Bachelor's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

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Enhancing Kelp Cultivation through Mechanical Innovation

Design, Development, and Evaluation of a User-Friendly Coupling Mechanism

Bachelor's thesis in Mechanical Engineering
Supervisor: Anna Olsen
Co-supervisor: Aurora Tung Nilsen
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Preface

Both authors of this thesis have a genuine interest in the blue economy and consider it an important field to explore, both academically and professionally, given the opportunities the ocean presents in addressing present and future challenges.

With backgrounds in chemistry and business administration prior to mechanical engineering, we decided early on that writing our bachelor's thesis on kelp cultivation would intersect our backgrounds, interests, and future prospects. Eager to nurture our interests and develop our engineering skills, we approached SINTEF Ocean to propose writing our bachelor's thesis on kelp cultivation, knowing they are at the forefront in this area.

We express our sincere gratitude to SINTEF Ocean for facilitating this project, enabling us to be part of the growing and intriguing emergence of a new industry that holds significant relevance for the future.

This thesis would not have been possible without the guidance and support of our mentor at SINTEF Ocean, Aurora Tung Nilsen, who proved to be an invaluable discussion partner and a constant source of constructive feedback throughout the various stages of the project.

We would also like to extend our thanks to our supervisor at NTNU, Associate Professor Anna Olsen, Programme Director for Bachelor of Engineering in Mechanical Engineering, for providing us with insightful feedback and guidance.

Abstract

Kelp cultivation has seen a surge in interest over the last decade. Given its potential use in areas such as CO_2 capture, material and food production, it is difficult to overstate its significance. Unfortunately, little research has been done on the subject of optimising facilities for kelp cultivation. The aim of this thesis is therefore to provide insight into the product development process of a mechanical clip on device for use in kelp cultivation. The thesis is part of a project in collaboration with SINTEF Ocean, describing the transformation of a market opportunity into a working prototype.

An examination of global cultivation methods and practices was undertaken to enhance our understanding of the industry's status quo. This review identified key factors for optimising kelp cultivation and offered invaluable insights into the technical requirements and user needs.

To navigate the design and development process in line with the project goals, we employed a systematic approach rooted in established theories and models in the product development field. The chosen methodology adopted a toolkit of strategies, which were tailored to suit the unique needs of each development stage. This toolkit encompassed user-centred design, frequent idea generation, prototyping, iterative development and testing, and also incorporated more traditional, sequential methods.

By adhering to the methods, the KelpClip eventually emerged as a promising solution, showing promise for both technical requirements and satisfying the outlined project goals.

Sammendrag

Kultivering av tare har hatt en enorm økning i interesse det siste tiåret. Potensielle bruksområder som CO_2-fangst, material- og matproduksjon gjør tare til en av de mest aktuelle marine ressursene vi har for øyeblikket. Det er derimot forsket lite på optimalisering av kultiveringsanleggene. Målet med denne oppgaven er derfor å gi innsikt i prossessen bak utviklingen av en klips-mekanisme for bruk innen tareoppdrett. Oppgaven er en del av et prosjekt som ble gjennomført i samarbeid med SINTEF Ocean og beskriver utviklingen fra markedsmulighet til funksjonell prototype.

For å få bedre forståelse av tareindustrien og dagens situasjon, utforsket vi de vanligste kultiveringsmetodene og identifiserte de viktigste momentene for å maksimere potensialet. Dette ga verdifull innsikt i de tekniske kravene, samt behovene til sluttbrukeren.

For å styre design- og utviklingsprossesen i samsvar med de overordnede prosjektmålene, ble det implementert en systematisk tilnærming. Denne bygger på allerede godt etablerte teorier og modeller om produktutvikling, og tar i bruk flere forskjellige metoder, som er tilpasset til den aktuelle fasen av prosjektet. I hovedsak ble det brukt metoder som brukerfokusert design, hyppig idégenerering, prototyping, iterativ utvikling og testing, men det ble også tatt i bruk mer typisk sekvensiell metodikk.

Ved å følge den nevnte metodikken, ble produktet ”the KelpClip” utviklet. Denne klipsen er en lovende løsning med tanke på de tekniske kravene og prosjektmålene.

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1 Introduction

This section provides an overview of the project, outlining its rationale, objectives and goals, assumptions and limitations, and the methodology employed. The purpose of this introduction is to establish the context and framework for the study and present a clear roadmap for the project's progression.

1.1 Background and Motivation

Kelp Cultivation and Its Importance

The harvest of wild kelp has been an essential part of coastal communities' livelihoods and culture for thousands of years (Pérez-Lloréns et al. 2020). In regions such as Europe, North America, and Asia, kelp was gathered from intertidal zones and shallow waters, where it was accessible during low tides (Mouritsen et al. 2021). The harvesting techniques varied depending on local traditions and available tools, but the practice generally involved cutting the kelp fronds without damaging the holdfast, allowing the seaweed to regrow. The advent of kelp cultivation can be traced back to ancient China and Japan, where rudimentary farming methods were initially employed to grow kelp for food and medicinal purposes (Pati et al. 2016).

Over time, as refining technologies advanced, the number of different applications for kelp-derived products increased. Because of kelp's high content of hydrocolloids, such as alginate, agar, and carrageenan , it has become a key component in a multitude of products we use every day, including gelatinous foods, medicine, and cosmetics to mention a few (Bixler and Porse 2011). As demand for these products grew in line with global trade, cultivation techniques also evolved and expanded, particularly in East and South-East Asian countries.

According to a report (*Seaweeds and microalgae* 2021) published by the Food and Agriculture Organisation of the United Nations (FAO), global seaweed production rose from 2.2 million tonnes (wet weight) in 1969 to 35.8 million tonnes in 2019, 50 years later, as displayed in figure 1.

Region	**Total production**	**Share of world production**	**Seaweed cultivation**	**Seaweed harvest**	**Share cultivated**
Asia	34,826,750	97.4%	34,513,223	313,527	99.1%
Americas	487,241	1.4%	22,856	464,385	4.7%
Europe	287,033	0.8%	11,125	275,908	3.9%
Africa	144,909	0.4%	117,791	27,118	81.3%
Oceania	16,572	0.0%	14,140	2,432	85.3%
World	**35,762,505**	**100.0%**	**34,679,135**	**1,083,370**	**97.0%**

Table 1: World seaweed production, 2019

This increase was primarily due to a rise in cultivation, which accounted for 97% of worldwide production in 2019, while wild harvest levels remained stable. The majority of this growth took place in Asia, which accounted for 97.4% of global production in 2019. In contrast, Europe and the Americas contributed only 2.2% of world production, with 4.4% of that being cultivated. This shift towards cultivation, driven by East and South-East Asian countries and increasing demand, can be seen as an "agricultural revolution" within the seaweed industry.

Opportunities and Benefits

In recent years, kelp farming has gained renewed attention due to its potential for mitigating the ongoing climate crisis. Kelp's ability to capture carbon and heavy metals from the ocean is particularly promising (Znad, Awual and Martini 2022). Research conducted by SINTEF estimates that a cultivation facility could capture approximately 3000 tonnes of CO_2 per square kilometre per year (Ask 2023).

Kelp cultivation not only has the potential to partially reverse environmental damage but can also serve as a more environmentally friendly alternative to fossil fuels. Kelp can be converted into biofuels, such as bioethanol, through various processes, including fermentation and anaerobic digestion (Adams, Gallagher and Donnison 2008). The use of kelp-derived biofuels could reduce greenhouse gas emissions and help achieve climate change mitigation goals (Farghali et al. 2023).

Furthermore, kelp can contribute to increased food security without competing for land area. As a highly nutritious and sustainable food source, kelp can be integrated into the human diet to a greater extent, providing essential vitamins, minerals, and dietary fibre (*Kelp Benefits* 2020). Kelp also offers a viable alternative to conventional animal feeds, as it is rich in proteins and essential nutrients (Peñalver et al. 2020). The cultivation of kelp can thus alleviate pressure on both agriculture and aquaculture and reduce the environmental footprint of food production.

Kelp can also efficiently absorb excess nutrients, such as nitrogen and phosphorus, from surrounding waters, helping to mitigate the effects of eutrophication and improve water quality (Tasoff 2023). This forms a symbiotic relationship in areas with intensive food production where nutrient pollution is a significant concern. An attempt at this can be seen in 1.

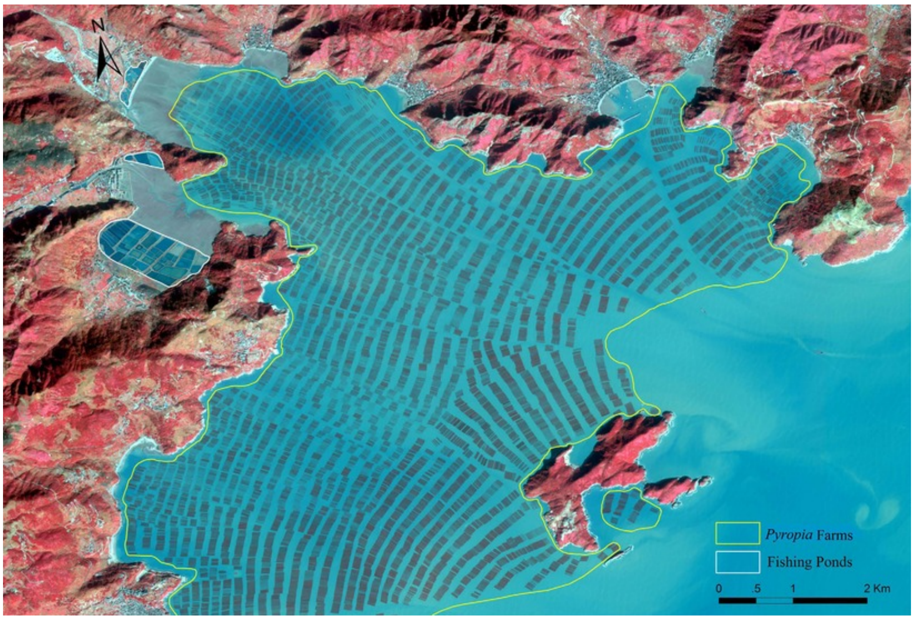


Figure 1: Satellite image of large scale kelp cultivation site in China, in an attempt to reduce eutrophication (Xiao et al. 2017).

Additionally, kelp cultivation can serve as artificial kelp forests, and can contribute to the restoration of marine ecosystems by providing habitat for various marine organisms and promoting biodiversity. Kelp forests can serve as nursery grounds for various marine organisms, supporting sustainable fisheries and enhancing overall marine health (Eger et al. 2022).

Kelp cultivation can also stimulate the blue economy by creating new job opportunities, or be utilised in the production of bioplastics, offering a sustainable alternative to petroleum-based plastics (SINTEF 2020).

In conclusion, kelp cultivation presents a wide array of opportunities and benefits, ranging from climate change mitigation and food security enhancement to the restoration of marine ecosystems and the development of sustainable industries. By embracing and advancing kelp cultivation, we can address multiple global challenges and work towards a more sustainable future.

Challenges and Bottlenecks

Despite kelp's promise and its widespread use, large-scale cultivation remains limited, particularly outside of Asia. One of the main bottlenecks is the high degree of manual labour involved in the process. The industry's heavy reliance on manual labour likely contributed to its boom in Asia, where there is easy access to shallow waters and affordable labour in addition to long traditions and cultural significance. However, the reliance on manual labour poses several challenges for the expansion of kelp cultivation in regions where labour costs are higher, such as in Western countries.

Figure 2: Manual labour in shallow waters, Indonesia (Farmer 2019).

For kelp cultivation to have a positive impact and enable western countries to be competitive in the industry, it must undergo an "industrial revolution". In other words, innovative solutions and technologies must be developed to increase efficiency and productivity, making large-scale cultivation economically viable where labour is more expensive or offshore farming is required. This includes developing automated and mechanised systems, establishing robust and scalable infrastructure, and reducing production and maintenance costs.

There are also several other major hindrances to achieving industrialisation, such as increasing market acceptance and growth by developing attractive consumer products and spreading awareness, supply chain optimisation that ensures stable and efficient flow of raw materials and finished products, improving processing of raw material, species selection and breeding, biotechnological advancements and genetic engineering, developing sustainable cultivation practices including responsible site selection, and developing regulatory frameworks for the emerging industry.

1.2 Project Goals and Objectives

Research Objective

In collaboration with SINTEF Ocean, this project aims to develop a novel mechanism for connecting lines or ropes used in kelp cultivation to overcome some of the challenges associated with manual labour and drive the "industrial revolution" of the industry. The project focuses on improving working conditions, increasing efficiency by reducing manual labour, and making large-scale production more accessible and cost-effective. Further, the project aims to contribute to the advancement of the kelp industry and promote further research and innovation. The process of cultivating kelp and the description of the cultivation facility are further explained in chapter 2.

Result Goals

To ensure the success of this project, several result goals have been established to guide the development process. These goals are specific, measurable, and considered achievable within the constraints explained in 1.3. The result goals are as follows:

Explore different approaches of cultivation: Establishing a basic understanding of the industry today and the different approaches towards cultivation. This should ideally include all main approaches to seaweed cultivation of industrial scale both locally and globally.

Design and model a multitude of concepts for basic testing: To get an overview over what is possible, it is important to research existing solutions and build upon these to match the application. By generating a wide range of concepts and assessing them against essential criteria, we can efficiently discern successful designs from those that fall short.

Choose a concept to develop further: By choosing one concept, it is easier for the project group to focus on details that may have been missed or ignored during the preliminary design process.

Develop realistic simulation parameters in compliance with project scope: The prototype will not be made from proper material. Therefore, it is crucial to define proper parameters for simulating the design virtually. Loadings and fixtures need to be made realistic and kept consistent between iterations to help optimising the design further.

Make functioning prototype: For usability testing as well as presentation purposes, a full scale model of the prototype should be made using cheap and easy to access production techniques.

Employ simulation and basic testing procedure to obtain final results: The final prototype should be tested for usability and run through the same simulation procedures as earlier iterations to afford accurate comparisons to previous designs.

Impact Goals

The project not only seeks to address immediate challenges within the industry, but also aims to achieve broader impact goals that can benefit various stakeholders. These goals encompass learning, fostering sustainable growth, and inspire future research and development in the kelp cultivation sector.

Enhancing engineering skills: By working on this project, the project group will gain valuable experience in product development, problem-solving, and the practical application of engineering principles. This hands-on experience will foster professional growth as engineers and innovators in the field.

Enabling industry growth: The development of the mechanism has the potential to contribute positively to kelp cultivation processes, making large-scale production more accessible and cost-effective. This innovation can contribute to the growth of the kelp industry, providing new economic opportunities.

Supporting sustainable development: By streamlining kelp cultivation and expanding its potential, this project can support the adoption of kelp as a sustainable alternative to fossil fuels, land-intensive agriculture, and other environmentally harmful practices. In doing so, the project will contribute to the global effort to combat climate change and promote sustainable development.

Inspiring future innovations: The insights gained from this project can serve as a catalyst for further research and development in the field of kelp cultivation. By demonstrating the feasibility and benefits of mechanisation, this thesis can inspire other researchers or entrepreneurs to explore new technologies and approaches that can advance the industry even further.

By achieving these impact goals, the project aims to leave a lasting and positive legacy that extends beyond the development of a single mechanism, fostering a more sustainable, innovative, and prosperous future for the kelp cultivation industry and those involved in it.

1.3 Project scope

Assumptions

Scalability: It is assumed that the developed mechanism can be effectively scaled up for use in large-scale kelp cultivation scenarios. The project's focus on efficiency and productivity may not fully account for the challenges associated with scaling the mechanism to commercial size.

Transferability of findings: The project assumes that the findings and recommendations from the thesis will be applicable to the development of related technologies and contribute to a broader understanding of mechanisation in the kelp industry. However, it is possible that some findings may be specific to the developed mechanism and may not be directly transferable to other contexts or applications.

Growthline modification: It was assumed that the growthline could be modified with an eye splice or a carbine hook at the end of the line.

Growthline reusability: It was assumed that the growthline could be reused for the expected lifetime of the mechanism.

Limitations

Schedule misalignment: The schedule for the thesis and the deployment and harvest of kelp does not align, which prevents testing the mechanism in a real cultivation scenario. This limitation may restrict the evaluation of the mechanism's performance and impact in a real-world setting, potentially affecting the project's ability to demonstrate its practical benefits.

Access to resources and expertise: The project may be limited by the availability of resources and expertise in specific areas, such as marine biology, materials science, or manufacturing. This limitation could affect the project's ability to fully address all aspects of the mechanism's development and evaluation, potentially leading to knowledge gaps or suboptimal design choices.

Environmental impact assessment: A comprehensive assessment of the mechanism's environmental impact, including its long-term effects on marine ecosystems and the life cycle assessment of its materials and production processes, may be beyond the scope of the thesis. This limitation could result in unforeseen environmental consequences or hinder the project's ability to accurately gauge its sustainability.

Connecting points: The project only concerns the connection between the longline and the growthline, not the growthline to the floating buoy.

1.4 Methodology & Thesis Structure

The development of the kelp cultivation mechanism follows a systematic and comprehensive approach, which includes several major milestones and primary activities. This structure ensures the project progresses efficiently and addresses each aspect of the mechanism's development.

- Literature review and industry analysis
- Methodological framework
- Requirements analysis and specification
- Concept generation and evaluation

- Detailed design and simulation
- Prototype development and testing
- Iteration and refinement
- Final design evaluation
- Discussion of key results
- Conclusion

Literature review and industry analysis: The project commences with a thorough review of existing research, products, and practices related to kelp cultivation. This foundational knowledge identifies gaps in current solutions and informs the new mechanism's development. It also fosters a comprehensive understanding of the user's needs, providing insight into cultivation practices.

Methodological framework: Before diving into requirement specification, the theoretical framework guiding the project is established. This includes a discussion of the product development theory adopted, the design approach to be used and the planned evaluation methods. This framework is key to aligning the project's approach with established engineering practices.

Requirement analysis and specification: Drawing on the literature review and industry analysis, the project group establishes specific requirements for the mechanism, such as user-friendliness, performance criteria, cost constraints, efficiency increases, and compatibility with existing kelp cultivation setups. These requirements are documented in a formal specification (see chapter 4).

Concept generation and evaluation: The team develops multiple conceptual designs for the mechanism, considering the previously defined requirements and specifications. These designs are assessed against the requirements, allowing selection of the most promising concept for further development.

Detailed design and simulation: The chosen concept undergoes a detailed design phase where all components and aspects of the mechanism are refined and optimised. Computer simulations evaluates the mechanism's performance under various conditions, identifying potential areas for improvement.

Prototype development and testing: The team constructs a functional prototype of the designs and tests them in controlled environments to validate its performance and ease of use. These tests offer valuable feedback on the design, revealing necessary modifications or improvements.

Iteration and refinement: Based on prototype testing and simulations results, the design undergoes further iterations and refinements, addressing identified issues or opportunities for improvement. This iterative process continues until the mechanism meets the project's result and impact goals.

Final design evaluation: Once the mechanism's design is finalised, a comprehensive evaluation is conducted. This assessment measures the mechanism's performance against the project's goals and requirements.

Discussion of key results: After the final evaluation, the key results and significant findings from the development process, prototype testing, and final evaluation are discussed. This section highlights the successes and challenges encountered throughout the project and provides a basis for future work.

Conclusion: This section encapsulates the entirety of the project, summarising the development journey of the kelp cultivation mechanism, the findings from the various stages of development and testing, and how it addresses the needs identified at the project's outset. The conclusion also identifies areas for future research and potential improvements.

By adhering to this methodology, the project systematically advances through the stages of development, ensuring a rigorous and efficient approach to designing, testing, and refining the kelp cultivation mechanism. It should, however, be noted that the actual progression of the project may be less linear than presented above.

2 Kelp Cultivation

2.1 Common Kelp Cultivation Methods

Kelp, a subspecies of seaweed, is a marine organism of remarkable versatility, celebrated for centuries for its nutritional, industrial, and ecological offerings (Pérez-Lloréns et al. 2020). The increasing global interest in seaweed farming emphasise the need for an in-depth understanding of various kelp cultivation techniques. These methods, which have been developed to account for the diversities in geographical locations, available resources, economic considerations, and target applications, include:

- Longline cultivation
- Raft cultivation
- Seabed cultivation
- Tank or pond cultivation
- Integrated Multi-Trophic Aquaculture (IMTA)

Each of these techniques presents unique features, benefits, and challenges, and they are amongst the most common methods, although there exists an array of variations and combinations.

The necessity to comprehend these kelp cultivation techniques is important for evaluating their adaptability in different scenarios, for leveraging their strengths, and for overcoming their limitations. This understanding fosters a platform for innovation, facilitating the optimisation of these techniques towards a sustainable, large-scale production of kelp. This section intends to provide a exploration of these widespread kelp cultivation methods. It delves into the practicalities of each method, their scalability, environmental impact, and economic feasibility, thus offering a comprehensive perspective on the current state of kelp farming practices.

Longline Cultivation

Longline cultivation is one of the most common methods employed in seaweed farming. This method involves attaching young kelp to vertical growthlines that are fastened to horizontal longlines, submerged beneath the water surface (Tullberg, Nguyen and Wang 2022). The longlines are tethered securely to an anchoring system and kept buoyant with the aid of flotation devices. The kelp is then allowed to grow naturally in the ocean environment, benefiting from the rich nutrients and sunlight that the open sea provides. An example on longline cultivation is displayed in figure 3.

Figure 3: Longline cultivatoin with partially mechanised harvest, Alaska (Rosen 2023).

One of the main advantages of the longline cultivation method lies in its flexibility. This method can adapt to a variety of water depths, enabling kelp farming in locations that may not be suitable for other cultivation methods.

Though the need for infrastructure is relatively low, consisting mostly of lines, floats, anchors and boats for setup and harvest, it can be complex due to the need for an efficient anchoring system to secure the longlines. This complexity may lead to higher initial costs in comparison to other methods. Nevertheless, once established, longline systems can be relatively easy to maintain, thus reducing the demand for labour-intensive tasks.

The scalability of longline cultivation is high due to its open-sea nature and relatively low infrastructure cost, which allows the expansion of the farming area horizontally across the ocean surface and vertically through the water column. The expected yield can be substantial, particularly in regions with nutrient-rich currents.

In terms of environmental impact, longline cultivation can have a low footprint if managed correctly. Although kelp farming provides benefits such as nutrient bioextraction and carbon sequestration, the longline method can potentially interfere with marine traffic, disrupt local ecosystems, and contribute to visual pollution. Moreover, longline kelp farms are at the mercy of ocean conditions. Factors such as harsh weather, temperature fluctuations, and ocean acidity can affect kelp health and yield.

The longline method's potential for industrialisation has been proven effective in large-scale operations, particularly in Asia where manual labour predominantly carries out the process. With the advancement of technologies such as automated seeding and harvesting systems, longline cultivation presents a viable option for industrial-scale kelp production in countries with high labour costs or where offshore cultivation is necessary.

Raft Cultivation

Raft cultivation, also referred to as floating cultivation, is a method extensively utilised in Asian countries (Chengkui 1984). This technique incorporates the use of raft structures, typically composed of tied-together wooden frames, that float on the water's surface. The kelp is attached to ropes or nets strung across these rafts, as illustrated in figure 4, or by suspending vertical lines from the raft into the water, where it can grow freely. This method is often used in sheltered bays and inlets where the water is calm and nutrient-rich.

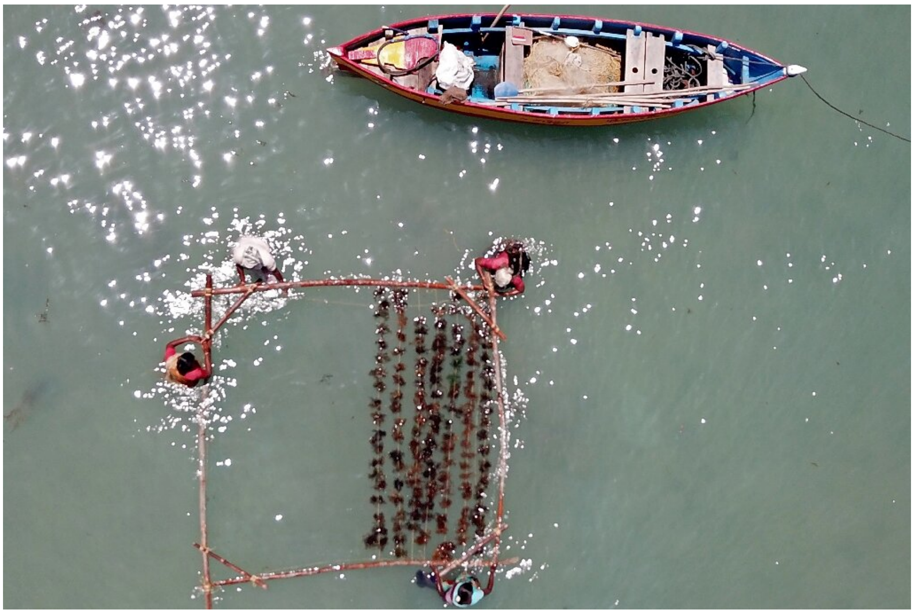


Figure 4: Raft cultivation in India, which has a 8,000-kilometre coastline (Srivastava 2023).

Raft cultivation, similar to longline cultivation, can adapt to different water depths and utilise the water column efficiently. In addition, it has the ability to be utilised in areas where traditional anchoring mechanisms might be problematic, making it well-suited for areas with shallow water and soft substrates, where anchoring longlines might be challenging.

The infrastructure for raft cultivation is more complex than the longline method due to the need for raft construction and maintenance and is highly dependent on the environment in which it will operate. Particularly rafts constructed with less robust materials are susceptible to damage from severe weather conditions and potent ocean currents. This vulnerability necessitates the development of raft structures with enhanced durability and the implementation of protective measures to safeguard against adverse weather conditions if the rafts are situated in unsheltered areas or offshore.

With these improvements, and the incorporation of automation and operational efficiency, raft cultivation could emerge as a viable option for large-scale offshore operations. Automation in raft cultivation is still in its infancy, with most tasks requiring manual labour as of now. Therefore, labour intensity can be quite high, especially during the harvesting phase. A high degree of automation will be necessary to justify the relative high cost of infrastructure with this method in areas with high cost of labour and the need for robust rafts.

The scalability of this method is comparable to longline cultivation, with the primary limitation being available suitable water space, but with an increased need for automated tasks to justify the elevated cost of infrastructure. The yield can similarly be significant, especially in nutrient-rich waters.

The environmental impact is also a concern for raft cultivation. While it shares similar benefits and concerns with the longline method, raft cultivation in sheltered areas might have a more pronounced impact on local ecosystems due to potential shading effects on the seabed. On the upside, these areas are often less exposed to harsh weather conditions, enhancing the resilience of the kelp farm. For offshore cultivation, the same considerations apply as with the longline method.

One of the most intriguing prospects of raft cultivation is the potential integration with renewable energy production, such as floating solar panels, as depicted in figure 5. This cohabitation would allow for the simultaneous cultivation of seaweed or other marine species beneath the solar panels, thereby increasing the productivity of the system while contributing to sustainability efforts. This concept, while still largely theoretical, could significantly enhance the economic viability and environmental benefits of raft cultivation in the future.

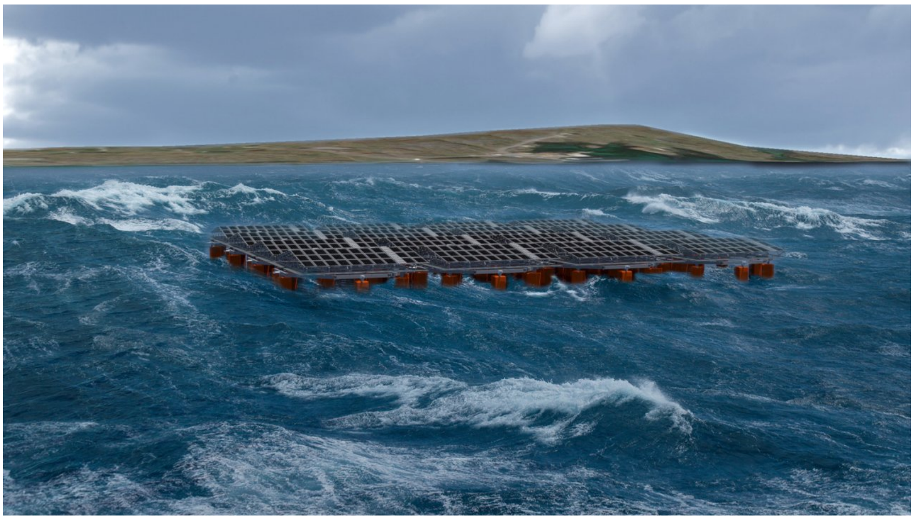


Figure 5: Floating solar plant proposed by Equinor (Equinor 2023).

In summary, while raft cultivation presents a high level of scalability and potentially high yields, it also comes with significant infrastructure requirements and requires a high degree of automation if the facility is situated in exposed areas with high cost of labour. However, the potential for integration with renewable energy production holds promising prospects for the future of this method.

Seabed Cultivation

Seabed cultivation is a low-tech and cost-effective method that involves the direct seeding of kelp spores onto substrates, such as rocks or artificial structures on the seafloor (Chengkui 1984). Predominantly employed in shallow coastal areas, it is a technique that has been practised for centuries, especially in regions like coastal Japan and China. As the seaweed grows directly on the substrate, it draws nutrients from the surrounding water, eventually growing large enough to be harvested by hand or using specialised tools. An illustration of seabed cultivation is depicted in figure 6.

Figure 6: Seabed cultivation, Zanzibar (Franz 2023).

Water depth is a critical determinant in seabed cultivation. It needs to be shallow enough for divers to reach the plants for planting and harvesting, yet deep enough to prevent the seaweed from being exposed during low tides. The optimal depth may vary based on the seaweed species and local tidal conditions.

Compared to other cultivation methods, seaweeds grown on the seafloor are naturally protected from extreme weather events, less susceptible to damage from waves and storms, while also reducing visual impact, as farming operations occur beneath the water surface, maintaining the natural aesthetic of the coastal landscape. However, the seaweed may be more vulnerable to changes in water quality or temperature, as well as potential damage from bottom-dwelling organisms or human activities. Additional challenges can stem from sedimentation, fouling organisms, and limited light availability, which could significantly impact the health and growth of the kelp.

Seabed cultivation's economic efficiency is one of its primary advantages. The minimal infrastructure requirements result in lower initial setup costs than other cultivation methods. However, its scalability can be limited due to the manual labour required for planting and harvesting, which can be intensive and potentially hazardous. Moreover, automation in seabed cultivation is limited, and the outlooks for automating this type of cultivation are a lot bleaker than with the two methods discussed prior. This is primarily due to the relatively low yield compared to the cost of implementing automated tools, which in this case would have to be some form of underwater drone, as there is no substantial infrastructure. It is also reasonable to assume that other more drastic methods of harvest, such as raking up the seabed, would inflict significant damage to the local ecosystem when being done on a regular basis.

Given its reliance on specific local conditions and the labour-intensive nature of operations, seabed cultivation may not be the optimal choice for larger, commercial operations seeking to industrialise kelp production, and it's certainly not feasible in offshore environments. However, for smaller-scale farming or ecological restoration projects, this method offers a cost-effective and environmentally friendly solution.

Tank or Pond Cultivation

Tank or pond cultivation is a land-based approach to seaweed farming, distinguished by its ability to provide a controlled environment for seaweed growth (Andersen 2005). This method, depicted in figures 7 and 8, entails the cultivation of seaweed in constructed tanks or ponds, which can be either open-air or enclosed. Such setups typically employ pumped or flowing seawater to supply necessary nutrients to the seaweed.

Figure 7: Tank cultivation by Monterey Bay Seaweeds (Fehrenbacher 2017)

Figure 8: Pond cultivation, Queensland (Norwood 2022)

Although the ability to regulate environmental factors such as water temperature, nutrient concentration, and light exposure can significantly augment growth rates, yield, and quality, the maintenance of these optimal conditions can be energy and resource-intensive, escalating operating costs. Moreover, the infrastructural demands for tank or pond cultivation considerably exceed those of other methods, necessitating substantial investment for the construction of tanks or ponds, water supply and treatment systems, and possibly temperature-controlling greenhouse structures.

Another potential constraint of tank or pond cultivation systems is their substantial spatial requirements. Such systems typically necessitate considerable land area for the infrastructure installation, which not only inflates setup costs but could also cause potential conflicts with other land uses.

However, tank or pond cultivation presents substantial opportunities for automation. The controlled environment and land-based nature of these systems permit the integration of automated monitoring and control systems, thereby reducing labour intensity and enhancing efficiency. Tasks like nutrient dosing, water exchange, temperature control, and even harvesting can be automated using sensors, pumps, and computer-controlled systems.

Given their designed resilience to adverse weather and water quality fluctuations, these cultivation systems are less susceptible to environmental conditions. The controlled nature of these systems also allows for the prevention of nutrient leakage and the minimisation of other potential environmental impacts, although careful management of water and energy use is imperative for sustainability. Nonetheless, it is important to note that the absence of the symbiotic relationships inherent in kelp's natural ocean environment in these land-based cultivation systems could potentially affect the health and productivity of the kelp and its surroundings.

While tank or pond cultivation presents promising prospects for automation and good yields, its scalability is limited by the high operational and infrastructural costs, as well as competition for land area. This is particularly significant when considering the cost-effectiveness of cultivating kelp, which typically commands a low market value. Despite these challenges, land-based cultivation could serve as an effective strategy for cultivating high-value species, such as wakame or dulse, or genetically modified kelp species engineered for enhanced protein content, increased hydrocolloid levels, or other desirable traits. Given that these land-based cultivation systems can prevent the unintentional release of these genetically modified species into the wild, they could provide a safe and controlled platform for the growth of these genetically enhanced species, contributing to advancements in aquaculture and marine biotechnology.

Integrated Multi-Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) is a more advanced cultivation method that combines the farming of multiple, complementary aquatic species in the same system (García-Poza et al. 2020). This arrangement allows waste products from one species to serve as nutrients for another, fostering a balanced, sustainable ecosystem that enhances the system's overall productivity. IMTA, depicted in figure 9, can be implemented in both land-based and offshore settings.

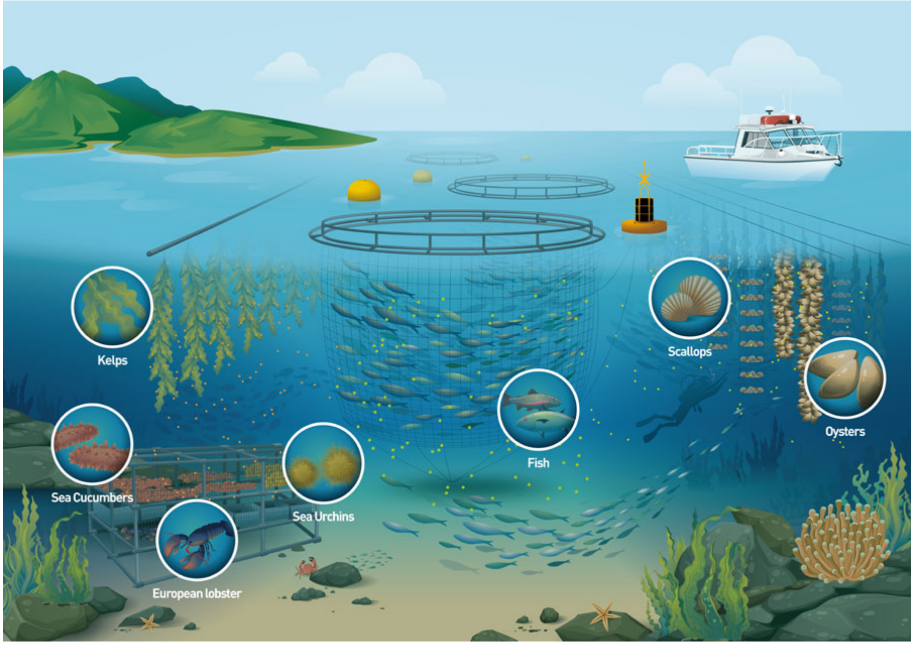


Figure 9: An illustration of the IMTA concept proposed by the Marine Institute in Ireland (Foras Na Mara Marine Institute 2023)

The infrastructural requirements for an IMTA system can be substantial and can greatly vary based on the species being cultivated, as well as local conditions and regulations. For infrastructure concerning kelp cultivation in such a system, the same requirements mentioned under each respective method is still hold true, with the addition of considerations regarding the interactions between different species. The decision on which kelp cultivation method to implement also depends on whether kelp cultivation was incorporated in the system's design or is being added to an existing cultivation facility, and whether the seaweed is the central focus or serves to bolster other more valuable species.

The yield from IMTA systems can be considerably high due to the cultivation of multiple species, while the quality of the produce is dependent upon the system's balance and management. Generally, the labour intensity for IMTA systems exceeds that of monoculture systems, given the need to manage and harvest multiple species. However, the higher yields and potential profits from the multitude of species can counterbalance these costs. While certain tasks can be automated, like feeding and water quality monitoring, the complexity of these systems often necessitates significant human oversight and intervention. Additionally, the intricacy of managing multiple species and their interactions may restrict the size and expansion of these systems, thereby limiting the scalability of this method.

Typically, the environmental impact of IMTA systems is less than that of monoculture systems. By emulating natural ecosystems, these systems can more efficiently utilise waste, reducing the need for external inputs and mitigating potential nutrient pollution. Nonetheless, it's crucial to maintain a well-balanced system to prevent any one species from outcompeting the others, which could lead to ecological imbalance.

In summary, IMTA systems offer numerous advantages. They can augment the productivity and economic viability of aquaculture operations by offering multiple sources of revenue. Additionally, they have the potential to reduce environmental impact by recycling waste products within the system, thus diminishing nutrient pollution in surrounding waters. However, IMTA systems also present certain challenges. They necessitate a sophisticated understanding of the biological interactions among multiple species and require careful management to uphold balance within the system. Despite these challenges, IMTA represents a potentially sustainable and efficient approach to kelp cultivation, marking it as a promising avenue for future research and development in the field.

Comparative Evaluation of Kelp Cultivation Methods

Identifying viable methods for large-scale cultivation is pivotal for the growth of the industry. This discussion compares and contrasts the five major kelp cultivation methods elaborated on in previous sections, focusing on their suitability for large-scale offshore farming. Each method presents unique advantages and challenges in terms of scalability, adaptability, productivity, and sustainability. Understanding these factors is critical in determining the most effective method to maximise the potential of kelp cultivation in offshore environments.

Longline Cultivation: This method is scalable, adaptable to offshore environments, and one of the most productive. Opportunities for automation can help to reduce labour costs and increase efficiency. However, its implementation requires careful consideration of the site's physical characteristics and environmental conditions, such as depth, currents, and wave action. It also needs substantial infrastructure, and the exposed longlines might be vulnerable to damage during extreme weather events.

Raft Cultivation: Raft cultivation offers high biomass yield in a relatively small area, making it suitable for high-density farming in near-shore environments. It also allows easy access for manual harvesting. However, its scalability in offshore conditions is limited, and it's prone to weather-induced damage due to its surface positioning. The raft structures can also present navigational hazards and may cause visual pollution.

Seabed Cultivation: Seabed cultivation is a low-tech, cost-effective method predominantly practiced in shallow coastal areas. While it offers natural protection against weather events, its scalability is limited due to the manual labour required, and it may be vulnerable to changes in water quality or temperature. This method is unlikely to be viable for large-scale offshore cultivation.

Tank or Pond Cultivation: This land-based approach can enhance yield and quality by providing a controlled environment for seaweed growth. It also presents substantial opportunities for automation. However, its infrastructural and operational costs are high, and it necessitates considerable land area. This method is unsuitable for offshore environments.

Integrated Multi-Trophic Aquaculture (IMTA): IMTA fosters a sustainable ecosystem that enhances overall productivity by cultivating multiple complementary aquatic species. This method presents multiple revenue sources and reduces environmental impact by recycling waste. However, the complexity of managing multiple species and their interactions may limit its scalability. While possible in offshore settings, IMTA systems require significant planning, understanding, and management.

For large-scale cultivation in an offshore environment, longline cultivation stands out as the most viable method due to its scalability, adaptability, and productivity. It allows for high-density planting of kelp, has potential for automation, and is proven to work well in offshore environments. However, successful implementation would require careful site selection and robust infrastructure to withstand potential environmental stressors. If the complexity of managing multiple species in an offshore setting can be effectively addressed, IMTA systems incorporating longline kelp cultivation could offer a promising sustainable and productive alternative. The same can be true for raft cultivation, but in this scenario, the kelp would be added value rather than the primary objective.

2.2 SINTEF Ocean's Cultivation Facility

As previously stated in this chapter, the longline method is a frequently employed technique for cultivating kelp, especially in large-scale operations situated in offshore environments. This reasoning underpins why SINTEF Ocean opted to utilise this method and further refine it, in conjunction with addressing the challenges and bottlenecks highlighted in 1.1. Prior to delving into a more detailed description of the process from collecting reproductive spores to harvest, it is advantageous to first describe the structure of the cultivation facility.

An illustration of the cultivation facility used for this project is depicted in figure 10. The longline is situated 10 metres below sea level, tethered to mooring lines at each end. The growthlines are subsequently also 10 metres long, attached to the longline at one end and individual floating buoys at the other. The growthlines are evenly distributed with approximately 1.5-2 metres of free space between each line. Proper spacing is vital to ensure the plants receive sufficient sunlight for growth and to minimise the risk of the lines becoming entangled. The system is then expanded into parallels to make up the three dimensional space.

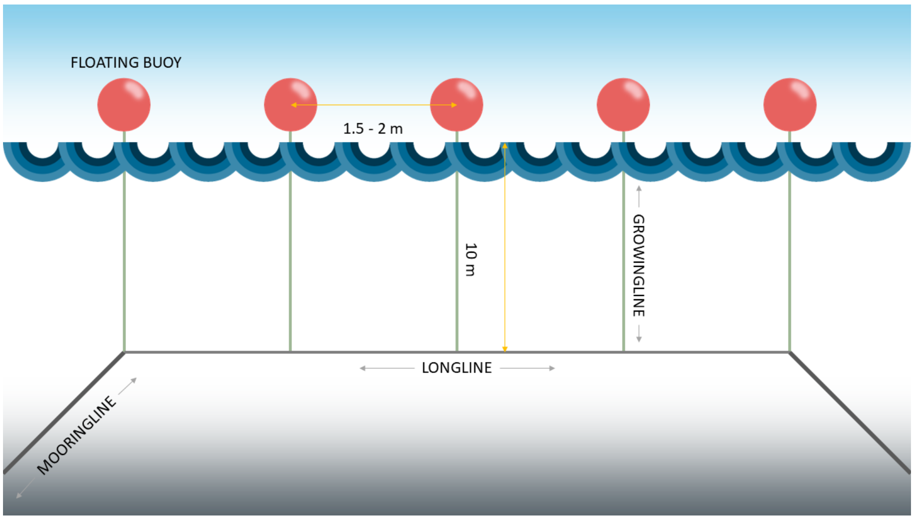


Figure 10: Illustration of the cultivation facility used in this project

All connections involving lines are, as previously implied, bound by hand. The need for more efficient methods becomes evident, considering this facility consists of about 8,000 growthlines. Even at this scale, it is still for research purposes, and it can be reasonably assumed that a commercially viable large scale cultivation facility, subjected to the market, might consist of several thousands more lines.

2.3 Kelp Cultivation Process Using the Longline Method

Given the relevance of the longline method, and it being the starting point of this project, this particular process will be elaborated in more depth. There is no industry official standard, but most technology-reliant cultivation sites researched in this project have had a similar processes. Furthermore, the process is also applicable for other cultivation methods than the longline method. For the description of the process, most information is based on two detailed publications made by the University of Connecticut (Redmond et al. 2014) and Ocean Approved (K. Flavin, N. Flavin and Flahive 2013), as well as information acquired from SINTEF Ocean and a prior excursion to Hortimare's testing facility north of Bergen. The process involves several steps and has in this project been divided into six stages:

Collection of reproductive tissue: The first step in the kelp cultivation process involves harvesting mature kelp with reproductive tissue, also known as sori, from wild populations or existing kelp farms.

Propagation and seeding: The sori contain the spores necessary for the propagation of new kelp plants. The harvested reproductive tissue is then treated to induce spore release, typically by immersing it in seawater under specific conditions. The released spores are subsequently seeded onto suitable substrates, such as twine or a spool.

Incubation: The seeded substrates are incubated in a controlled environment, such as land-based tanks or nurseries, to promote sporeling development. During this stage, optimal light, temperature, and nutrient conditions are maintained to ensure healthy growth.

Figure 11: Incubation chamber, Hortimare

Figure 12: Sporelings, Hortimare

Deployment of kelpings at cultivation facility: Once the sporelings have developed into small kelp plants, also known as kelpings, they are transferred to the cultivation facility for further growth. This transfer is done manually, transfering each seeded spool to a growthline before tying the growthline to the longline system. The current state of this process represents a major bottleneck in the production chain, limiting the scalability of kelp farming operations. The development of this mechanism represents an effort toward making kelp farming a more efficient, profitable, and sustainable enterprise.

Operating and monitoring: The kelpings are left to grow in the ocean for several months, depending on the species and local conditions. During this period, the kelp farm is regularly monitored to check the health of the kelp and identify any potential issues, such as fouling organisms, storms, or equipment failure.

Figure 13: Visual inspection at Hortimare's testing facility

Harvest and processing: Once the kelp has reached its desired size, it is harvested. This can be done manually or with the help of mechanised equipment, such as cranes or boats. The same bottleneck as mentioned in the deployment stage also holds true for the harvest stage, where all the growthlines previously tied to the longline, has to be untied. The harvested kelp is then transported to processing facilities where it is cleaned, dried, and processed into various products.

Preparation for next cycle: After the harvest, the cultivation facility is prepared for the next cultivation cycle. This involves cleaning and repairing any damaged equipment, re-seeding new spools, and repeating the process from the beginning.

In summary, the longline method of kelp cultivation involves a series of steps from collection of reproductive tissue to the harvest of mature kelp. While this method has proven effective for large-scale kelp farming, ongoing research and development are needed to improve efficiency, reduce labour requirements, and ensure the sustainability of kelp cultivation at larger scales, especially during the deployment and harvesting stages.

3 Method

This chapter aims to explain the methods used to guide the design and development of the product, drawing upon established theories and models in product development. It provides a detailed account of our design process, which encompasses elements such as understanding the user perspective, defining core challenges, generating and refining ideas and concepts, as well as prototyping.

The chapter also outlines the approaches and tools utilised for evaluating the design's effectiveness, including computer simulations. Further, it explicates key design considerations, including material selection and production method.

By providing a transparent and thorough account of the methods adopted, this chapter serves to demonstrate the rigorous approach taken in our research, design, and evaluation processes. The chapter is structured according to the distinct stages of the product development process, making it easier for readers to understand the progression of the project and the rationale behind our decisions at each stage. Moreover, this structure enables us to highlight how various product development theories and models were employed and adapted to our specific context. This flexible, hybrid approach to product development, which combines elements of classic and contemporary theories, is a key aspect of our methods and is discussed in more detail in the following sections.

3.1 Product Development Theories & Methods

Product Development (PD) is often described as the transformation of a market opportunity or problem into a commercial product (Ulrich and Eppinger 2016). This transformation process is typically broken down into distinct phases to ensure a systematic and effective approach (Cooper 1990; Ulrich and Eppinger 2016).

Historically, several influential PD models and methodologies have been introduced, such as the Stage-Gate model by Cooper (Cooper 1990) and the Spiral model by Boehm (A. Brown n.d.). These models emphasize a structured, sequential approach and iterative development, respectively. Furthermore, Ulrich and Eppinger's work (Ulrich and Eppinger 2016) presents a comprehensive model of the PD process, stressing the role of risk management, stakeholder communication, and iterative refinement.

In recent times, methodologies focusing on flexibility, iteration, and user involvement have gained prominence. Agile development methodologies (*Principles behind the Agile Manifesto* 2023) and Lean Product Development (Khan et al. 2011) endorse adaptive planning, evolutionary development, and waste reduction. Simultaneously, Design Thinking (T. Brown 2008) has introduced a human-centered approach to innovation, emphasising empathy with the user and the iterative process of ideation, prototyping, and testing.

While not strictly adhering to any one model, our project has implicitly drawn upon elements of these theories, shaping our PD process in response to the particular demands of our project. We began with a form of a fuzzy front-end process, involving idea generation and concept refinement (Elverum and Welo 2014; Stevens 2014), which bears similarities to the user-centered and iterative approaches suggested by Design Thinking and Agile methodologies. As the project progressed, we found the need for structured evaluation and decision-making, akin to aspects of the Stage-Gate model. Therefore, these theories serve as an underlying framework, providing a toolkit of approaches adaptable to the project's specific requirements and stages.

3.2 Design Approach

One of the most important features of the product is that it should be easy to use and require little to no training. To develop a user-friendly product, we considered the principles of design thinking to be a great starting point. Design thinking is a human-centred approach to the design process, that focuses on understanding the needs and perspectives of the people who will use the product, and using that understanding to create solutions that meet their needs (Razzouk and Shute 2012). The key to design thinking is to keep the user at the centre of the process, and to iterate and refine solutions based on their feedback and needs (Verganti, Dell'Era and Swan 2021).

User Perspective

The first step naturally involves acquiring the user's perspective, and there are several ways to do this. Ideally, direct observation of the workers deploying growthlines would have provided invaluable insights. We had initially planned to visit the SINTEF Ocean's cultivation facility at Frøya in Trøndelag, Norway for this purpose. However, this plan was reconsidered due to two primary reasons. Firstly, the time schedules for kelp deployment at the cultivation facility did not align with this project's timeline. As a result, such an excursion would lean more towards novelty than towards the acquisition of valuable information. Although an excursion would undoubtedly have *some* value, the justification for the long travel, cost, and expected outcome fell short. Additionally, the workforce deploying the growthlines mainly consists of seasonal workers, reducing the number of available interviewees.

Given these circumstances, we had to seek alternative methods to understand user needs. One significant way we achieved this was through the comprehensive review of common kelp cultivation methods detailed in section 2.1 as well as the information gathered regarding the kelp cultivation process using the longline method detailed in section 2.3. This review served to familiarise us with the user environment and the specific tasks performed by the workers, thereby helping us gain an empathetic understanding of the user perspective.

In addition to this, engaging in conversations with individuals possessing the knowledge we sought proved to be the best alternative to first-hand observation and interviews. Regular meetings with our supervisor at SINTEF Ocean provided a wealth of insight into important aspects to consider, especially in the early idea generation phase.

Furthermore, one of the authors of this paper has previously visited another cultivation facility north of Bergen. This facility, owned and operated by Hortimare, specializes in supplying high-quality seedlings of *Saccharina Latissima* and *Alaria Esculenta.* The visit provided significant insight, offering a walkthrough of the entire process detailed in 2.3, as well as firsthand observation of the cultivation facility and employees performing various tasks, such as inspecting the kelp.

Defining Core Challenges

Having gained a comprehensive understanding of both the user perspective and the kelp cultivation process, we moved forward to pinpoint and define the primary challenges involved in the task of securely connecting the growthline to the longline.

The initial challenge is tied to the labour-intensive nature of the prevailing cultivation methods. As expounded upon in section 2.3, the manual method of attaching each growthline not only requires substantial time and effort, but is also physically demanding of the workers. This raises concerns not only for worker welfare, but also impacts the overall efficiency and potential scalability of the operations.

For large-scale operations to be viable, substantial enhancements in productivity are essential. Thus, there is a pressing need for innovative approaches that can revamp the kelp cultivation process, aiming for a system that is more efficient and demands less labour.

The complexity inherent in the product development process presents a further challenge. As detailed in this chapter and section 4 on product requirements, developing a mechanism to secure the growthline efficiently and reliably was a multifaceted task. Striking the right balance between functionality, user-friendliness, durability, and cost-effectiveness necessitated several rounds of iteration and adaptation.

These connections need to endure diverse environmental conditions, ranging from powerful currents and storms to the corrosive effects of the marine environment. A failure in these connections could have serious consequences, from crop and revenue losses to the generation of marine debris.

Idea Generation

The idea generation phase commenced once we had a thorough understanding of the user perspective and the core challenges associated with connecting vertical growthlines to the horizontal longline. We employed a variety of techniques to stimulate creativity and encourage a wide range of ideas. These included brainstorming sessions, mind mapping, and frequent discussion session both internally in the group as well as with our supervisor at SINTEF Ocean.

During the brainstorming sessions, the group members were encouraged to share their thoughts freely, without fear of judgement. We found this to be a particularly effective method for generating a large number of ideas in a short amount of time. One rule we adhered to during these sessions was to refrain from immediately critiquing or analysing the ideas. This was to ensure that creativity was not stifled and that a wide range of ideas could be explored. Sketches from the early idea generation phase and through the whole development phase are found in appendix B.

Mind mapping was another technique that we utilised. This involved visually organising information, starting with a central concept (in this case, connecting vertical growthlines to the horizontal longline) and branching out to related sub-topics or ideas. Mind mapping helped us to see the connections between different ideas and to organise our thoughts in a clear and logical manner. Mind maps from the project are found in appendix C.

The goal of the idea generation phase was not to come up with a perfect solution immediately, but rather to explore a wide range of possibilities. Once we had a list of potential solutions, we could then proceed to the concept generation phase, where we would further refine and develop our ideas.

Concept Generation

Following the idea generation phase, the group moved into the concept generation phase. The focus in this phase shifted from quantity of ideas to quality, with an emphasis on developing, refining, and assessing the feasibility of the ideas generated in the previous stage.

The first step in this phase was to review all the ideas that had been generated and to select the most promising ones for further development. We used a variety of criteria to evaluate the ideas, including their potential effectiveness in addressing the core challenges, their feasibility given the resources and technology available, and their compatibility with the requirements and constraints identified in the user perspective and core challenge definition phases.

Once we had selected the most promising ideas, we began to develop these into more detailed concepts. This involved fleshing out the specifics of each idea, such as how it would work in practice, what materials and technologies would be needed, and how it would be used by the workers in the kelp cultivation process. We also considered potential issues or challenges that might arise with each concept, and brainstormed ways to mitigate these.

During this phase, we made extensive use of sketches to help visualise the concepts and to communicate the ideas more effectively. We also used digital tools such as CAD (Computer-Aided Design) software, more specifically Fusion 360 by Autodesk, to create more detailed and precise 3D-models of our concepts.

The concept generation phase was iterative, meaning that we went through multiple rounds of development and refinement based on feedback and new insights. This allowed us to continuously improve our concepts and to adapt them to new information or changes in the project requirements. At the end of this phase, we had a set of well-developed concepts ready for further refinement and prototyping.

Design Refinement

The refinement process commenced with a thorough examination of each concept. The team paid detailed attention to its functionality, user-friendliness, durability, cost-effectiveness, and congruity with the identified requirements. An important aspect of this stage was the implementation of feedback loops, which entailed iterative cycles of evaluation and revision, enabling us to incrementally improve the designs.

During this stage, we adopted a critical stance, pinpointing areas of potential weakness or complication in each design. An integral part of this stage was the rigorous testing of the designs or prototypes ourselves. This hands-on approach afforded us crucial insights into the practical application of our designs. Through simple testing and visual inspection, we were able to assess the functionality and durability potential of our concepts in a tangible manner, significantly aiding our refinement efforts. Additionally, we evaluated if the mechanism was sufficiently intuitive for users with no prior exposure to the device.

With these insights, we proceeded to address the identified problem areas through modifications to the designs. We prioritised adjustments that would enhance functionality and user experience. However, in doing so, we were mindful to maintain a balance in our design decisions, ensuring that improvements in one aspect did not negatively impact other crucial facets.

Digital tools were integral to our refinement process. With Autodesk's Fusion 360, we had the capability to manipulate our 3D models, implementing adjustments that could drastically affect the mechanism's performance. Moreover, these tools offered us the ability to visualise the revised designs, making the implications of the changes much easier to evaluate and understand.

Upon each round of revision, we re-evaluated the updated design against our product requirements, ensuring alignment with our initial vision. This iterative refinement process continued until we were confident that we had optimised each concept to the sufficient extent, thereby ensuring the prototypes were ready for subsequent testing and further iterations.

Prototyping

After obtaining the refined model for each of the main concepts, 3D-printing of the physical model was set in motion. Ultimake Cura 4.9.1 was used as slicer software for all models, which were subsequently printed at MAKE NTNU using their Ultimaker 2+ printers. Printing parameters were set in accordance to specifications needed for basic testing. Most importantly, the infill setting needed adjusting for each new design to prevent breaking of key features such as the spring holders and handle. In addition, several adjustments needed to be made due to the time scheduling of the print. These were mainly related to resolution and supporting structures and did not have a significant impact on the preliminary testing. A preview of the KelpClip model in Cura as well as the print settings is illustrated in figure 44 in appendix A.

Project Progression & Documentation

Meetings with the external supervisor at SINTEF Ocean were scheduled for every other week. During these meetings the group provided an update on the work so far and what the plan was going forward. Meetings with the internal supervisor at NTNU was scheduled as needed.

The group tried to keep meetings at a weekly basis, where each member presented what had been done since the last meeting, if things went as expected or if any challenges occurred, and if so, what work remained from the previous week. Afterwards, the group discussed any potential challenges and made a plan for the following week, as well as updating the timeline as we progressed or when needed, caused by any potential delays. In addition, the group had established a forum where an open and continuous dialog could take place. This proved to be an effective tool in addition to weekly meetings.

3.3 Evaluation Approach

In the development of the deployment mechanism, an effective evaluation approach was critical. This ensured that the product we designed effectively addressed the core challenges we had identified. The comprehensive evaluation process included testing, user feedback, product requirement assessment, and simulations.

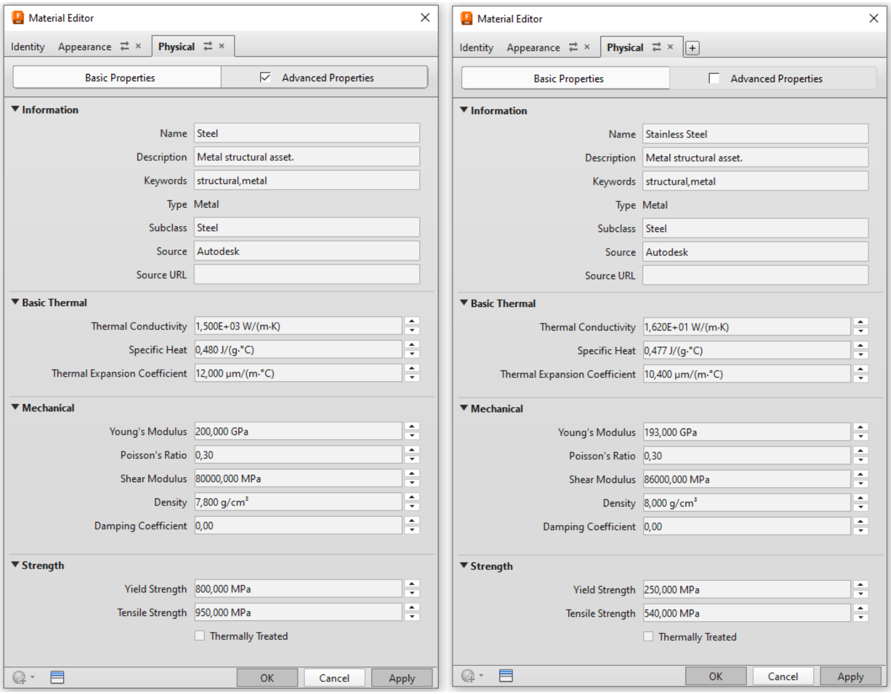
Testing was a fundamental element in our evaluation. Initial prototypes were thoroughly assessed to expose any design flaws and determine the effectiveness of the proposed solutions. The insights gathered from these early stages of testing significantly influenced the subsequent design adjustments.

User testing, as implied in section 3.2, was not carried out by the end-users themselves. However, we found that testers without any knowledge of the mechanism's purpose were potentially more beneficial in determining the intuitiveness of the solution, particularly in terms of user-friendliness.

Along with testing and user feedback, our concept was continually evaluated against the product requirements throughout the development process. This approach ensured that every design decision contributed to a final product being functional, durable, and cost-effective.

Simulations were another major component of our evaluation. We employed simulations to predict and assess the mechanism's performance under conditions that would replicate the expected forces the mechanism would face. This predictive measure enabled us to anticipate potential challenges and adjust our design in parallel with physical prototype creation.

For more accurate results from the simulations, we applied the chosen material, Duplex Stainless Steel 2205 (DSS 2205), to the back and top plates, as well as to the block inside the top plate of the final design. The material data is provided in 14. Before deciding on material and production method, generic stainless steel was used.



Information
Name: Steel
Description: Metal structural asset.
Keywords: structural,metal
Type: Metal
Subclass: Steel
Source: Autodesk
Source URL:
Basic Thermal
Thermal Conductivity: 1,500E+03 W/(m·K)
Specific Heat: 0,480 J/(g·°C)
Thermal Expansion Coefficient: 12,000 μm/(m·°C)
Mechanical
Young's Modulus: 200,000 GPa
Poisson's Ratio: 0,30
Shear Modulus: 80000,000 MPa
Density: 7,800 g/cm³
Damping Coefficient: 0,00
Strength
Yield Strength: 800,000 MPa
Tensile Strength: 950,000 MPa
☐ Thermally Treated

Information
Name: Stainless Steel
Description: Metal structural asset.
Keywords: structural,metal
Type: Metal
Subclass: Steel
Source: Autodesk
Source URL:
Basic Thermal
Thermal Conductivity: 1,620E+01 W/(m·K)
Specific Heat: 0,477 J/(g·°C)
Thermal Expansion Coefficient: 10,400 μm/(m·°C)
Mechanical
Young's Modulus: 193,000 GPa
Poisson's Ratio: 0,30
Shear Modulus: 86000,000 MPa
Density: 8,000 g/cm³
Damping Coefficient: 0,00
Strength
Yield Strength: 250,000 MPa
Tensile Strength: 540,000 MPa
☐ Thermally Treated

Figure 14: Material properties used in simulations, generic stainless steel to the left and DSS (Duplex Stainless Steel) 2205 to the right (Swisssteel-international 2023).

The findings from our testing, user feedback, product requirement assessments, and simulations all fed back into our iterative design process.

4 Product Requirements & Development

This section provides a comprehensive account of the design and evaluation process followed for the development of the mechanism. Initially, the focus is on establishing the product requirements, structured into five distinct subcategories that cover the aspects of the product's intended function and desired attributes. The subsequent sections then delve into the product development process, tracing the journey from preliminary considerations about the mechanism placement and installation methods, to the more complex aspects such as the design of the locking mechanism and the growthline connector. Finally, the section concludes by evaluating the proposed design against the initially stated product requirements, thereby providing a holistic assessment of the product's feasibility, utility, and performance.

4.1 Product Requirements

In the realm of product development, the establishment of a comprehensive set of product requirements is an essential step. These requirements form the blueprint for the design phase, shaping decision-making processes and ensuring alignment with overarching project objectives. Furthermore, the criteria set forth in these requirements are tailored specifically to address the complexities inherent in large-scale offshore kelp cultivation. Consequently, the meticulously compiled product requirements function as a strategic guide, leading the way towards the development of an innovative mechanism.

Physical Properties

The physical properties of the mechanism, such as height, width, length, and weight, are essential for ensuring compatibility with the longline system and maintaining a balance between structural stability and material usage, while ensuring a secure connection. The mass of the mechanism should be minimised to reduce material usage, transportation and storage costs, while the spacial dimensions should be minimised to reduce drag from ocean currents. It is also important to bear in mind that the user will often wear bulky gloves when considering the physical dimensions in relation to user-friendliness.

- **Length**: The top-to-bottom dimension of the mechanism should be between 50 - 200 mm.
- **Width:** The side-to-side dimension of the mechanism between 50 - 150 mm.
- **Thickness:** The front-to-back dimension of the mechanism 20 - 100 mm.
- **Weight:** The mass of the mechanism should be less than 2000 g.

Functional Performance

The mechanism's primary function is to connect the growthline to the longline securely. It must remain stable along the longline and be compatible with existing kelp cultivation systems, with varying longline diameters.

- **Positioning stability:** The mechanism's ability to maintain its position along the longline without unintentional movement, ensuring a secure connection and minimising the risk of disconnection during operation.
- **Compatibility:** The mechanism's ability to work seamlessly with the current longline systems being used in the industry, ensuring a smooth integration and minimal disruption to existing operations. This means being compatible with longlines with diameter 24 mm - 28 mm.

User Experience

Ease of installation, use, and maintenance are key factors in the adoption and success of the mechanism. The design should be user-friendly and straightforward to operate, minimising errors and improving efficiency. Safety is of paramount importance, and the mechanism must minimise the risk of accidents and injuries during installation, use, and maintenance.

- **Installation:** The simplicity and speed of attaching the mechanism to the longline, ensuring a straightforward process that reduces the risk of errors and improves efficiency.
- **Usability:** The user-friendliness and intuitiveness of operating the mechanism, enabling operators to work effectively and safely with minimal training or guidance when attaching and detaching the growthline.
- **Maintenance:** The simplicity and accessibility of performing maintenance tasks on the mechanism, ensuring a streamlined process that minimises downtime and maximises operational efficiency.

- **Safety:** The mechanism's ability to minimise risks and hazards during operation and maintenance, ensuring the well-being of operators and reducing the likelihood of accidents or injuries.

Durability and Reliability

The mechanism's durability is crucial for its long-term performance. It should have a long service life, reducing the need for frequent replacement and minimising waste. The material used for the mechanism should have a high load-bearing capacity, ensuring it can withstand the forces encountered during operation. This also includes resistance to corrosion, maintaining effective operation in the marine environment.

- **Load-bearing capacity:** The maximum vertical force the mechanism can support without failure, ensuring it can maintain a secure connection between the longline and growthline. It should ideally withstand a vertical force of 10.4 kN, which also is the capacity of the growthline, which has a safety factor = 2.5.
- **Corrosion resistance:** The mechanism's ability to resist degradation due to exposure to water and other corrosive elements, ensuring long-term durability and minimal environmental impact.

Economic Factors

The simplicity and cost-effectiveness of producing the mechanism should allow for mass

be carefully balanced against its performance and durability. The mechanism should be suitable for mass production and scalable to different sizes or production volumes.

- **Manufacturability:** The simplicity and cost effectiveness of production. The expense of producing the mechanism, including materials and labour, on a large scale to meet the demands of the kelp cultivation industry.
- **Post-processing efficiency:** The ease and effectiveness of final processing steps of the mechanism. This also includes any cost concerning assembly of the mechanism.
- **Scalability:** The ability to adjust the mechanism's design or production to accommodate different sizes or production volumes, providing flexibility and adaptability for various cultivation operations.

4.2 Product Development Process

The following section examines the steps and decisions taken in the journey from concept generation to the finalised design of the mechanism. Furthermore, it encapsulates the iterative process of refining the design through various stages, each addressing a different attributes of the product. Key aspects such as mechanism placement, installation methods, the locking mechanism, and the growthline connector are examined, providing detailed insights into the thought process and technical considerations that have shaped the development of the mechanism. The objective is to trace the progression of the design while elucidating the rationale behind each design choice, thereby ensuring a transparent and well-documented development process.

Mechanism Placement

During the idea generation phase, we first needed to establish the placement of the mechanism. Given that the overall objective was to connect the growthline and the longline, the mechanism could be primarily placed on either line or split between the two. We considered three different scenarios for the placement of the mechanism:

1. The mechanism is placed exclusively on the growthline.
2. The mechanism is placed exclusively on the longline.
3. The mechanism is split between the growthline and the longline, with each line having an opposite connecting part attached to it.

To determine the ideal distribution and placement for the mechanism, we first had to consider where user interaction takes place. The longline is anchored to the sea bottom and usually not moved or replaced very often. Therefore, the longline was not expected to be replaced within the anticipated lifetime of the mechanism. Conversely, the growthline is attached and detached regularly. Currently, there are two growing seasons per year, with efforts being made to extend this to three. This means the growthline is attached with the deployment of young kelp, referred to as "kelplings", at the start of a season and detached when the kelp has matured and is ready for harvest. With the existing cultivation setup and practices, this amounts to four such interactions per year.

We concluded that a user-friendly product was more vital in proportion to how frequent the user interactions with the mechanism were. Following that line of thought, user-friendliness was more crucial if the mechanism were to be placed on the longline than if it was placed on the growthline. One could argue that a user-friendly design could be made in all three placement scenarios. However, considering the product requirements mentioned in section 4, especially the mechanisms (or by extension the growthline) being able to withstand a great amount of vertical force and to stay locked in place along the desired position on the longline, as well as production costs compared to the value of the harvest, it was deemed unfeasible to meet all the demands. More often than not, prioritising one aspect would be at the expense of another.

Scenario 1, in which the mechanism is placed exclusively on the growthline, was not considered a viable option for this project. Meeting the structural requirements, functionality, and user-friendliness would be too expensive to produce in that quantity, relative to the value of the harvest. The only requirement that could be down-prioritised in this scenario would be user-friendliness. However, considering this scenario would require the most interactions (four times a year), the trade-off was deemed non-ideal.

To decide between the remaining scenarios, we needed to assess the security of the growthline's connection to the mechanism. We evaluated whether connecting the rope-end as is to the mechanism on the longline (scenario 2) would be sufficient or if it would be better to have a connector attached between the mechanism on the longline and the growthline (scenario 3).

Scenario 2 faced some of the same issues as scenario 1. Although the proposed designs met all requirements while being user-friendly, they were more expensive to produce while actually offering less user-friendliness than the alternative. The project assessed multiple variations of scenarios 2 and 3 and discovered that scenario 3 was the ideal candidate, serving as a middle ground between the two extremes.

Installation Methods

Before delving into the two connecting parts, the options for different installation methods of the mechanism had to be thoroughly analysed.

Another design consideration we had to take early on was whether the mechanism's design required it to be inserted at one of the ends of the longline or if the mechanism could be clamped around the longline.

A mechanism that would have to be inserted at the end implies that the mechanism can be thought of as having a cylindrical shape without the possibility to open it. On the contrary, a clamping mechanism would require two parts joined by, for example, a hinge that could be opened and closed, or be similar to a C- or U-clamp.

Structurally, the "insertion mechanism" would be superior in most cases, thus requiring less material and weight, which could further drive production costs down in order to achieve the same structural integrity. One could argue that with the assumptions made prior, such as the longline and the mechanism being stationary for the expected lifetime of the mechanism, it could be worth taking the time to use such a mechanism. However, it became clear early on in the idea generation phase that it would most likely fail to deliver on the project goals beyond the structural requirements. Maintenance and replacement of "insertion-mechanisms" towards the centre of the longline would require a considerable effort, since all of the preceding mechanisms holding tons of kelp would also have to be taken off first, which realistically is not a viable solution. One could, with reasonable certainty, expect the overall cost to be far greater than what could potentially be saved in production.

The most significant advantage of the clamping mechanism is the ability to install the mechanism directly on the longline, making it more versatile, modular and more likely to be used by both SINTEF Ocean and other cultivators. The major concern with the clamping-mechanism was, as mentioned, the structural integrity and not meeting the other structural product requirements. The other main concern was the possibility of the longline slipping out of the mechanism due to harsh weather or unforeseen events.

After some initial concepts, the project group was sufficiently confident that a clamping mechanism could meet both the result goals and the impact goals, and that the upsides greatly outweighed the downsides.

Up until the decision was made about mechanism placement and installation method, most concepts were focused on being attached to the growthline. As visible in 30, none of the first generation designs allows for installation on the longline in the same manner as a clamping mechanism could. The group concluded however that all the concept could potentially be iterated to achieve this, thus making other factors more instrumental in the decision on which design to develop further.

Locking Functionality

With the decision to employ a clamping mechanism, attention was concentrated on the critical design of how it would be locked on the longline. The significance of this functionality cannot be overstated as it ensures the mechanism, and by extension, the growthline, remain secure in its designated position on the longline for the necessary duration. Furthermore, it has been determined that the optimal distribution of the mechanism necessitates that the main component, or the mechanism itself, be placed on the longline, with the growthline connected through a straightforward connector. This distribution strategy underlines the comprehensive examination in this section. Multiple different locking mechanisms were appraised, generally categorised into two groups: those predominantly utilising friction for fastening, and those integrating cam mechanisms.

For the friction based mechanisms, two variations were considered; Concept A1 and C1. Both these concepts were developed early in the concept generation phase, before the decision about the mechanism placement discussed section in 4.2 was made. Thus, the possibility to redesign the concepts to fit on the longline had to be evaluated as well.

Concept A1 (Figure 15) functions similarly to a fishing reel. Upon insertion of the growthline and securing the lid, the spikes in the tightly fit housing would prevent the growthline from slipping. However, after building a prototype and conducted tests, it was discovered that this design was potentially damaging to the growthline, with a significant concern that the spikes would fray fibres in the growthline under repeated or strong movement. Additionally, this design lacked adaptability to different rope sizes, as the housing needed to be dimensioned for a specific diameter. Moreover, it was considered more challenging to produce in large quantities, and needed a considerable redesign effort to ensure compatibility to the longline.

Figure 15: Prototype of concept A1.

For concept C1 (Figure 16), friction was also the primary factor preventing the growthline from moving undesirably. This mechanism operates similarly to a common descender mechanism used in climbing. The shape of the engaged mechanism creates ”channels” for the growthline, thereby creating loops and multiple contact points with the mechanism's surface, generating friction without damaging the growthline, as with concept A1. This concept also allowed for different rope sizes and was considered a much more affordable solution considering mass production compared to concept A1, in addition to be easier to adapt to the longline. After the prototype was made and some basic testing conducted, the concept was however deemed to not generate enough friction considering the expected forces it would undergo without major design changes.

Figure 16: Prototype of concept C1.

Similarly to the two previous concepts, concept B1 was also designed for the growhtline. It does, however, differentiate itself by incorporated both friction *and* rotating cams to prevent unwanted movement along the rope. The section view of the concept is displayed in figure 17. If, for example, the rope was to be pulled to the right side, the left (green) cam would prevent line movement by rotating clockwise, and the right (red) cam would contribute negligible stopping force, and vice versa.

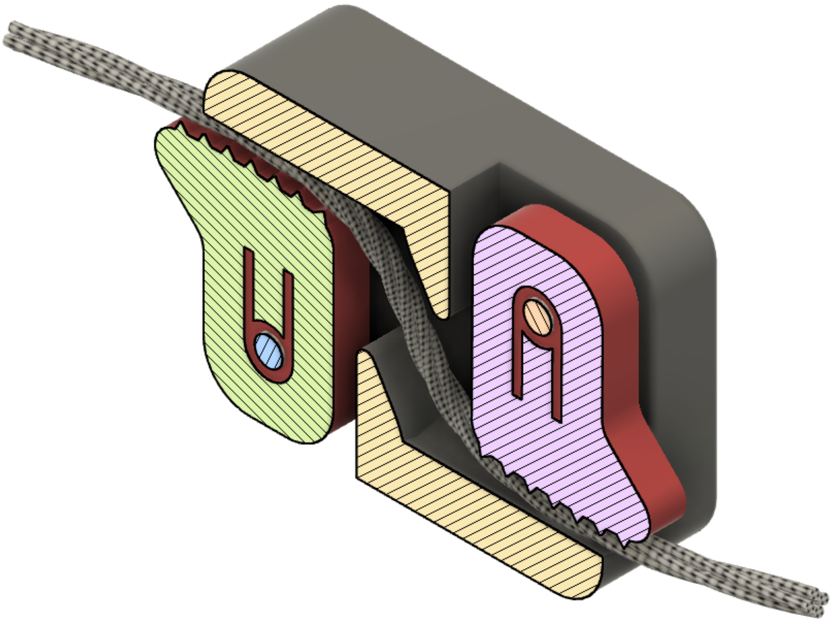


Figure 17: Section view of concept B1.

Two cams were necessary in concept B1 to prevent undesired line movement, as one cam would only prevent movement in one direction. An earlier version of concept B1 with only one cam is depicted in figure 18.

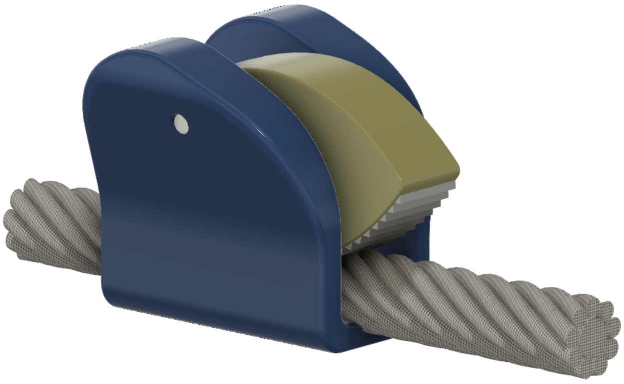


Figure 18: Early concept with cams.

In concept B1, the cams were naturally urged to rotate inward by inserting a torsion spring in the groove near the axle of each cam, as well as in a matching groove in the housing, totalling four springs. An extra set of grooves for the torsion spring was made for practical reasons, as this version was 3D-printed as a prototype to test the cam concept. The 3D-printed prototype is displayed in 19. It is important to note that there was paid little attention to the housing in this concept, as it served mostly as a proof of concept by testing the idea of using rotating cams.

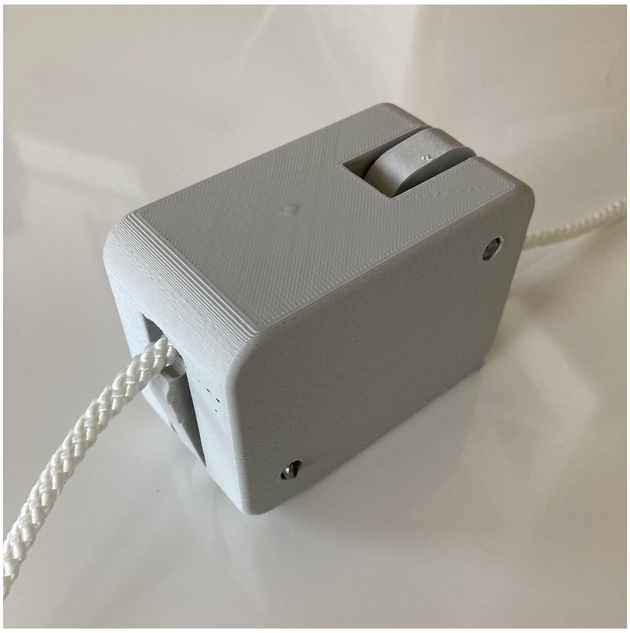


Figure 19: Prototype of concept B1.

The key difference with the cam design over the frictional designs is the reliance on the stopping force generated when the cam hits the housing wall, thereby preventing further rotation. By implementing this concept, the design relies less on friction than concepts A1 and C1, reducing the need for potentially dangerous loaded springs and improving the ability to withstand a greater amount of force. The limiting factor would be the material and its geometry rather than spring force.

In the process of iterative design and prototyping, we recognised the unique benefits that the B1 mechanism offered over other alternatives. B1 presented a effectively way of inhibiting undesirable movement along the longline, a feature critical to our application. Unlike A1 and C1, which primarily relied on friction, B1 managed to overcome the challenges with relying on friction with a mechanical cam system, potentially reducing the need for high-force springs and increasing the system's capacity to withstand substantial force. These attributes marked B1 as a promising candidate for further development, as it exhibited a potential to enhance durability, functionality, and safety. Despite the need for further refinements in terms of mass production suitability and adaptability to the longline, the underlying principle of the B1 design was considered significant enough to warrant its continued evolution.

The evolution of our design process so far has been primarily centred on mechanisms that are affixed directly to the growthline, including the A1, B1, and C1 concepts. However, the focus towards designing components that can be attached to the longline shifted at this point, and opened new opportunities. Therefore, from concept B2 and onwards, the designs are developed with the longline in mind.

In conjunction with this new approach, we saw the need to integrate a connector for the growthline, to ensure a secure and easily manoeuvrable attachment. It quickly became clear that the most cost-effective and straightforward solution would be to incorporate an eye into the end of the growthline. This solution could be paired with a simple carabiner hook serving as the connector, which can be sourced commercial off-the-shelf. This coupling would not only provide secure and adjustable attachments, but also support easy installation of the growhtline after the locking mechanism is installed on the longline. The detailed discussion of the growthline connector, including the utilisation of a carabiner hook, will be discussed further in the next section.

In order to adapt concept B1 for attachment to the longline, in accordance with the installation method discussed in 4.2, concept B2 was developed, as illustrated in figure 20.

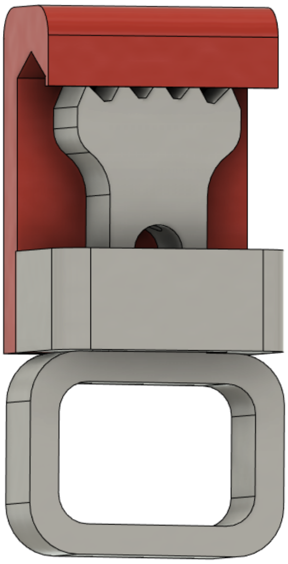


Figure 20: Concept B2.

In this design, the longline rests in the holder of the back plate, with the top plate pushed down to secure the longline. The top plate can be retracted by the use of a spring and axle, to enlarge the gap between the two plates, allowing for the insertion of the longline. Similar to concept B1, further rotation of the backplate is inhibited by the housing walls.

In order to verify our previous suspicions about the use of springs and solely friction-based locking instead of cams, concept B3 (Figure 21) was developed. However, preliminary simulations and prototype testing revealed that the spring force necessary for this variation would be undesirable, and that the advantages of relying on cams exceeded that of relying on purely friction.

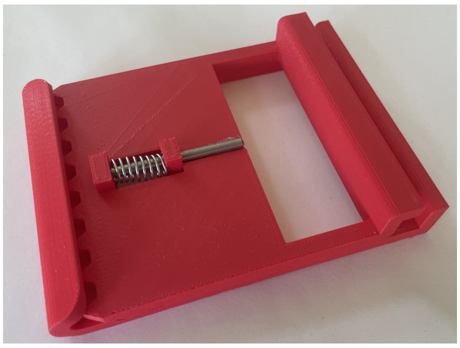


Figure 21: Prototype of concept B3.

This finding led us back to cam-based designs, resulting in the development of concept B4, as shown in figure 22.

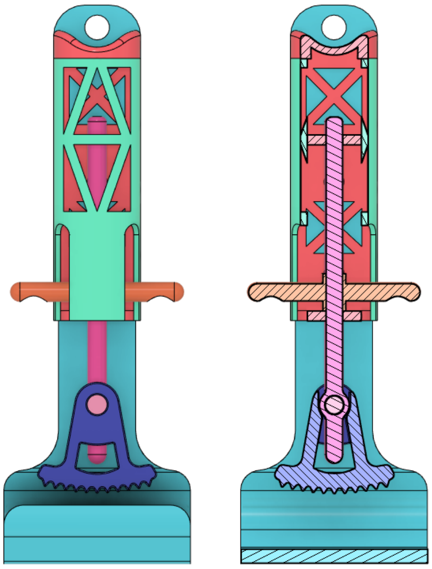


Figure 22: Concept B4, including section view.

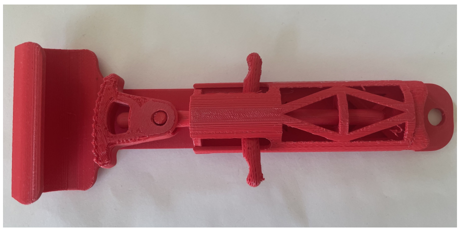


Figure 23: Prototype of concept B4.

This design introduced a more sophisticated cam that relied on stopping walls inside the cam itself. Another discovery, made through prototyping and testing, was that the holder in which the longline is situated caused the cam to exert force on the longline off-centre with different line diameters. To remedy this, an improved shape for the holder was developed, allowing for longlines with diameters between 24 mm and 28 mm to be inserted, whilst ensuring that the line is centrally positioned relative to the cam. This improvement is depicted in Figure 24.

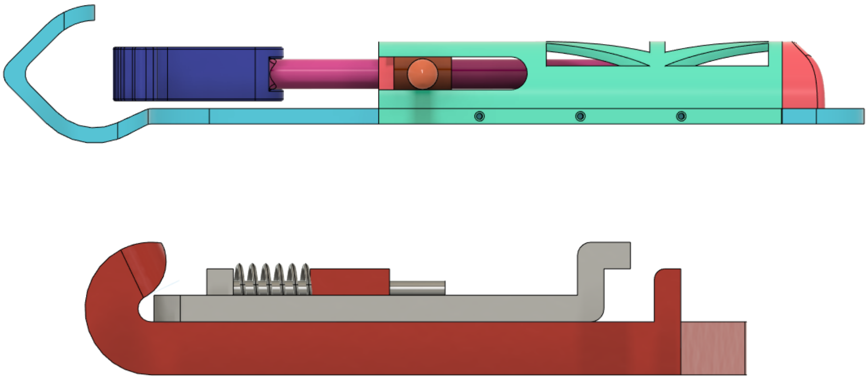


Figure 24: Improved holder shape to ensure the cam applies force at the centre of longlines with varying diameters.

Although design B4 showed promise during prototype testing, it had a major drawback; the overall cost of production and maintenance. The complex geometry of the cam, especially the internal hollow space, would require sophisticated machining, as well as be susceptible to corrosion due to the extra surface area. In addition to its intricate geometry, this design involves a significantly larger number of components, thereby increasing assembly time and production cost, and introducing more potential points of failure.

Based on the insights gained from the product development process, we decided to combine the most beneficial attributes of each concept into what ultimately became the final design; the KelpClip. The final design model is displayed from all sides in figure 25 and the prototype in figure 26.

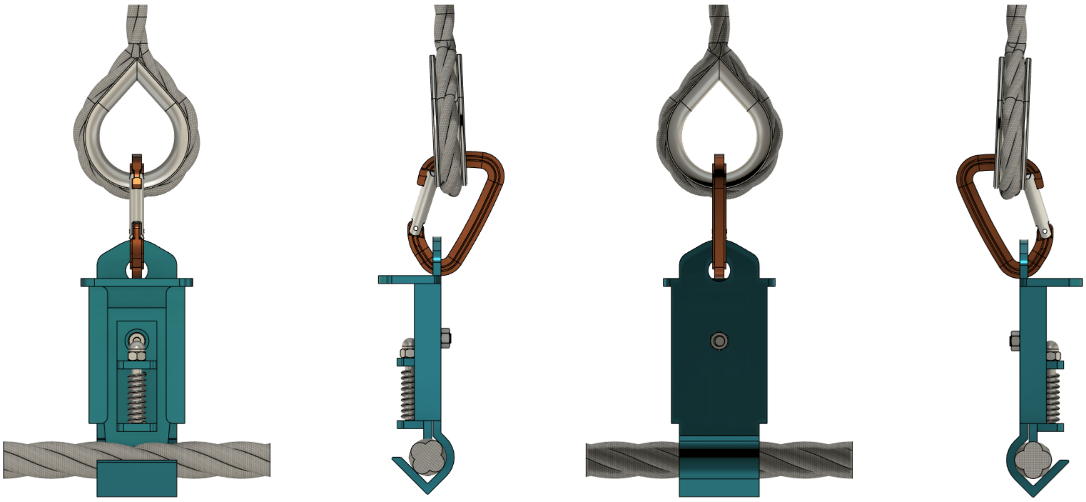


Figure 25: The KelpClip.

Figure 26: Prototype of concept the KelpClip.

The rotating cam, or top plate, in the final design was inspired by concept B2, with a notable improvement. As the positioning of the top plate will vary depending on the diameter of the longline, the surface area on the side wall of the top plate that comes into contact with the housing wall will also vary, leading to some top plate positions being more prone to high stress concentrations.

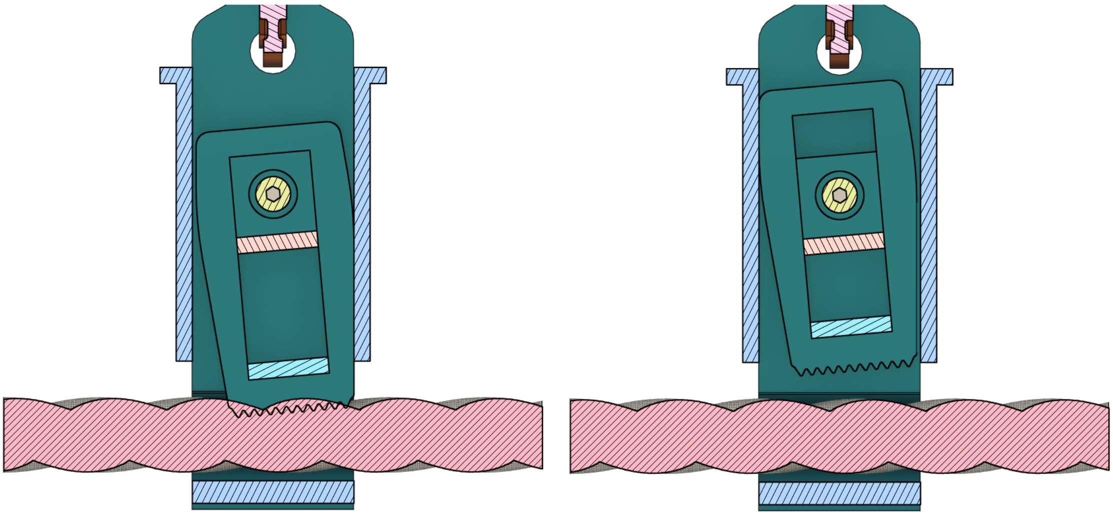


Figure 27: Top plate coinciding with back plate stopping wall.

To counteract this issue, the shape of the top plate was designed such that when the spring is fully extended, maximum surface area is in contact with the stopping wall, located at the bottom of the top plate. This design leaves a gap between the top plate and the stopping wall on the opposite side (left model in Figure 27). Conversely, when the spring is fully retracted, the interface between the top plate and the stopping wall is located at the top of the top plate, leaving a gap on the opposing side.

The rationale behind this distribution of surface area when the spring is fully extended or retracted is based on the assumption that the spring force is minimal when fully extended, resulting in less frictional force and greater reliance on the stopping wall. Hence, to avoid damaging stress concentration, the surface area in contact with the stopping wall should be larger. In this design, the top plate lies parallel to the stopping wall when fully extended or retracted, allowing for a large surface area at the point of contact. The stress will vary depending on the position of the top plate between these two extremes. To mitigate this, the top plate was slightly rounded, but this aspect was not thoroughly examined, suggesting a potential area for future work on shape optimisation. This is further discussed in section 5.2.

Modifications were also made to the handle, redesigning it so that it could be manufactured through the same metal sheet extrusion process used for the back plate. This design necessitates only a 90-degree bend to align it correctly. Importantly, the handle aligns with the stopping walls, an improvement which counteracts the momentum generated when retracting the top plate during longline installation. This preventive measure ensures the handle maintains its form, thus extending its usability without requiring extra material. A more comprehensive explanation of the operation of this mechanism is provided in section 5.1.

In the ideation phase, other potential locking mechanisms were also considered. One such example was the use of a spring-loaded lever combined with a ratchet mechanism, often found in torque wrenches. This design features a spring-loaded clutch mechanism that produces an audible click when the preset torque is reached. Once the torque reaches the set value, the mechanism disengages, producing the characteristic click sound and signaling that the desired torque has been applied. Paired with a ratchet mechanism, the assembly would permit rotation and torque application in one direction, while allowing free rotation in the opposite direction.

Another alternative concept was to employ a ”freewheel” mechanism, commonly used in bicycles. This concept shares similarities with the torque wrench mechanism, permitting torque to be applied in one direction, but it often involves more moving parts, leading to increased complexity and size.

Growthline Connector

As discussed 4.2, we decided it would be beneficial to have a connecting part between the mechanism and the growthline. One could argue that the same logic could be applied to the longline as well, inserting eyes of metal every two metres or so. It could potentially be the most cost-efficient solution, as every part of such a setup could be purchased of the shelf. The drawback of this idea, is the flexibility a more modular approach provides, such as with an attachable / detachable coupling mechanism. If for example another species were to be cultivated, a solution with fixed spacing might prove to be either too far between, decreasing the potential yield, revenue and positive environmental impact, or placed too close, creating inadequately light condition, space to grow and potential nutrient deficiency, or the development of sick plants. It is reasonable to assume that the rigidity such a solution provides, is less than ideal considering the state of the kelp cultivation industry is still largely in a research stage. It could however prove to be a great solution, but it is in that case important to be fairly certain of the spacing through research, in addition to be able to stick to cultivating a particular species for a extended period of time. This should be closely considered by each individual cultivator before investing in such a solution, and weighing it up against the alternative costs, such as a more sophisticated mechanism or by manual labour.

Figure 28: Anchor line with metal eye (*How to Splice Three Strand Rope* 2023).

Materials Considerations

As previously mentioned, the final product needs to withstand high stress levels (10.4 kN). In addition to smart design, choice of material is paramount in relation to stress capacity. Because of the appliances marine environment and expected durability, it is also important that the material exhibits a high degree of corrosive resistance. Lastly, when considering the aforementioned parameters, price becomes an important factor. The wide array of steel types available were narrowed down by a simple screening process to three types commonly used for marine applications. Values for these are shown in table 2.

Table 2: Most relevant properties and prices for three material candidates (*MatWeb* n.d.)(Zhu et al. 2020)(STIndia 2023).

	Yield strength [Mpa]	Corrosion rate [mm/y]	Price [EUR/kg]
SS 316	250	0.07	4.99
SS 317	275	0.06	4.99
DSS 2205	500	0.03	3.68

DSS (Duplex Stainless Steel) 2205 exhibits the best overall material properties, while also being the cheapest of the three types. As an additional remark, studies have shown DSS 2205 to be superior when exposed to seawater over longer periods of time ($\approx$ 2 years), maintaining passivation throughout (Zhu et al. 2020).

Production Method

Several production methods have been considered for the final design, among the most promising are sheet fabrication and die casting. Although sheet fabrication requires several tools and steps during production such as stamping and bending, it is likely more economically efficient than die casting at this scale, especially when considering the planar geometry of the unbent design (NADCA 2023).

4.3 Evaluation Against Product Requirements

To get a better understanding of how certain concepts and designs were more promising than others, they were evaluated based on a weighted version of the product requirements introduced at the start of this chapter. In table 3 the weights used are displayed, as well as how the first generation concepts and the final design performed. The aggregate score in each category is displayed in figure 29.

Table 3: Weighted product requirements and evaluation of different concepts.

	A1	**B1**	**C1**	**KelpClip**	**Weight**	**Description**	**Requirement**
Physical Dimensions							
Length	9	6	7	8	5	Top-to-bottom dimension	$50 < x < 200$ mm
Width	9	8	8	9	5	Side-to-side dimension	$50 < x < 150$ mm
Thickness	7	5	8	6	5	Front-to-back dimension	$20 < x < 100$ mm
Weight	6	5	8	5	5	Mass while maintaining structural stability	< 2000 g
Functional Performance							
Positioning Stability	2	9	3	8	10	Ability to maintain position on longline	
Compatibility	1	8	8	8	7	Seamless integration with existing systems	24 mm $\leq Ø \geq$ 28 mm
User Experience							
Installation	3	4	5	8	7	Simplicity and speed of attachment	
Usability	6	4	5	9	8	User-friendly and intuitive operation	
Maintenance	4	3	7	5	6	Ease and accessibility of upkeep	
Safety	8	8	8	8	4	Minimisation of operational risks and hazards	
Durability and Reliability							
Load-bearing Capacity	3	9	5	8	6	Maximum weight support without failure	10.4 kN vertically
Corrosion Resistance	7	7	7	7	7	Ability to resist degradation from exposure to water	
Economic Factors							
Manufacturability	4	4	6	9	9	Simplicity and cost-effectiveness of production	
Post-processing Efficiency	6	3	5	7	7	Ease and effectiveness of final processing steps	
Scalability	5	4	6	8	7	Ability to adjust production for different volumes	

Figure 29: Aggregate scores for the different concepts in each evaluated category.

In evaluating the various concepts, it was essential not just to consider the current status of each concept, but also the potential for improvement and development. This approach was clearly illustrated when comparing the total scores of concepts C1 and B1. Even though C1 scored higher overall, B1 was selected for further development. The decision hinged on B1's exceptional performance in a specific category, functional performance.

As highlighted in our previous discussions, the cam-mechanism inherent in B1 held significant promise for future enhancements, suggesting that B1's potential had not been fully realised at the time of evaluation. This observation also underscored that the initial weighting of the various requirements may have been somewhat misaligned, reflecting a possible bias toward the current capabilities rather than the developmental potential of the concepts.

Weight description

The physical dimensions of the mechanism, namely its height, width, length, and weight, all receive equal weightage (5) in the assessment of its functionality. These factors don't entirely dictate the mechanisms performance, and the exact dimensions are somewhat flexible and subject to specific design solutions, which explains their mid-tier scoring.

When turning to functional performance, the ability of the mechanism to maintain its position on the longline is of paramount importance (10). This requirement is critical because slippage could disrupt the uniform distribution of kelp, potentially reducing yield or even causing damage to the plants. This is why it's given the maximum weightage. Compatibility with existing systems (7), on the other hand, receives a slightly lower score, although it's still highly relevant. The goal here is to design a solution that can be integrated into the already established frameworks, minimising disruptions and fostering easier adoption. However, some adaptations could be acceptable, hence a lower score.

The user experience of the mechanism is heavily dictated by its ease of installation (7) and usability

(8). In the harsh and physically demanding environment of offshore cultivation, ensuring a simple, straightforward installation process and intuitive operation is highly beneficial. It minimizes time and effort spent on setup and adjustments, thus promoting efficiency. Safety (4), though important, is slightly less critical in this particular context. Maintenance (6), while vital for ensuring longevity and consistent performance, isn't as crucial as the other aspects of the user experience.

Durability and reliability of the mechanism hinge upon its load-bearing capacity (6) and corrosion resistance (7). These are factors that will determine how well the mechanism can stand up to the rigors of its operational environment over time. Given that the device will be deployed in marine environments, corrosion resistance is somewhat more important, as degradation from constant water exposure can lead to failure over time. Additionally, it is expected that the requirement of 10.4 kN is exaggerated, thus further lowering the load-bearing capacity weight.

Finally, in terms of economic factors, the focus is on manufacturability (9), post-processing efficiency (7), and scalability (7). All three are critical for large-scale cultivation. Manufacturability is given a higher score as the ability to produce the mechanism cost-effectively and in large quantities is fundamental for commercial success. Post-processing efficiency and scalability are both important, but given that they rely on the overall design and successful implementation of other factors, they score slightly lower.

5 Results

5.1 The Final Design

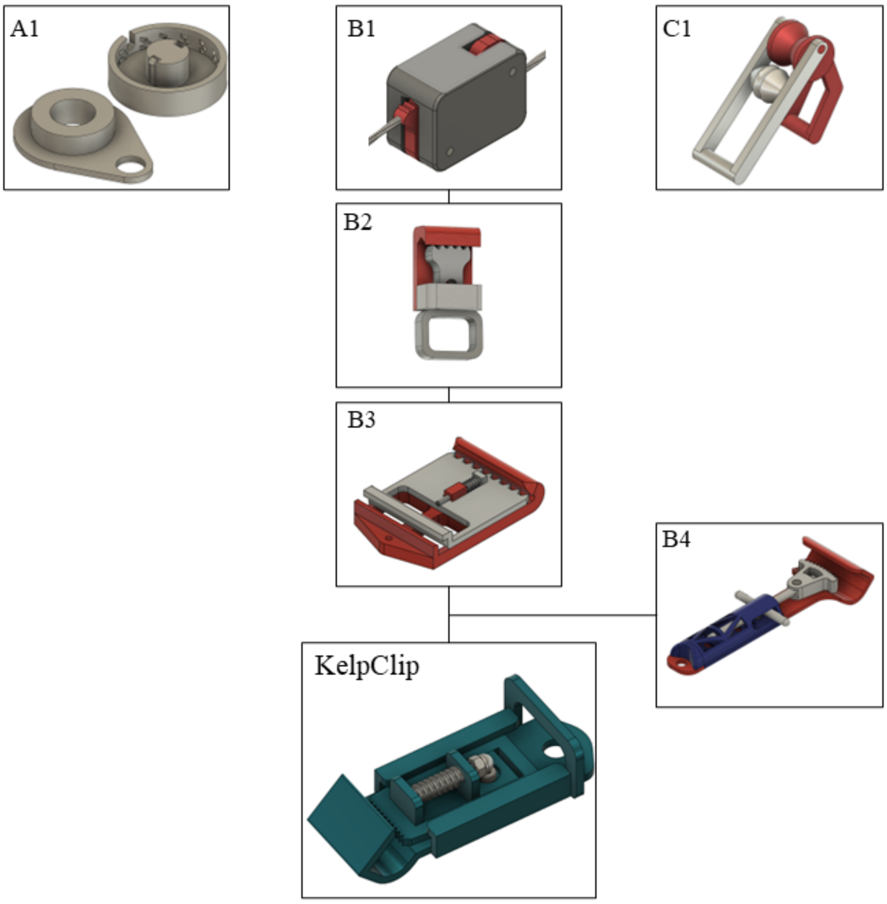


Figure 30: Concept evolution.

A number of designs were made into prototypes by 3D-printing. These are shown in figure 30. These were chosen based mostly on their anticipated functional capabilities. The top-most concepts each have their own unique way of inducing friction. As is seen in the figure, the group chose to concentrate on the clamping approach. This was improved upon through an iterative process, as one of the main problems with the initial mechanism was releasing the rope. The two pictures at the bottom of the figure illustrate the two final designs. Due to sheer complexity of assembly, production and the many moving parts, the left-most model (KelpClip) is considered the most optimal.

The KelpClip-mechanism is operated by squeezing the handle at the back and the wall in front of the spring together. This will temporarily open the mechanism and allow for rope insert. By releasing the spring, the teeth of the top-plate will grasp the rope in place. The clip also features a cam-like mechanism which will kick in once the rope is pulled from either side. Once pulled, the top-plate will rotate accordingly, causing the teeth to penetrate further into the rope. This is caused by the rotating block through which the axle slides.

A rendered photo of the final design is depicted in figure 31, attached to the 28 mm diameter longline in one end, and connected to the 16 mm diameter growthline through a carabiner hook in the other end.

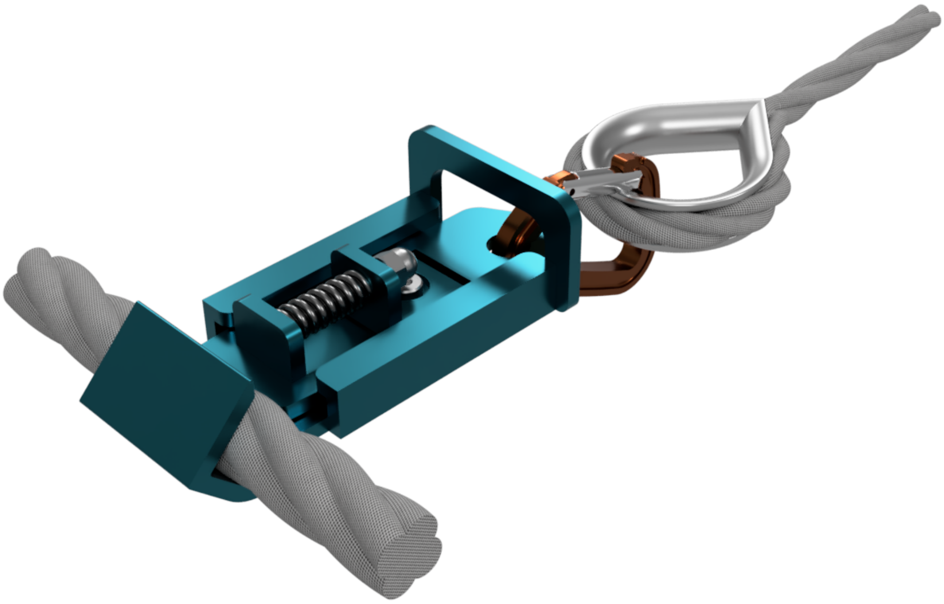


Figure 31: Render of the final design up close.

To acquire a sense of scale, two of the mechanisms are also displayed at relative scale along the longline distanced two metres between each other, in figure 32.

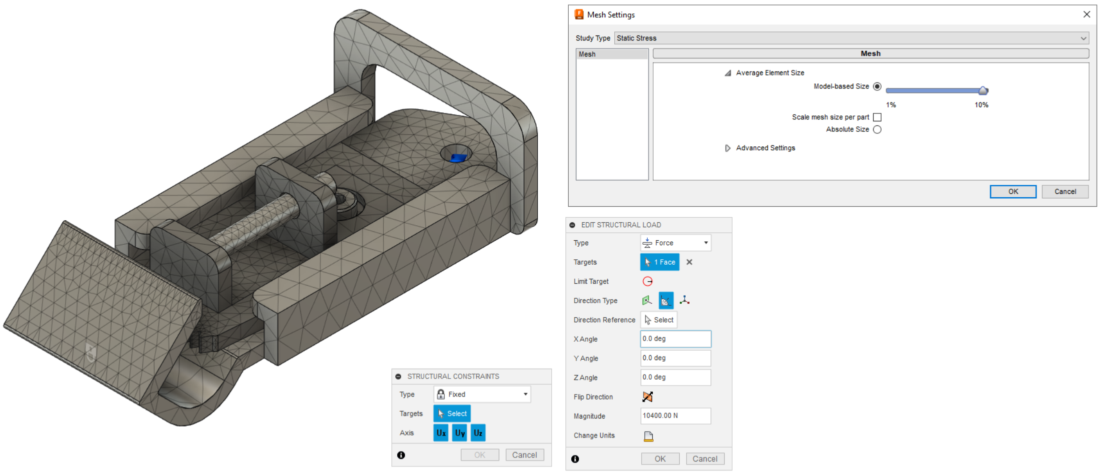
Figure 32: Render of final design placed with 2 m distance, at relative scale.

5.2 Simulation Results

This section delineates the outcomes of the conducted simulations, which were set up to examine the structural integrity of the proposed mechanism under axial and lateral force conditions.

Axial Forces

The first simulation tested the effects of axial, or vertical, static force (10.4 kN) on the final design. The force was applied at the hole that links the mechanism to the carabiner hook, which in turn attaches to the growthline. To simulate the presence of the attached longline, the longline holder was fixed in all six degrees of freedom. Figure 33 illustrates the initial settings of the simulation.



Mesh Settings

Study Type: Static Stress

Mesh

Average Element Size

Model-based Size ●

1% 10%

Scale mesh size per part ☐

Absolute Size ○

Advanced Settings

STRUCTURAL CONSTRAINTS

Type: Fixed

Targets: Select

Axis: Ux Uy Uz

EDIT STRUCTURAL LOAD

Type: Force

Targets: 1 Face

Limit Target

Direction Type

Direction Reference: Select

X Angle: 0.0 deg

Y Angle: 0.0 deg

Z Angle: 0.0 deg

Flip Direction

Magnitude: 10400.00 N

Change Units

Figure 33: Initial settings of static load cases 1 and 2.

The displacement of the mechanism under an axial static load of 10.4 kN is depicted in figure 34. The figure presents both the actual and adjusted deformations to assist in visual interpretation.

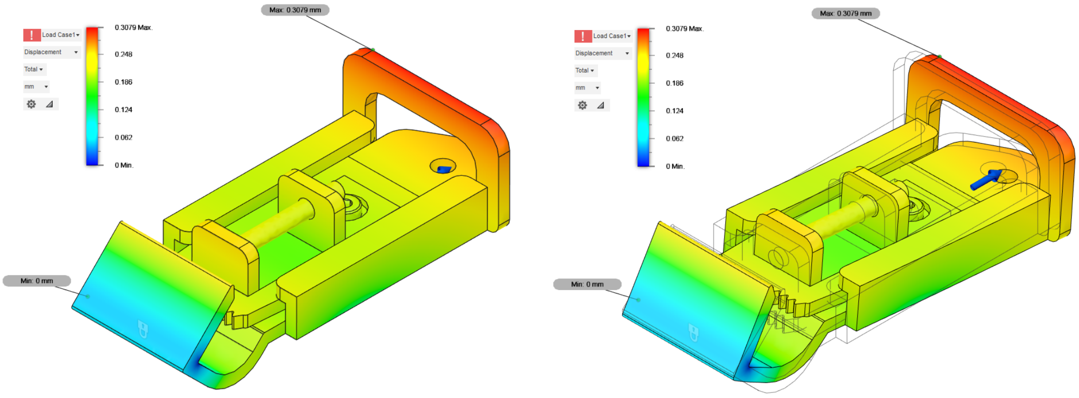


Figure 34: Static load case 1 displacement: actual (left) and adjusted (right).

The most substantial displacement, amounting to 0.3079 mm, is observed at the handle of the mechanism.

Subsequently, the stress distribution within the mechanism was evaluated, with the results displayed in figure 35.

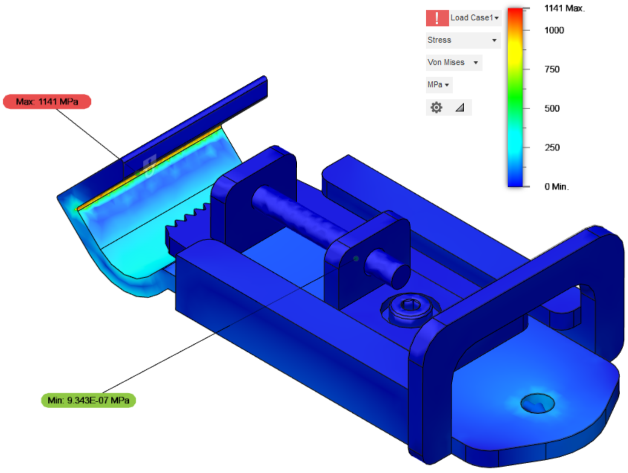


Figure 35: Static load case 1 stress (Von Mises).

The most significant stress concentration, registering at 1141 MPa, is located at the longline holder—the point where the movement constraint was applied. Moreover, a noteworthy stress concentration is observed around the hole at the top of the mechanism, where the vertical load was applied.

Additionally, to ascertain whether certain areas were over-designed or under-designed, a safety factor simulation was performed. The lowest safety factor, 0.6193, is found at the holder, as shown in figure 36.

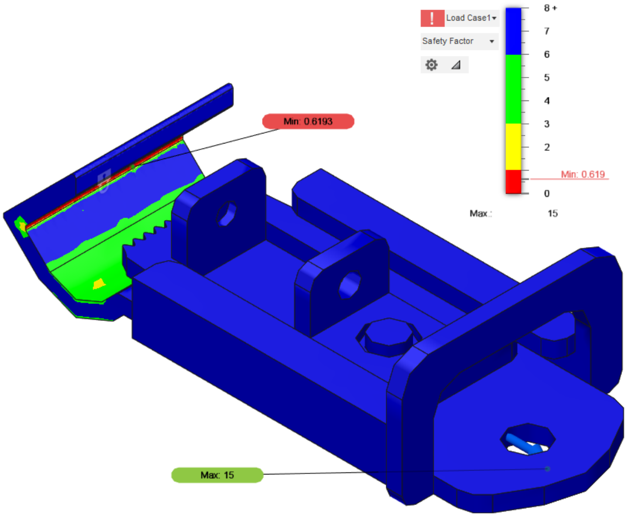


Figure 36: Static load case 1 safety factor.

To further examine the force transfer under realistic conditions, a similar simulation was run, incorporating a simplified, oval carabiner hook. The settings for this simulation mirrored those of the previous simulation, but with the force now applied on the carabiner hook. Figures 37 and 38 present the results.

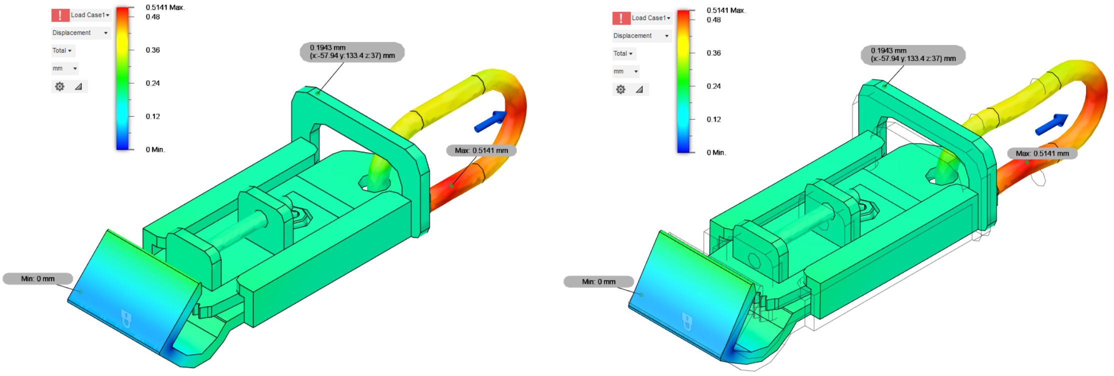


Figure 37: Static load case 2 displacement: actual (left) and adjusted (right).

As evidenced in figure 37, the displacement within the mechanism itself has notably decreased. Instead, the displacement is primarily absorbed by the structurally less robust carabiner hook, which shows a displacement of 0.5141 mm—almost double that in the previous simulation.

Moreover, the stress concentration has risen at the interface between the carabiner hook and the hole in the mechanism, registering at 1085 MPa. The stress at the longline holder also increased compared to the simulation without the carabiner, amounting to 1217 MPa, as shown in figure 38.

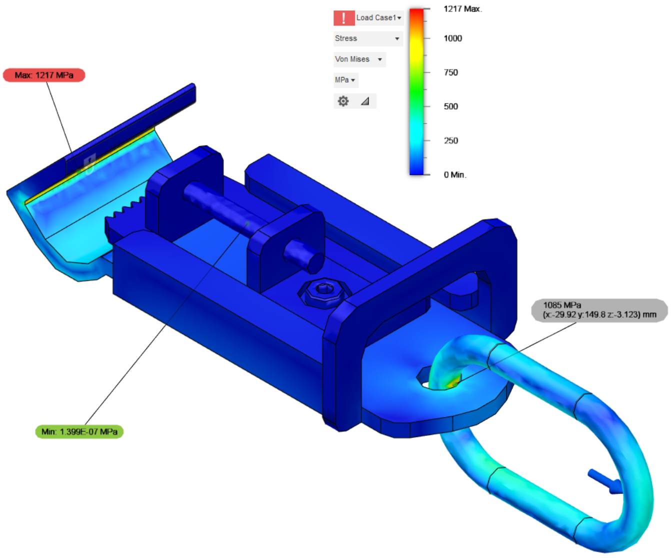


Figure 38: Static load case 2 stress (Von Mises).

Lastly, the safety factor simulation indicated the lowest value at the interface between the carabiner hook and the hole, a mere 0.226, as shown in figure 39.

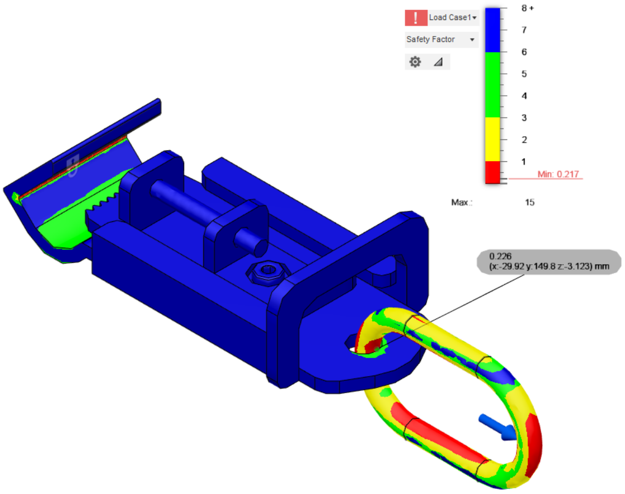
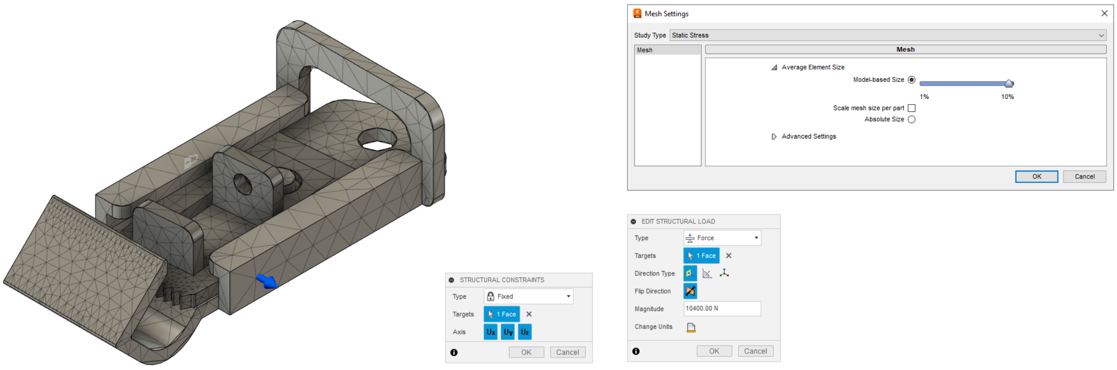


Figure 39: Static load case 2 safety factor.

Lateral Forces

The second set of simulations applied a lateral force of 10.4 kN to the sidewall of the top plate. To mimic how the mechanism is fixed along the longline, which is elaborated in section **??**, the top plate was rotated by 5 degrees to touch the stopping wall on the back plate. Additionally, the rear side of the opposing stopping wall was restrained from moving in any direction. The initial settings for this simulation are displayed in figure 40.


Mesh Settings

Study Type: Static Stress

Mesh

Average Element Size

Model-based Size ●

Scale mesh size per part ☐

Absolute Size ○

STRUCTURAL CONSTRAINTS

Type: Fixed

Targets: 1 Face

Axis: Ux Uy Uz

EDIT STRUCTURAL LOAD

Type: Force

Targets: 1 Face

Magnitude: 10400.00 N

Figure 40: Initial settings for static load case 3.

Like in the previous simulations, displacement was first examined, with results displayed in figure 41. The most substantial displacement, 0.3505 mm, is observed at the top corner of the stopping wall. As a consequence of the opposing side of the mechanism being fixed, a visible warping effect is noted, increasing towards the point where the top plate and the backplate's stopping wall coincide.

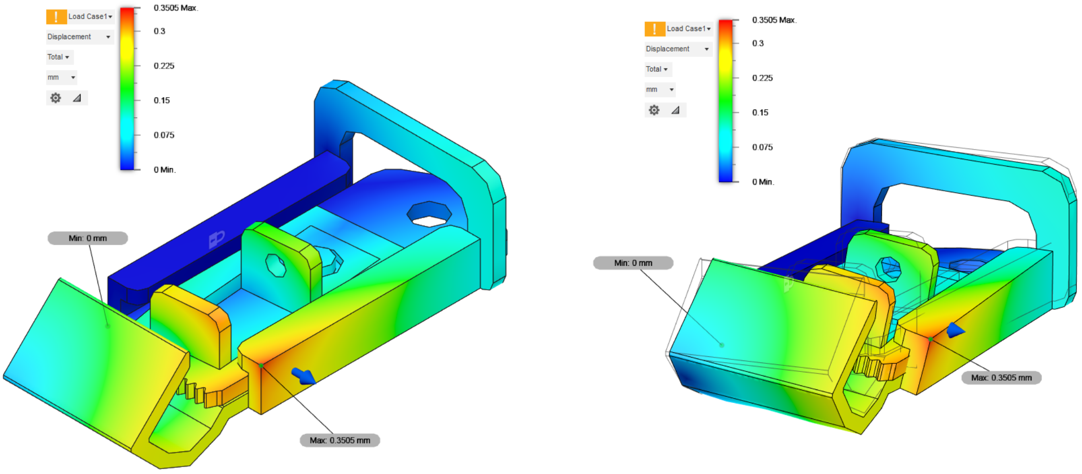


Figure 41: Static load case 3 displacement: actual (left) and adjusted (right).

The principal stress concentrations for this simulation were observed at the point where the top plate and stopping wall coincide, amounting to 465.6 MPa. In addition, significant stress was detected on the opposite side and on the partially threaded bolt that serves as an axle for the top plate, as depicted in figure 42.

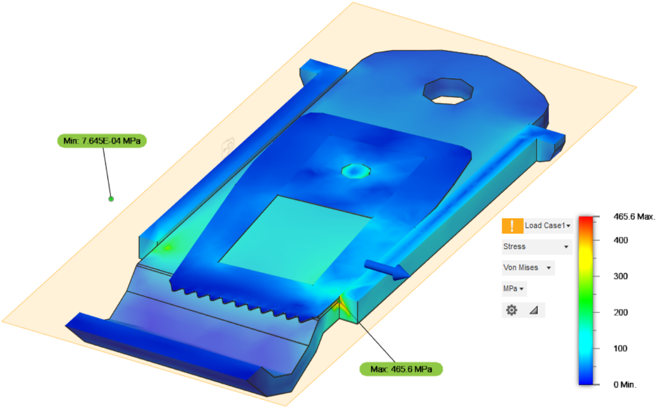


Figure 42: Static load case 3 stress (Von Mises).

The safety factor simulation identified two points of concern: the bolt with a safety factor of about 1.115 and the point where the top plate and the stopping wall coincide, showing a safety factor of 1.718, as shown in figure 43.

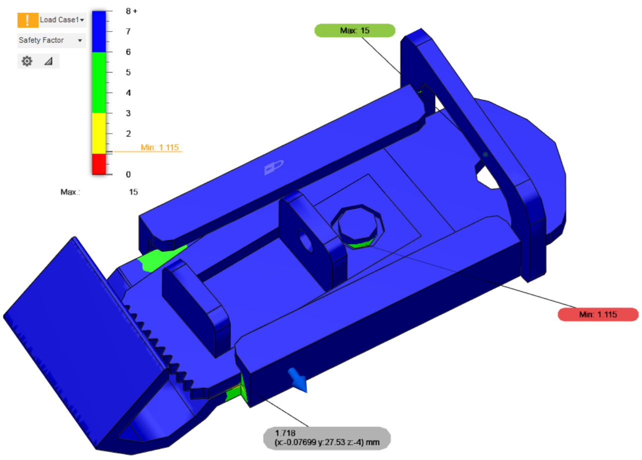


Figure 43: Static load case 3 safety factor.

5.3 Usability

To test intuitiveness of the concept, a group of students at the faculty of natural sciences, NTNU, were asked to connect the prototype to a rope, without additional information. They all managed to successfully connect the two within 10 seconds, with most of them completing the task in under 5 seconds. They were also asked to rate how intuitive the design was on a scale from 0-10. The group gave the design an average score of 9/10, which reflects a high usability with little to no guidance needed.

5.4 Production

Throughout the design process there has been a focus on economic efficiency and simplicity. In line with this, method of production has been investigated. Considering the material choices mentioned previously, as well as the geometry of the final design, some sort of sheet metal fabrication method is deemed the most viable. A combination of cutting, stamping and bending is sufficient to afford all geometries (except for the spring, axle and bolt) of the final design. These methods open the doors for mass production by being technologically simple and easily incorporated into a production line.

6 Discussion

6.1 Simulations

Simulations offer crucial insights into the design's performance, although it's important to remember that these represent idealised conditions. The degree to which the simulations mirror actual expected operational conditions needs critical evaluation. The static loads employed in the simulations might not fully encapsulate the dynamic forces the mechanism could encounter in real-world usage. Dynamic loading, impact forces, environmental conditions, or wear and tear could considerably influence the mechanism's performance.

These simulations rested on several assumptions, such as uniform material properties and the absence of friction or wear. However, these may not hold true in a practical setting, especially considering the mechanism is submerged in seawater. In addition, the imposed force of 10.4 kN is likely significantly overestimated. This was primarily selected owing to the load-bearing capacity of the growthline, which has a safety factor of 2.5. The longline's elasticity, which allows it to be pulled to the surface, a distance of 10 metres, suggests that the actual axial forces applied are substantially less than those employed in the simulation, where a stationary constraint was used.

A lateral force was incorporated into the simulation to emulate the mechanism's movement along the longline. This force arises primarily from ocean currents acting on the surface area of the kelp growing along the growthline, which is expected to increase as the kelp matures. The mechanism's design permits only lateral movement along the longline, provided that the mechanism doesn't fail. It's reasonable to suggest that the forces acting on the growthline in the actual environment are far from solely lateral. These forces heavily depend on local conditions and ocean currents. A fluid dynamic analysis, using data from the cultivation facility's location, is necessary for a more comprehensive understanding of the mechanism's structural integrity, although this is beyond the current paper's scope.

Future research should also investigate the top plate, which is pressed down on the longline by a spring. A scenario where the weight of the growthline pushes the mechanism downwards faster than the longline descends might arise, leading to the potential for the mechanism to rotate. If the mechanism does not rotate in this scenario, it's plausible that the spring of the top plate might retract if the back plate is pushed downwards, thereby opening up space between the top plate and the longline. This critical scenario merits attention in subsequent research, as it would result in the detachment of the growthline.

Moreover, the sliding mechanism of the top plate, designed to accommodate varying longline diameters, demonstrated in figure 27, is another area meriting future examination. The design exhibits the least stress at the coinciding interface between the top plate and the stopping wall when the slider is fully depressed, owing to the increased surface area. This surface area then decreases as the top plate is pulled upwards, before it starts increasing again. A dynamic study is recommended to assess the implications of these changing stress conditions. An alternative might be to design the top plate optimised for specific line thicknesses, which would trade off the current design's modularity and flexibility.

6.2 User-Friendliness

As previously mentioned, the user tests gave a fair indication of how well the product performs in the hands of untrained individuals. For a more detailed analysis, a larger sample size is required, as well as a thorough investigation into what specific aspects of the model contribute to an intuitive design. Some improvements to the testing may be for example investigating the effect of colour on the design, as well as incorporating instructions or pictograms onto the model surface and see how this affects the results.

The earliest concepts were not tested in relation to user-friendliness. This was because of other more basic issues with the designs, such as not keeping the rope in place or problems attaching it in the first place. The choice to not test them further was therefore made so that the group could concentrate on these basic issues or produce new and better concepts.

6.3 Material & Production

All of the physical models produced during the project duration were made using PLA 3D-printing, disregarding some spare parts such as springs and steel rods. As a result, the project could not produce any experimental results reflecting the actual capacity of the product. Although the material candidates (such as DSS 2205) are described as being heavily corrosion resistant, they will still display a certain degree of deterioration, depending on the environment and usage. The final design involves a sliding mechanism that could potentially be strongly inhibited due to corrosion between the plates. Researching the corrosive properties of the mechanism and material is therefore advised.

Production would likely be carried out according to the methods described in section 5.4. This is a direct result of the design process criteria of wanting to adhere to a cheap and simple production method. However, for the earlier concepts, this is not the case. Most of these concepts would be better suited to methods such as die casting or machining. The same may be applicable to future iterations should the project see further development, and should be investigated on an individual basis.

7 Conclusion

In chapter 2, five major kelp cultivation methods were described, and their unique features, benefits, and challenges presented. This provided an in-depth understanding of various cultivation techniques, evaluating their adaptability in different scenarios, and conditions to be met for leveraging their strengths and overcoming their limitations. These techniques were then reviewed based on attributes such as scalability, environmental impact, and economic feasibility. Understanding these factors was critical in determining the most effective method to maximise the potential of kelp cultivation in offshore environments. Furthermore, it identified that large-scale cultivation was pivotal for the growth of the industry in western countries. The understanding gained from the exploration of different cultivation methods provided a comprehensive perspective on the current state of kelp farming practices, which in turn served as a platform for innovation for further development of the KelpClip.

Methodologically, we primarily relied on a user-centered approach and an iterative development process, which naturally resulted in a bulk of different concepts being generated. A handful of the most promising concepts were turned into more sophisticated 3D-models using CAD software.

After the first generation of designs were made, a more rigid methodology was also implemented by evaluating the designs to a larger extent towards the more technical product requirements. This resulted in the decision to further develop concept B1 which differentiated itself from concept A1 and C1, showing greater promise concerning the locking capabilities along the longline, while also achieving high scores in relation to the other requirements. The process then, once again, shifted to a more iterative approach, into what eventually became the fifth generation design; the KelpClip.

Prototypes were made of all designs presented in the results. Especially the KelpClip prototype showed great promise when testing was conducted.

When evaluating the final design through simulations, the use of static loads analysis was used to simulate the axial and lateral loads. Even though a dynamic load simulation in conjunction with an analysis of fluid dynamics at the locality would be ideal, the two static loads were considered to be within the scope of the paper and yielding satisfactory results. Primarily because of the design of the final design only allowing for lateral movement along the longline, while the growthline applies the vertical force.

Taking into account the systematic approach and methods used, the project has proved to be a valuable learning experience for the authors. By being exposed to a genuine product development opportunity we have been able to improve upon our skills as engineers. It is also worth mentioning that working in a team, although not very big, has demonstrated the importance of good communication and cooperation.

The project has not only afforded a viable solution for kelp-cultivation efficiency, but also highlighted the importance of the continued use of kelp as a resource. In this way, we hope to inspire innovation and research within the field. Finally, we hope that this work contributes meaningfully to the growing field of sustainable kelp cultivation and the development of tools and technologies that support it.

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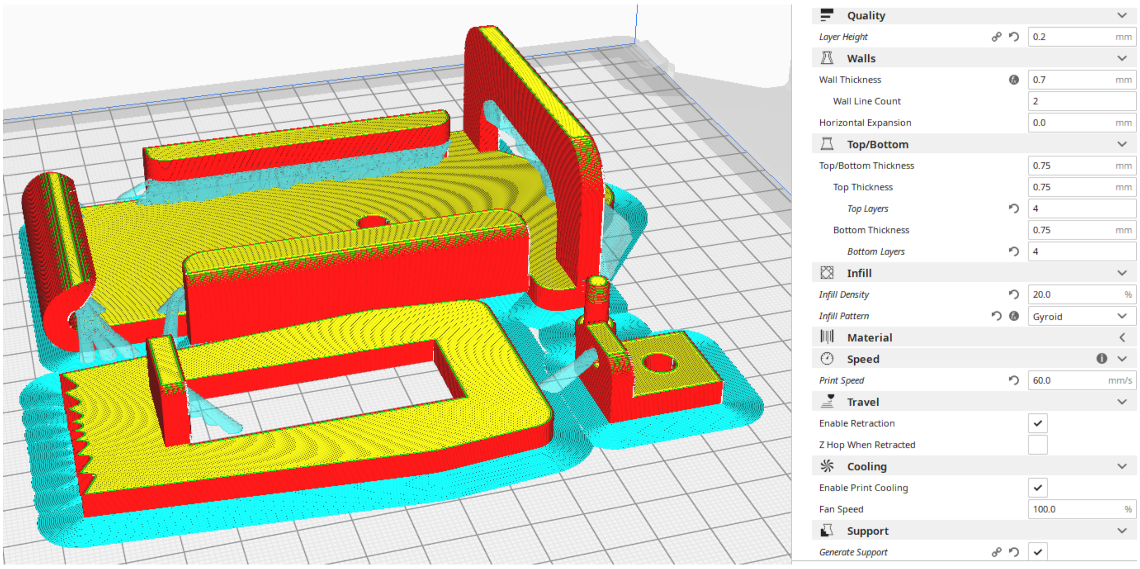
Appendix

A Print Parameters



Quality		
Layer Height	0.2	mm
Walls		
Wall Thickness	0.7	mm
Wall Line Count	2	
Horizontal Expansion	0.0	mm
Top/Bottom		
Top/Bottom Thickness	0.75	mm
Top Thickness	0.75	mm
Top Layers	4	
Bottom Thickness	0.75	mm
Bottom Layers	4	
Infill		
Infill Density	20.0	%
Infill Pattern	Gyroid	
Material		
Speed		
Print Speed	60.0	mm/s
Travel		
Enable Retraction	☑	
Z Hop When Retracted	☐	
Cooling		
Enable Print Cooling	☑	
Fan Speed	100.0	%
Support		
Generate Support	☑	

Figure 44: Model preview of the KelpClip in Ultimaker Cura 4.9.1.

B Sketches

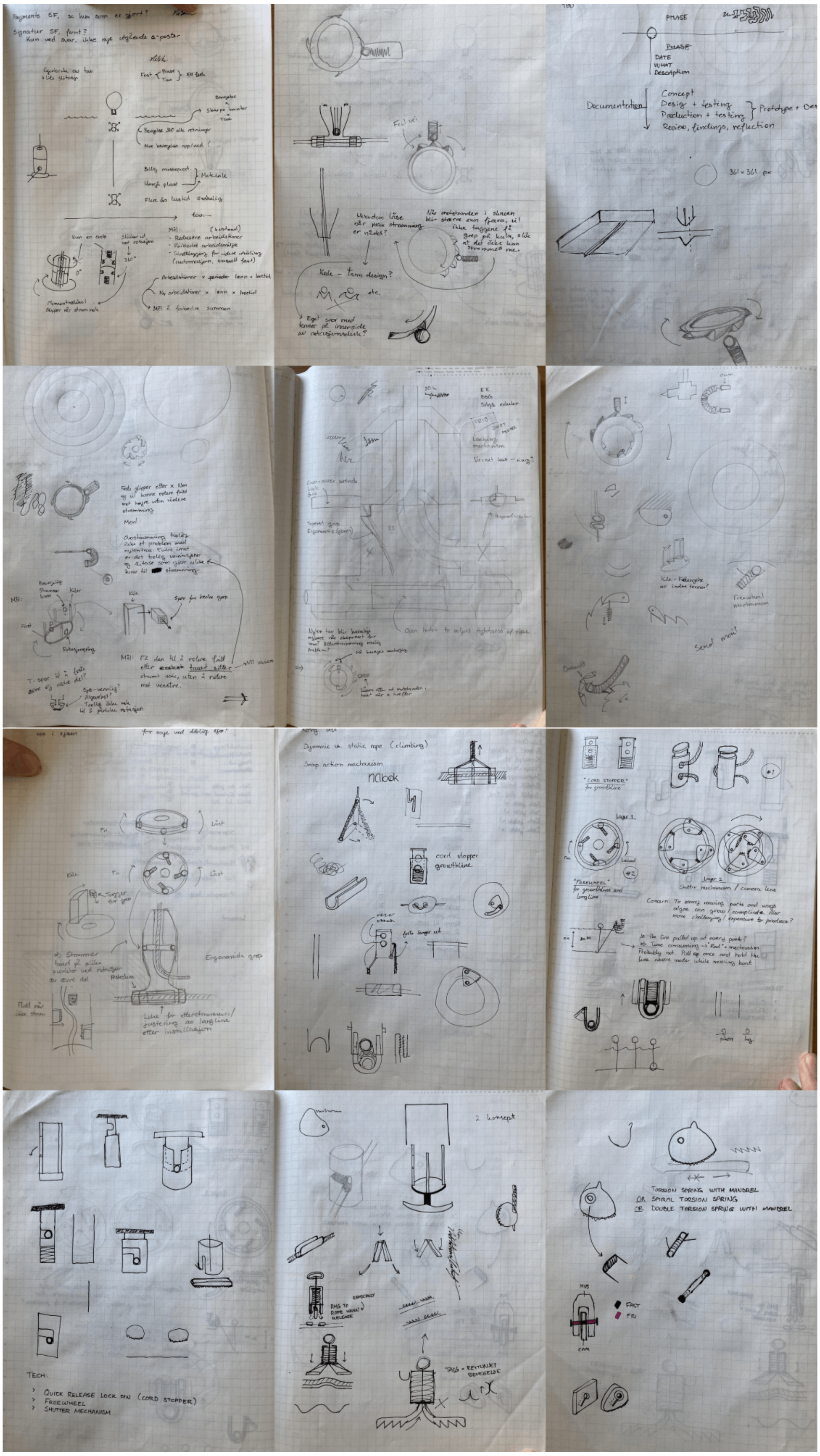


Figure 45: Sketches during the development process.

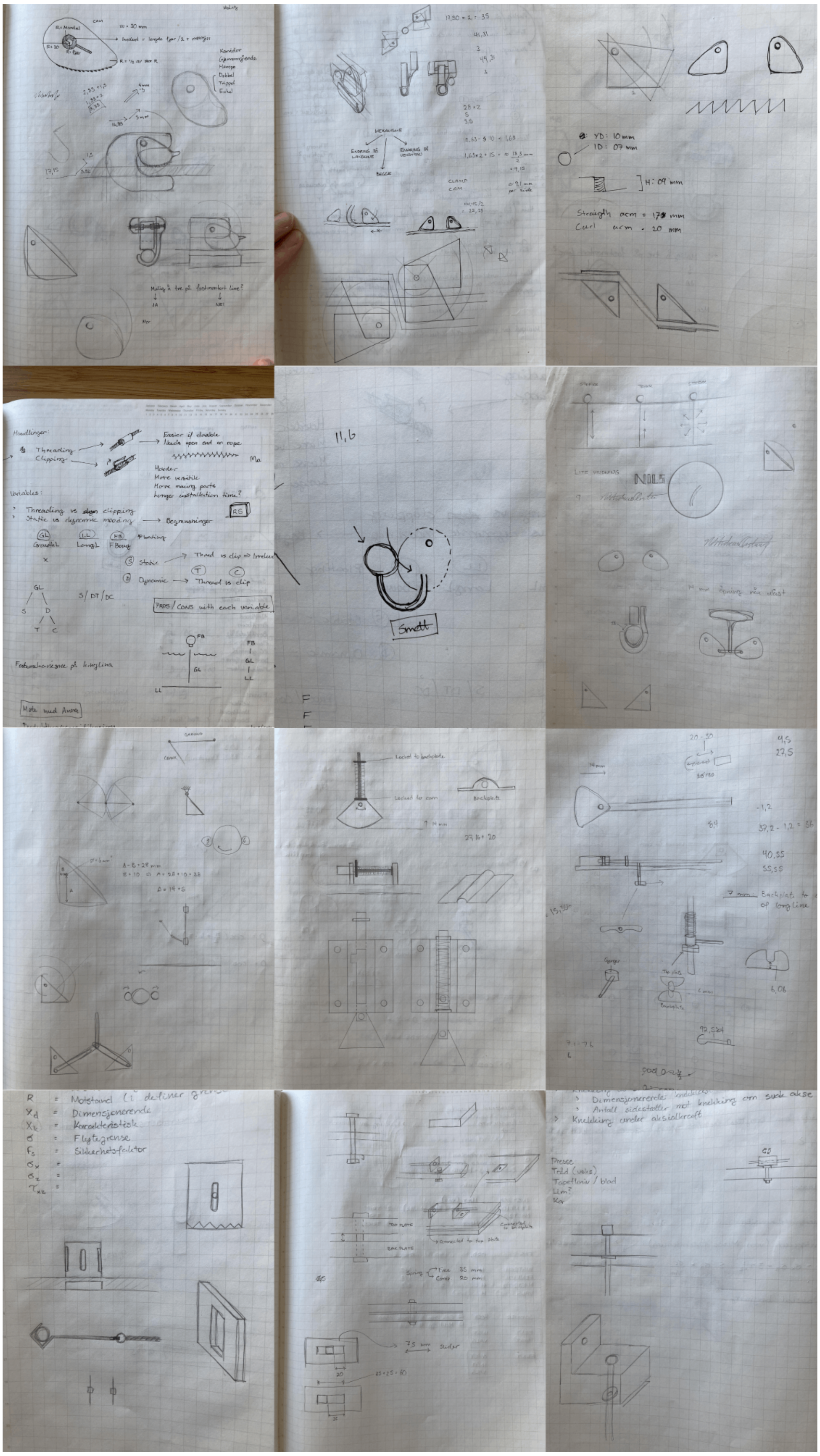


Figure 46: Sketches during the development process.

C Moodboard and mind map

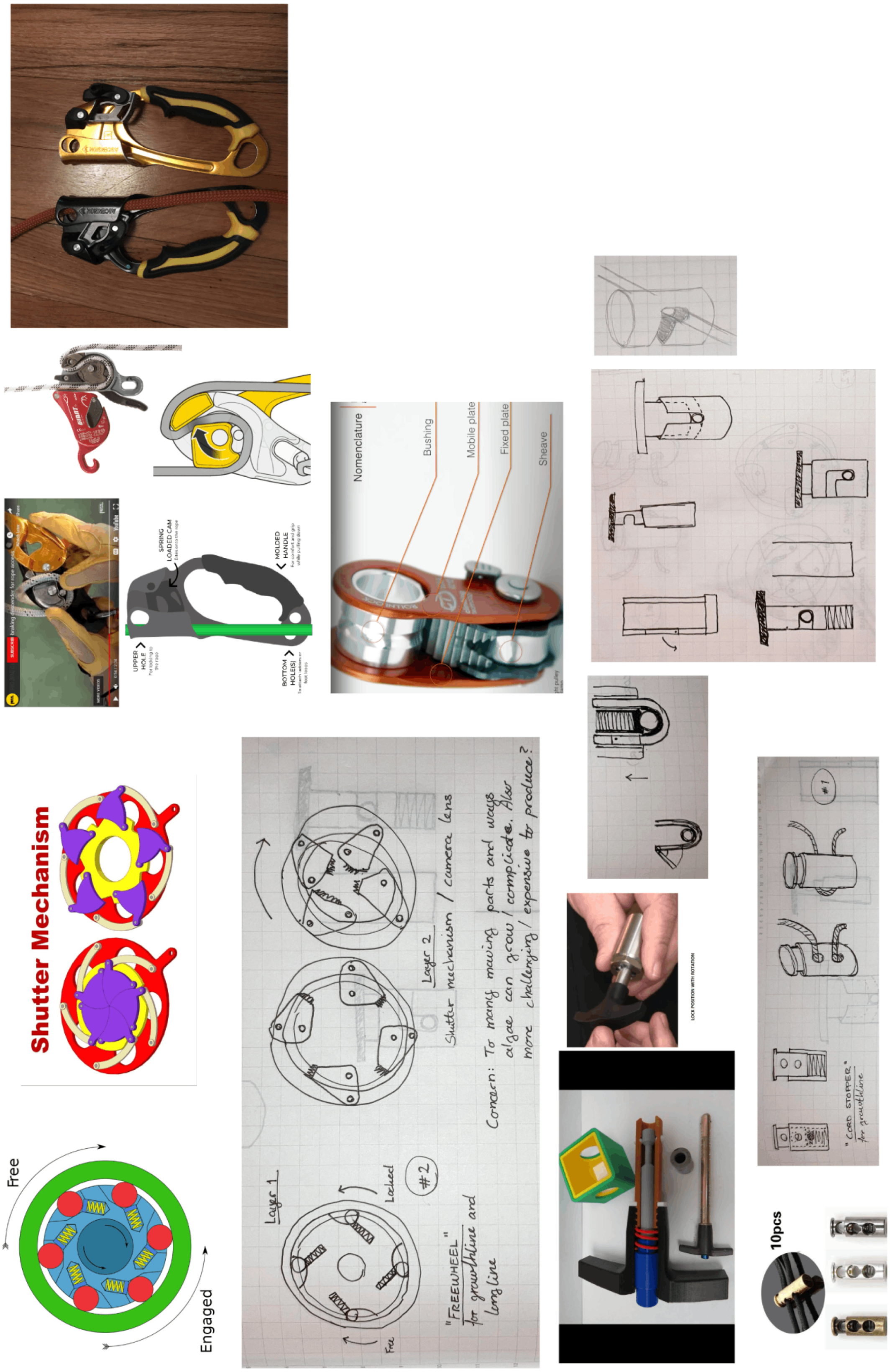
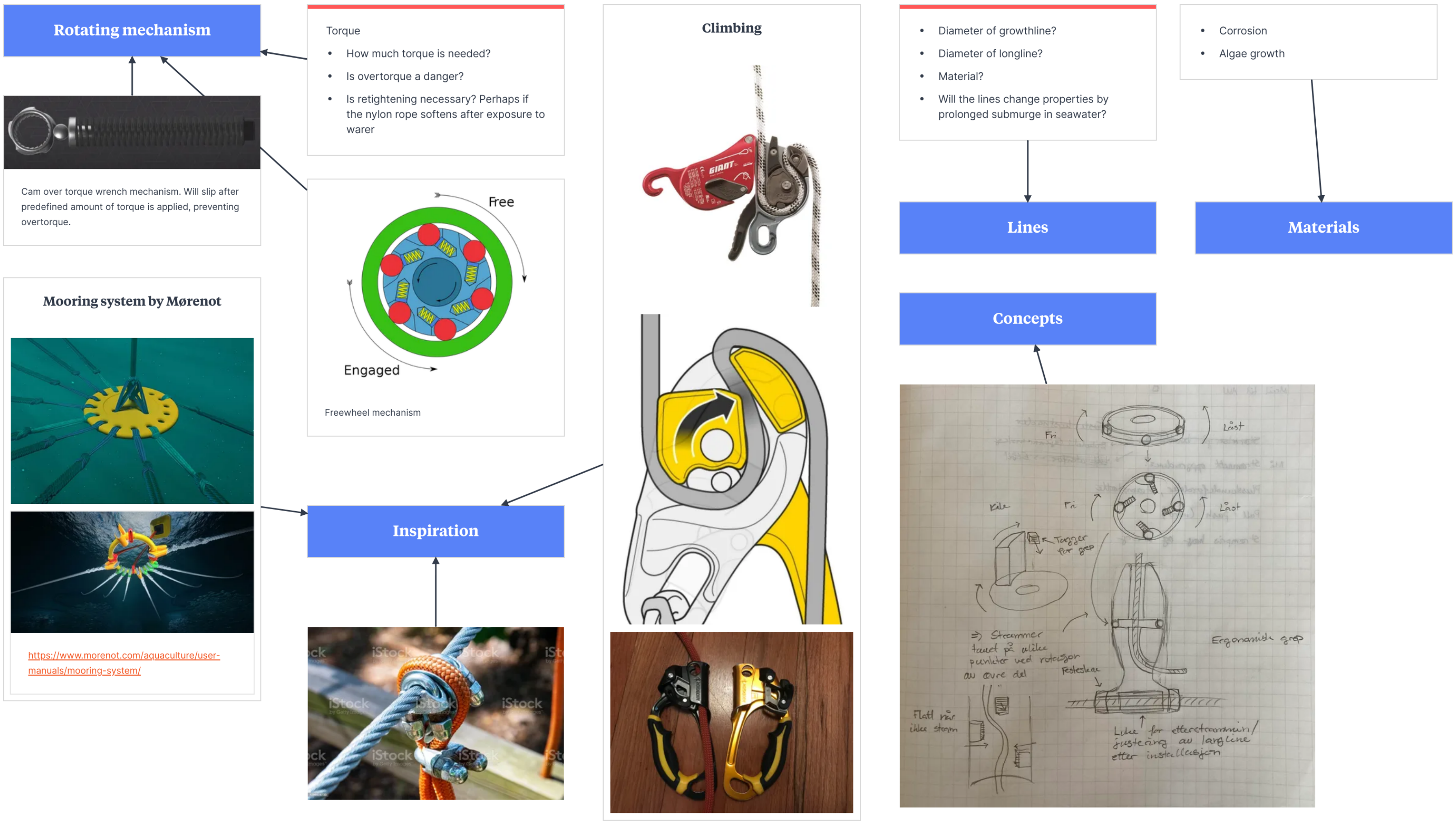


Figure 47: Moodboard from the idea generation phase.



Rotating mechanism

Cam over torque wrench mechanism. Will slip after predefined amount of torque is applied, preventing overtorque.

Mooring system by Mørenot

https://www.morenot.com/aquaculture/user-manuals/mooring-system/

Torque

- How much torque is needed?
- Is overtorque a danger?
- Is retightening necessary? Perhaps if the nylon rope softens after exposure to warer

Free

Engaged

Freewheel mechanism

Inspiration

Climbing

- Diameter of growthline?
- Diameter of longline?
- Material?
- Will the lines change properties by prolonged submurge in seawater?

Lines

Concepts

- Corrosion
- Algae growth

Materials

Figure 48: Mind map from the idea generation phase.

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