H.4
Geotechnical Capacities						
Axial capacity (geotechnical)	Q_{RAGD}	57.25	45.12	80,48	kN	H.6
Sliding capacity (geotechnical)	Q_{RLGD}	14.56	11.02	21,38	kN	H.7
Structural Capacities						
Axial capacity (structural)	Q_{RASD}	15.55	12.88	20,17	kN	H.8
Sliding capacity (structural)	Q_{RSSD}	35.24	26.55	52,02	kN	H.9

Table H.2: Summary of Geotechnical and Structural Capacities