Master's thesis

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Industrial lobster farming: a technical investigation and comparison of three different farming concepts

Master's thesis in Marine Technology
Supervisor: Pål Lader
Co-supervisor: Stig Omholt
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Abstract

The European lobster (*Homarus gammarus*) is a highly sought after seafood and there is substantial consumer demand for this species. Wild populations are at critical low points in several places, and the demand is several times greater than the annual catch. Although there have been several attempts in recent decades to establish a sustainable and economically viable industry for lobster production, these efforts have been largely unsuccessful. A major reason for this is that lobsters have to be kept separated due to their inherent cannibalistic habits.

The tendency to cannibalism incurs costs in terms of space requirements and the need for sophisticated control engineering technology throughout the entire production cycle as the lobsters need to be kept separated from each other. The availability of non-cannibalistic (or docile) European lobsters would possibly facilitate the development of an industrial-scale lobster farming industry, as they can then be communally reared. Since a research group at the Norwegian University of Science and Technology has made considerable progress toward the production of such lobsters, it is timely to make an assessment of whether access to docile lobsters may pave the ground for establishment of industrial-scale production of European lobsters. To this end, three alternative production concepts are examined and compared: state-of-the-art individual land-based farming, land-based production of docile lobsters by using recirculating aquaculture system (RAS) technology, and sea-based farming of docile lobsters.

A comprehensive literature review provided the basis for formulating functional requirements related to lobster farming. These were then used to guide the formulation of three putative production concepts to be compared. The evaluation was carried out by use of a set of criteria covering several critical aspects, such as production yield, control of the farming environment, ease of automation and production time. Despite the scarcity of empirical data, the three production concepts were also compared with respect to their probable production costs.

The analysis shows that the production and investment costs associated with the different production concepts vary significantly and that the production cost, in the case of docile lobster farming on land and in the sea, depend very much on the stocking density that can be achieved. In the sea-based farming system, the time it will take for a lobster to reach market size is considerably longer than in the land-based systems. However, numerical modelling results show that, compared to current practise in sea-based farming of other lobster species, the stocking density can be considerably increased before becoming exposed to critical water quality issues. The analysis suggests that if use of docile lobsters in a land-based system allows much higher stocking numbers than what can be achieved in an individual-based system, the availability of docile lobsters would represent a significant improvement. Since this result is highly dependent on the underlying assumptions, it should, however, be interpreted with some care.

Sammendrag

Europeisk hummer (*Homarus gammarus*) er særdeles ettertraktet som sjømat, og det finnes en betydelig forbrukeretterspørsel etter arten. Den ville bestanden er kritisk lav flere steder, og etterspørselen er adskillig høyere enn årlig fangst. Selv om det har vært flere forsøk på å etablere et økonomisk levedyktig hummeroppdrett gjennom det siste århundret, har disse forsøkene i stor grad vært mislykkede. En hovedårsak til dette er at hummerne må holdes hver for seg grunnet deres iboende kannibalistiske tendenser.

Tendensen til kannibalisme medfører høye kostnader i form av krav til plass og behovet for en avansert kontrollteknologi gjennom hele produksjonsprosessen, ettersom hummerne må holdes adskilt fra hverandre. Tilgjengeligheten av en ikke-kannibalistisk (Eng: *docile*) hummer vil muligens legge til rette for en industriell hummeroppdrettsindustri, da de kan oppdrettes felles i samme kar. Ettersom en gruppe ved Norges teknisk-naturvitenskapelige universitet har gjort betydelige fremskritt mot produksjon av slike hummere, er det nå på tide å vurdere om tilgang på ikke-kannibalistiske hummere kan legge grunnlaget for etableringen av en industriell produksjon av europeiske hummere. For å oppnå dette, blir tre alternative produksjonskonsepter undersøkt og sammenliknet: markedsledende landbasert individbasert oppdrett, landbasert oppdrett av ikke-kannibalistiske hummere i et resirkulerende akvakultur-system (RAS) og sjøbasert oppdrett av ikke-kannibalistiske hummere i flytende merder.

Et omfattende litteraturstudium dannet grunnlaget for formuleringen av funksjonelle krav knyttet til hummeroppdrett. Disse ble deretter brukt til å formulere tre formodentlige produksjonskonsepter for å bli sammenliknet. Evalueringen ble utført ved en rekke kriterier som dekket flere kritiske aspekter, som produksjonsutbytte, kontroll over oppdrettsmiljøet, automatiseringsmuligheter og produksjonstid. Til tross for begrensede empiriske data, ble de tre produksjonskonseptene også sammenliknet med hensyn til sannsynlige produksjonskostnader.

Analysen viser at produksjons- og investeringskostnadene knyttet til de ulike produksjonskonseptene varierer betydelig, og at produksjonskostnadene for de konseptene tilknyttet de ikke-kannibalistiske hummerene, i stor grad avhenger av oppnådde biomassetettheten som kan oppnåes. Innen sjøbasert oppdrett vil det ta adskillig lengre tid for en hummer å vokse til markedsstørrelse. Videre viser resultatene til, sammenliknet med praksis innen oppdrett av andre hummerarter, at det ikke virker å være et problem å øke tilstedeværende biomasse betraktelig med hensyn til gitte vannkvalitetsparametere. Analyseresultatene antyder at hvis bruken av ikke-kannibalistiske hummere tillater mye høyere biomassetettheter enn det som kan oppnås i konvensjonelt individbasert oppdrett, så vil tilgjengeligheten av en ikke-kannibalistisk hummer representere en betydelig forbedring. Fordi dette resultatet bygger på en rekke underliggende antagelser, bør resultatet imidlertid tolkes med forsiktighet.

Preface

This thesis represents the culmination of my studies in Marine Technology at the Norwegian University of Science and Technology (NTNU). The thesis is written in the spring of 2023 as a compulsory component of the Master of Science program, giving 30 credits. This thesis is a continuation of the project work conducted in the autumn of 2022, furthering the research and exploration in the chosen field of study. Certain elements have been reused and modified from this work.

In addition to my specialization in Marine Systems Design, I have also pursued the Minor in Aquaculture program, which has equipped me with fundamental knowledge in the field of aquaculture. As lobster farming has not been thoroughly covered in previous courses, a significant amount of time was dedicated to extensive reading, exploration, and in-depth research on the subject. Obtaining the required information for the comparison has been a challenge, and during discussions with various industry stakeholders, it has been observed that there has been minimal activity, while in other cases, excessive activity has hindered active participation. Further, some relevant information is probably nonexistent to this date. However, this work has been very educational, and interesting to work with.

I would like to thank my supervisor, Pål Lader, for providing support through the thesis work. Your enthusiasm has been very motivating. I am also very grateful for the discussions and feedback I have gotten from co-supervisor Stig Omholt. You have been a source of inspiration with your extensive knowledge. Further, I would like to thank Jan Ove Evjemo at SINTEF, for sharing knowledge on lobster farming, and Bård Skjelstad, for providing me with cost estimates. Further, I would like to thank Martin Føre for the discussions on automation, and Frank Spetland for the discussion on lobster biology. Lastly, I would like to thank my student colleagues at the office for much-needed coffee breaks, as well as friends and family, for your support.

Bernt Erik Sætran
Trondheim, June 9, 2023
Bernt Erik Sætran

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1 Introduction

1.1 Motivation

European lobster is one of the most valued seafood in the world [60], [69], [23], [35]. Annual fishing landings do not satisfy market demands, where landings are stable or only slightly increasing [93], leading to an increasing gap between supply and demand [27], [54]. Norway experienced a decrease in the lobster population during the 1950s, and the fishing yields have yet to recover [13]. Current landings have declined by over 95% [4]. Before this decline, about 24% of the European market was supplied with lobsters from Norway [1]. Strict measures are implemented to protect the remaining wild lobster population. To ensure the sustainability of local fisheries, these measures involve a time-limited fishing season and rules defining the sizes of lobster that can be caught.

For more than a century, various methods of lobster farming have been experimented with. These can be grouped into resource / stock enhancement, product enhancement, and full grow-out (closed-cycle culture) [69], [2], [60]. Resource enhancement aims to strengthen the natural stock to increase fishery yields. At the beginning of the twentieth century, efforts were made to create hatching and release sea ranching programmes for lobster larvae in Norway [25], with the intention of capturing the lobsters when they had reached market size. Product enhancement involves the preservation of low-quality lobsters, usually in storage tanks, until they are marketable. Wild-caught lobsters that lack a claw or are soft shelled are often subject to product enhancement, where they are grown until their value increases. Full grow-out produces lobsters from eggs to market size using different intensive farming systems. During the 1960s and 1970s, technical and biological feasibility of a full closed cycle grow-out was demonstrated using different farming methods [90], [69]. Since then, several farming systems have been tested in practical aquaculture [60], [27].

Resource enhancement has only a minor impact on sales as long as the supply of wild animals is low. High larva production costs combined with low recapture rates due to high predation have prevented the establishment of industrial-scale sea-ranching [65]. Thus, lobster farming appears to be the only feasible option for a substantive increase in the market supply of European lobster. In addition to filling the gap between supply and demand and allowing a frequent supply of lobster throughout the year, lobster farming would most likely relieve pressure on wild stocks.

However, the establishment of an industrial-scale lobster farming has also turned out to be challenging. An intensive full grow-out lobster farming system is capital intensive [30] due to high installation and operating costs [93]. The high costs are in part due to the inherent aggressive and cannibalistic traits of lobsters, making it necessary to confine each animal separately.

Recent technological advances facilitating automation and progress in development of technology for producing non-cannibalistic (docile) lobsters, allowing communal rearing, point to the possibility of simplifying farming operations. Furthermore, a farming solution that can handle European lobsters in an efficient manner could be applied to other cannibalistic salt and freshwater crustacean species. Thus, there seem to be ample reasons to explore the pros and cons of docile lobster farming.

1.2 Main objective

The main goal of this thesis is to perform a technical investigation and comparison between a set of lobster farming systems to assess the impact the availability of a docile lobster would have on industrial-scale lobster farming. To confine the scope of the work, the comparison is limited to three different production concepts: individual-based rearing of cannibalistic lobsters in an RAS environment (Concept 1), hypothetical communal rearing of docile lobsters in an RAS environment (Concept 2), and hypothetical communal rearing of docile lobsters in a sea-based environment (Concept 3).

1.3 Structure of the thesis

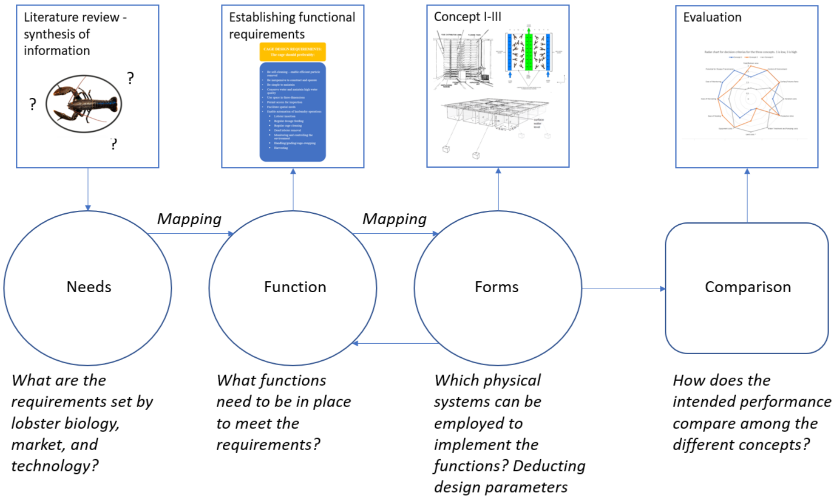


Figure 1: Design of the study

Figure 1 outlines the thesis workflow. First, an extensive review of the literature was conducted to provide an overview of the market situation, the aspects of lobster biology that need to be taken into account independently of production technology, and how these aspects define key functional requirements that are or must be met in the three targeted production environments. In order to provide a necessary foundation for conducting the comparison between the three production concepts, these functional requirements were then used as a background to evaluate possible layouts of production concepts 2 and 3 and identify the most promising ones. Finally, a set of decision parameters was defined, and these parameters were subsequently used to compare the different concepts and evaluate the results of the comparison.

Figure 2 displays topics of relevance to lobster farming related to biology, technology and economy that are addressed in the thesis. Other important aspects such as ethics, legislation, diseases, and environmental issues are not covered in this thesis, as its focus is on farming technology.

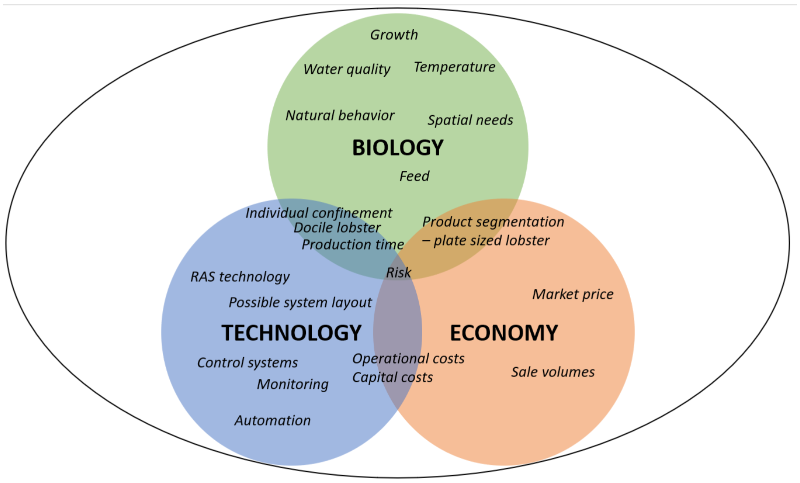


Figure 2: Topics addressed in the thesis

1.4 Contribution

This thesis contributes to the field of lobster farming in the following ways:

- Based on a comprehensive review of the literature, the thesis provides an overview of key biological and economic aspects of relevance to lobster farming. This is then used to specify a set of functional requirements that must be taken into account when designing an industrial lobster production facility. Together, this provides a background deemed instrumental for investors and entrepreneurs considering engaging in the development of an industrial-scale lobster production industry.

- The thesis provides two new numerical models specific to sea-based lobster farming, one that aims to estimate the production time, and one that focusses on the feasibility of increasing stocking density relative to current practise. These numerical models provide a scaffold for future experimental and theoretical work on sea-based lobster farming.

- The thesis explores various concepts of lobster production, how older concepts can be modernised by the use of new automation technology, and pros and cons attached to each of them. This elucidation is likely of interest to potential stakeholders who want to become familiar with what various production concepts may entail.

- The thesis provides estimates of the likely production costs associated with three distinct production concepts. Although the scarcity of empirical data makes these estimates quite tentative, the estimation procedure is likely to offer instrumental guidance on which data are necessary to collect to get more reliable estimates of production costs under various conditions.

- The comparative analysis of three distinct concepts of lobster production presented in this thesis is the first of its kind. By this, it is likely to serve as a reference and motivate more extensive comparative work aimed at deciding which production technology has the best prospects of becoming the foundation for a future large-scale lobster production industry.

2 An introduction to lobster farming

2.1 Market for European lobster

In Scandinavia, annual landings have declined dramatically in the last century, leading to higher prices on the market due to a growing gap between demand and supply [54]. The fishery sales association (in Norwegian: *fiskesalgslagene*) sets the prices for wild lobster caught in Norway [41]. In 2022, for live lobster up to $1.2kg$, prices ranged from NOK $295/kg$ in the Northern and Western parts of Norway [70], [88], [91] to NOK $330/kg$ in the southern parts of Norway [39]. In the United Kingdom and Ireland, landings are higher and the value of landings is roughly EUR $16/kg$ [55].

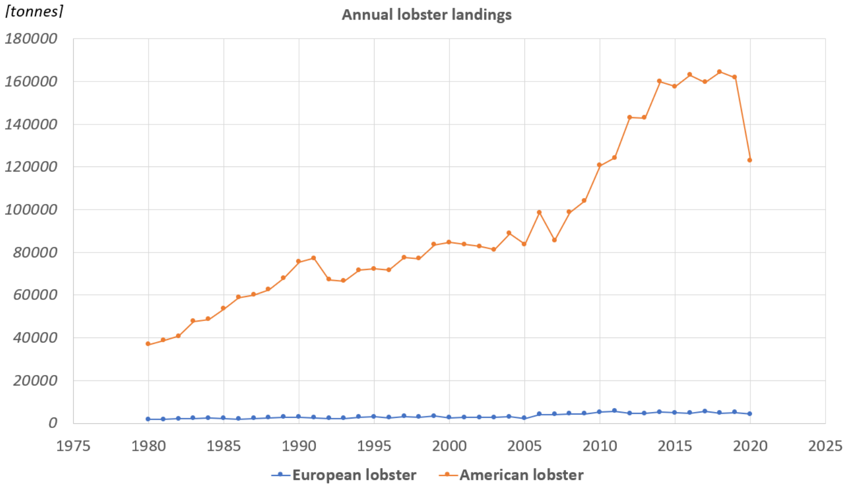


Figure 3: Lobster landings 1980-2020 in tonnes

Source: [37], [38]

As depicted in Figure 3, the landings of European lobsters are marginal compared to those of American lobster, for which the annual landings are approximately 5.000 tonnes and 150.000 tonnes, respectively. In Europe, lobsters are consumed mainly by the hotel, restaurant and institution sectors. France is the largest market for lobster and functions as a distribution hub for other European countries. Between 2009 and 2014, France imported approximately $8000 - 9000$ tons annually. European consumers prefer European lobsters to other lobster species, reducing import in years with increased European lobster landings [74]. Market preferences for European lobster are also caused by culinary experience and product quality, where American lobster is considered inferior to European lobster [35]. As European lobsters are more desirable than American lobster, the European lobster can obtain more than 80% higher price than its American relative [93], and in some cases even twice the price [74]. The prices of European lobsters fluctuate throughout the year. In France, the demand for lobster is at its highest around Christmas and New Year's Eve, and the sale price could be doubled compared to the summer months. Seasonal availability makes prices volatile, and prices oscillate between EUR $15 - 30/kg$ throughout the year [74].

Across Europe, different local laws limit wild harvest to only seasonal events, making steady supplies difficult. Furthermore, regulation restricts the capture of animals within a specific size. In Norway, the legislation limits the capture to individuals above $25cm$ total length (TL). All berried females are protected from fisheries and must be released if caught. The season starts on 1. October and lasts until 31 December. In the coastal area between the Swedish border through Agder municipality, stricter rules limit capture to $25-32cm$ TL, and the season ends on November 30. More rules, including requirements for fishing equipment used in Norway, are given in [40].

One of the many benefits of lobster farming is that it allows a constant supply throughout the year, which is particularly interesting when wild lobsters are not accessible from fisheries. In addition, it may be possible to reduce the volatility of the sale price and establish a stable lobster price by balancing supply and demand. The still-existing import of lobster into Europe shows the potential for a larger sales volume in European markets. Due to the limited natural stocks, industrial lobster farming is possibly vital in achieving a self-sufficient European lobster market.

2.1.1 Product segmentation - the plate-sized lobster

Growing lobsters in cages is both time-consuming and resource-consuming. To mitigate farming costs, it is suggested to farm a lobster up to approximately $250g$ and $\sim 20-22cm$ TL. In the American lobster, a close relative, and the other species of clawed lobsters *Homarus*, the growth rate begins to decline at approximately a size of $250g$. Therefore, a disproportionate amount of time and resources is required to double the weight to $500g$ [2], and prolonged growth after $250g$ is probably not economically feasible [93]. Therefore, creating a new market for an undersized lobster and producing this would reduce costs with respect to production time, spatial demands, feeding costs, and maintenance needs, compared to growing until the fishery size of approximately $450g$ and $25cm$ TL. This smaller product has the name plate-sized lobster or portion-sized lobster. At plate size, the lobster has not reached sexual maturity, giving the undersized lobster a unique taste [84]. From a culinary perspective, the product is exclusive, has a good reputation, reaches high prices on the market, and has higher demand than supply [49].

The product created by Norwegian Lobster Farm (NLF) has met these requirements. In land-based farming systems, lobsters about $250-300g$ at approximately $21cm$ TL are farmed [27]. Their pilot-scale production of lobsters will initially target gourmet restaurants and be sold alive, but large-scale farming could aim to penetrate the Asian market in the future [55]. According to NLF, their production costs per kilo of farmed European lobster are in their systems (excluding research and development) approximately NOK $190/kg$ (in 2021). Keeping a steady supply of high-quality, plate-sized gourmet food available throughout the year, it is possible to fetch farm-gate prices above NOK $500/kg$, which underscores that there exists a profit margin [26]. Plate-sized lobster is also documented to sell for prices NOK $650/kg$ [30].

2.2 Lobster biology

Unlike other marine industries, such as ship construction or oil and gas production, aquaculture is primarily a biological process. Technical farming systems must consider individual differences in behaviour, genetics, and physiology, and therefore viable farming depends on understanding the biology of the lobster. In other words, technical solutions must comply with the requirements given by the biology of the lobster. This section describes what prerequisites the lobsters' biology sets for the design and layout of cage systems used in the later stages of this work.

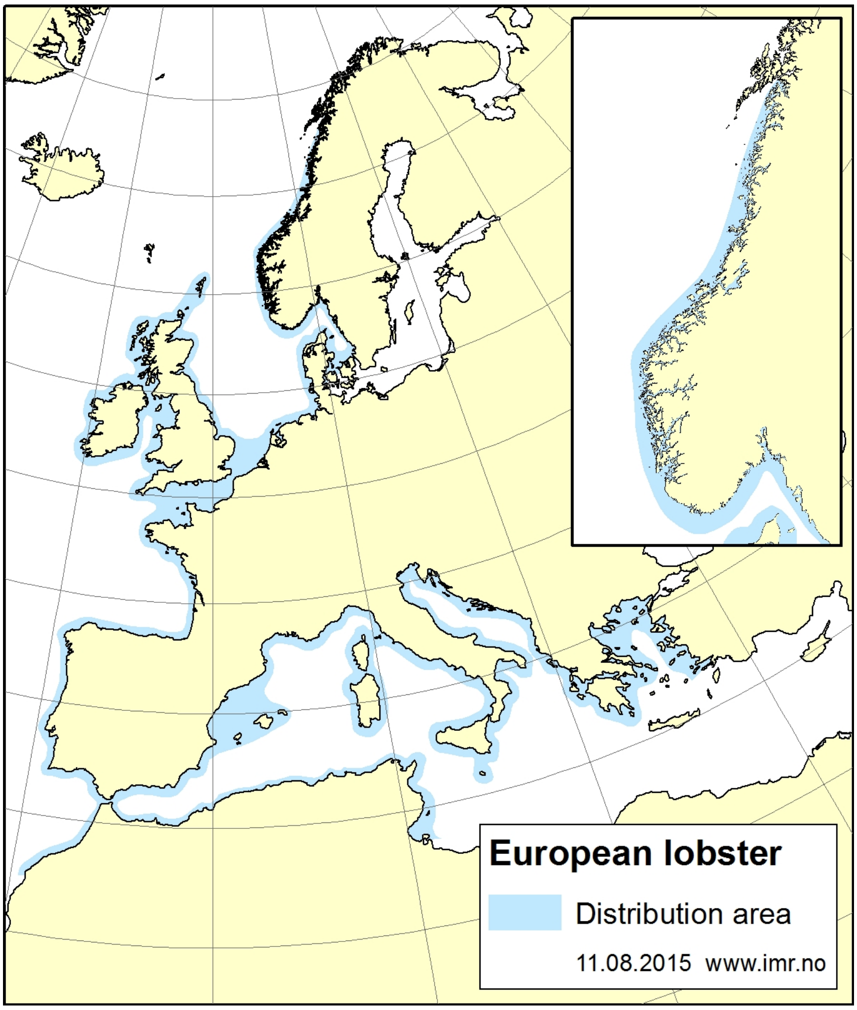


Figure 4: Prevalence of the European lobster

Source: [59]

Figure 4 shows the prevalence of European lobster, indicating its widespread presence from just above the polar circle in Norway to Morocco in the south, including the Mediterranean, the British Isles and some parts of the Black Sea. The lobster is benthic and lives on the sea floor. It prefers rocky substrates, where it finds shelter beneath rocks, crevices, and holes. Their preferred depths range from 5 to 40m [85]. Preferences regarding shelter change throughout the life cycle and are mainly size-dependent. It is impossible to accurately determine the age of a lobster due to the lack of physiological age markers [92]. However, research shows that male and female lobsters could reach a maximum of 40 and 70 years of age and reach a weight of 9,3 kg [52].

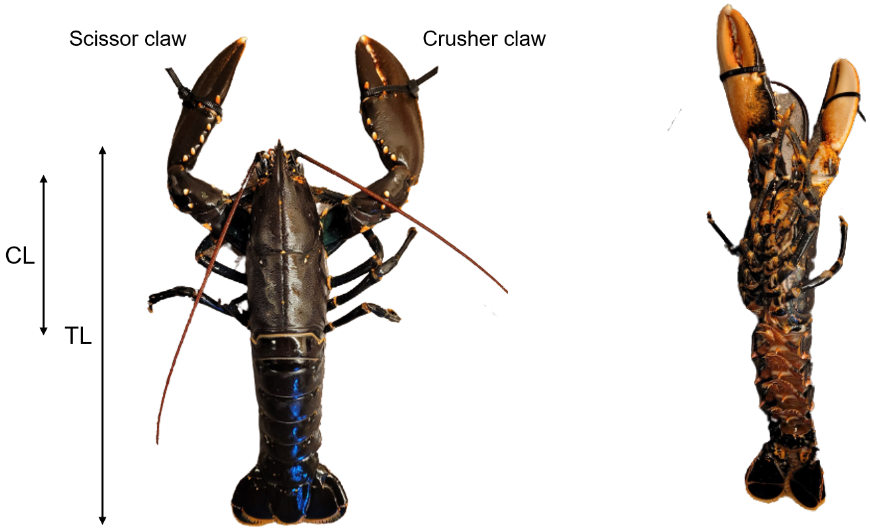


Figure 5: Common length measurements of the European lobster are total length (TL) and carapace length (CL). Note that the chelipeds are immobilized with strips

Figure 5 shows the length measures commonly used to describe the European lobster. Carapace length (CL) is measured from the posterior edge of the eye socket to the posterior edge of the carapax. Total length (TL) is measured from the anterior part of the carapax to the posterior middle part of the tail. These length measurements will be referenced later in this work. The lobster has a set of different claws: one scissor and one crusher claw. The scissor claw is the most responsive and has a serrated edge, which makes it practical for gripping. The crusher claw is used to crush mussels and mollusks, hence its name. Its tail could rapidly contract and create a thrust backwards.

2.2.1 Natural behaviour

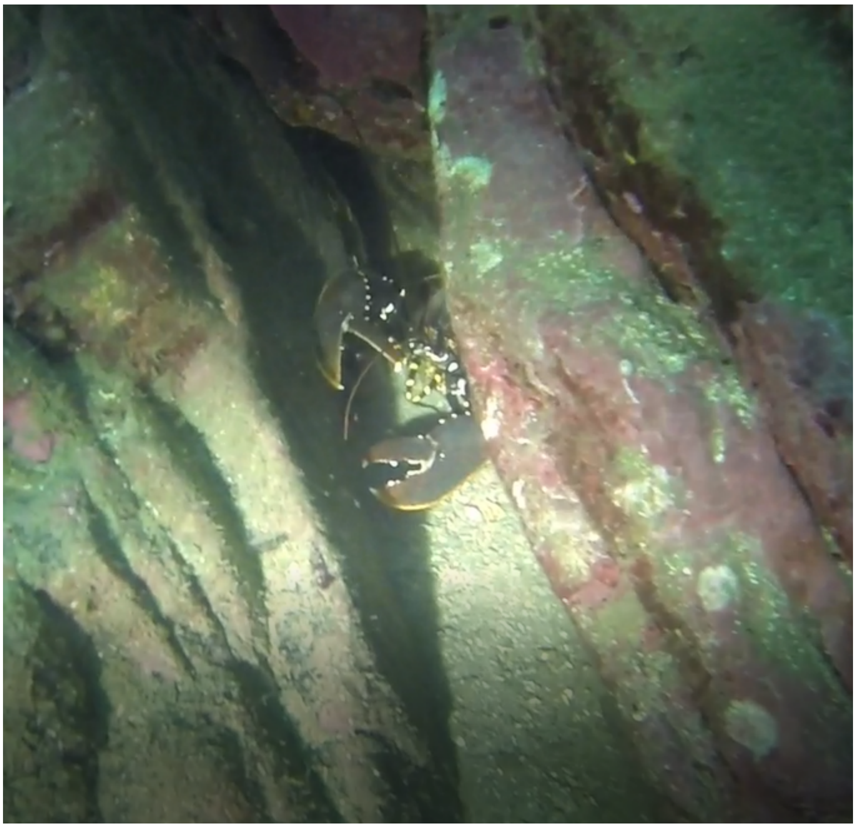


Figure 6: A wild lobster is exhibiting shelter-seeking behavior during daytime. Photo from a dive at 14m depth in southern Norway

European lobsters exhibit a preference for shelter residence during the day [20], [21], [58]. Shelter-seeking behaviour can also be seen in Figure 6. European lobsters are solitaire creatures and do not share shelters in other cases than copulation [58]. The shelter provides protection throughout the day and is often found in rocky crevices or beneath larger boulders. European lobsters tend to have a front and back opening in their burrows, which allows better water exchange [20]. In the early stages of life, where predators are more abundant, sufficient shelters are suggested to restrict survival more than access to food in certain areas [19]. Due to their nocturnal behaviour, they start foraging when the light intensity is low enough. The lobsters tend to forage relatively close to the shelter and could cover distances up to $300m$ during the night. However, this depends on each individual [20], [58].

The lobster is omnivorous and feeds on mussels, bivalves, hermit crabs, and carrions [85]. Some lobsters may wander around during the day in turbid or deeper waters, where the light intensity is consistently low [20]. As the size of the lobster increases, the number of predators able to catch them decreases. However, even these larger individuals continue to seek shelter. An explanation for this behaviour lies in the need for protection during molting and mating, in which lobsters are very vulnerable to predation.

European lobsters usually seek shallow hot water in the summer and more temperature-stable water at greater depths in the winter. Having a set of different shelters throughout the year, migration between shelters takes place at an individual level when the temperatures are favourable in the different water layers. Capture-recapture experiments show that they are predominantly stationary. Experiments with tagged lobsters in Kvitsøy between 1998 and 2000 showed that 40% of the lobsters were recaptured in their release zone. Furthermore, 84% of the lobsters remained within $500m$ [1].

2.2.2 Lobster growth

In the 1960s and 1970s, studies on clawed lobsters demonstrated the feasibility of growing lobsters to commercial size in only 2 years using heated water and daily feeding compared to the 5-7 years it takes in the wild [93], [89]. Possibilities for a production time of $450g$ in 3 years are also reported [69]. In the wild, a 22 cm lobster (estimated weights $250 - 300g$) could be between 9-11 years old [85]. These examples demonstrate that growth can vary significantly depending on environmental conditions, where temperature is the fundamental determinant of crustacean growth [93]. Being ectothermic (*cold-blooded*), the lobster's metabolism depends on the ambient temperature [51], and increased growth occurs for higher temperatures. For the American lobster, there is a proportional relationship between temperature and growth in the range $8 - 25°C$ [2] . Above $25°C$, high levels of stress and mortality are introduced. Below $5°C$, the lobster metabolism inhibits the animal from molting [92]. In farming, lobsters are not fed below $5°C$ [69], [25]. Low growth rates in colder water also explain why wild lobsters in Norway do not eat in the coldest winter months of January to March and only grow from April to September [60]. Therefore, growing in heated $18 - 20°C$ seawater results in an extreme increase in annual growth rate because the effect of winter growth inhibition is removed, allowing growth and molting throughout the year.

Other factors affecting growth rates are environmental conditions, food limitations, intraspecific interactions, and other stressful farming conditions [92], [60]. Lobsters grow by molting, which is the disposal of the old shell and the formation of a new and larger shell, making lobsters grow in a stepwise manner. The stages of the molting process are well documented [92], [2]. Briefly explained, the chitin from the shell is taken up and stored in the lobster. Subsequently, the lobster evacuates through an opening in the dorsal part of the shell. When the lobster has left its shell, it is very vulnerable to predation. At this stage in the molting cycle, the tissue absorbs water, and the lobster expands. After that, a new exoskeleton surrounding the soft tissue is formed and hardens to a certain degree in a few days. If still available, the same individual eats the old shell, providing valuable resources needed for further growth. During the preparation, recovery, and molting process, the lobster is forced to fast [68]. In the wild, a molting lobster behaves stationary within its shelter. Observations of lobsters barricading themselves for weeks are thought to be related to molting [58]. The time for the new shell to harden could take several months.

For a farmed lobster to reach $300g$ in heated seawater, it must molt approximately 20 times after becoming benthic [60]. This implies a total of approximately 25 molts from egg to plate. However, the amount of individual growth increase could vary greatly even when cultured under the same conditions.

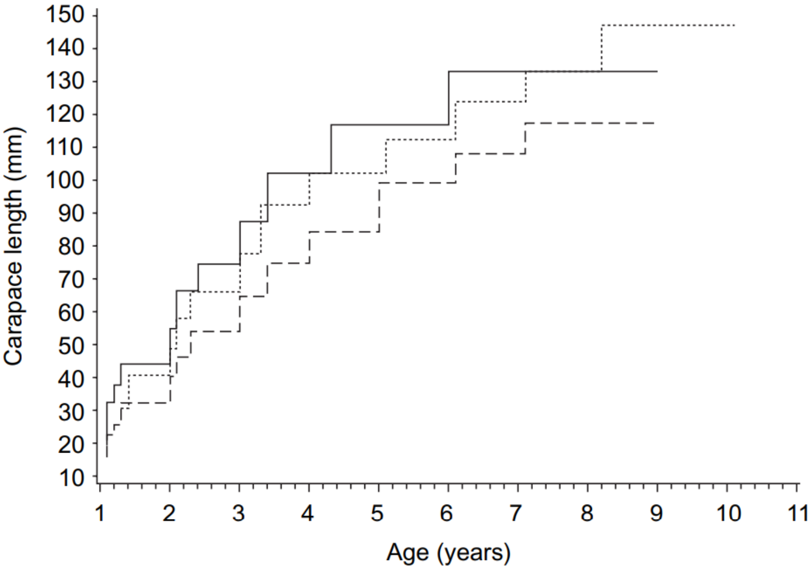


Figure 7: Individual growth trajectories for *Homarus americanus*, reared in the same facility

Source: [92]

As seen in Figure 7, there is individuality in growth trajectories among American lobsters, although reared under the same conditions. Figure 7 also shows a correlation between the frequency of molting and the age of the lobsters, decreasing with age. Growth variations are also observed in European lobster [60].

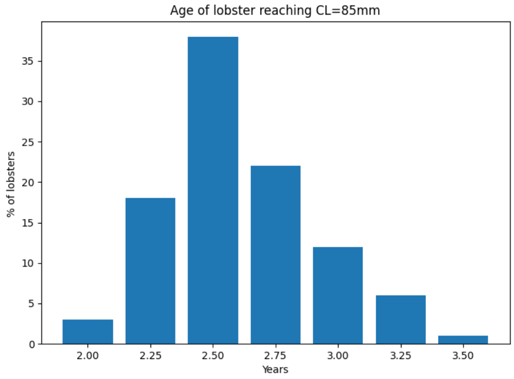


Figure 8: Age distribution of farmed European lobster reaching CL=85mm

Source: Modified from [93]

Figure 8 shows the time it took for different farmed lobsters to reach $CL = 85mm$. Implicitly it also describes growth variability in terms of variation in time to grow to the same size. To get a better understanding of why this variability exists and what it means for practical farming, it would be beneficial to explore the lobster production cycle.

2.2.3 Hatching

Present state-of-the-art lobster hatcheries use wild-caught "berried" (*ovigerous*) females kept individually in special hatching tanks until spawning. Using rapidly matured females reared at $20°C$ as broodstock has led to poor spawning rates, making it ineffective to use production animals as broodstock [60]. In an industrial setting, creating a consistent and high-performing broodstock is important to reduce the effect of variations within growth rates. Furthermore, by controlling genetics through selective breeding, faster growth can be achieved. This process also allows the targeting of other desired traits, such as increased survival and reduced aggression [55]. Creating a broodstock would also relieve pressure on wild stocks by eliminating the need to catch wild berried females and use them as broodstock [60]. In 2021, selective breeding was not yet established in the production sector [55].

The number of larvae each female lobster is able to produce varies greatly. Fecundity, or the number of eggs carried by each ovigerous female lobster, depends on the size, but generally ranges from 5.000 – 10.000 [93], [72], or 5.000 – 40.000 eggs per female [60]. A female lobster could carry semen from several males [21], making a culture of larvae offspring genetically different, underlining the need for broodstock for greater genetic control.

2.2.4 Pelagic stages: Stage I - Stage III

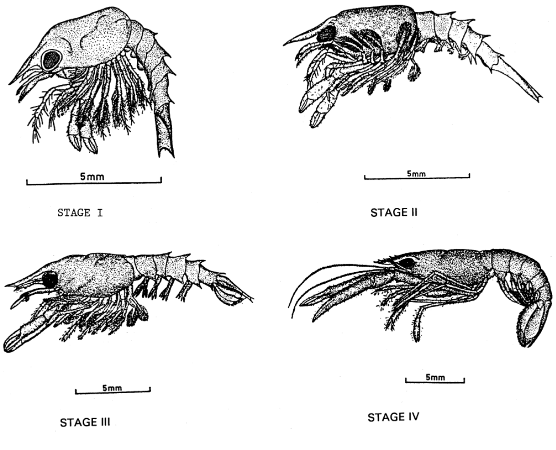


Figure 9: Morphological changes for European lobster from stage I - stage IV

Source: [69]

Ovigerous female lobsters are individually placed in separate incubators until they spawn. After spawning, newly hatched stage I pelagic larvae swim freely in the water column. The larvae are placed in special circulation tanks called incubators, which are designed to separate the larvae from their conspecifics and their mother for cannibalistic reasons. The larvae are picky eaters and are fed live food (brine shrimp - *A. salina*) to limit cannibalism to increase survival [26]. If not adequately fed, the larvae will eat each other [25]. The larvae will remain pelagic until stage III. The time it takes for the larvae to evolve from stage I to stage IV mainly depends on ambient temperature, and approximately 250 degree days [55]. Degree days are the product of temperature and days ($^{\circ}C \cdot d$). At elevated temperatures of $20 - 22^{\circ}C$, the pelagic stage takes approximately 10-14 days [12], with significant variations between individuals. At stage IV, the lobster undergoes metamorphosis and experiences significant developmental changes, including morphological changes such as more forward-facing claws and increased swimming control [62]. Rapidly sorting lobsters after reaching stage IV is essential to reduce further losses to cannibalism [13]. The more developed post-larvae can seek out less developed larvae and consume them. Reported losses to cannibalism during the pelagic phases are often 80% [93]. Measures such as providing a new start feed have shown results in increased survival, from 20% to 40% [14]. Current state-of-the-art hatcheries have a larval survival rate as low as $5 - 25\%$ and are described as a key bottleneck in production [55].

2.2.5 Benthic stages: Stage IV / V - Onward

At stage IV, lobsters begin to seek the bottom and become benthic and are called juveniles or postlarvae [62]. However, it is not until stage V that the lobster becomes truly benthic, and it takes between 12-30 days from hatching until stage V is reached [72]. Their appearances become more similar to those of lobster adults by developing outer characteristics such as antennas and more developed claws, as seen in Figure 9. It is important to quickly sort the newly developed individuals so that they do not consume their siblings. The state-of-the-art uses robotic systems and machine vision to automatically classify and transport stage IV juveniles into individual confinements [27]. In these farming systems, each lobster is individually cultivated until it reaches a plate size, which takes approximately 17.000 degree days at a steady temperature of $18 - 20^{\circ}C$. When farming at these temperatures, the time to grow to a plate-sized product takes 18 to 36 months, with an average of 24 months [26]. Two cage changes are necessary to provide the correct cage size in the growing phase using individual confinements [23].

2.2.6 Feed requirements

It is shown that European lobsters could be fed solely on a formulated diet from egg to plate [27], but some formulated lobster feeds only provide $50 - 80\%$ of growth rates compared to natural feeds [28]. Lobsters fed a pelleted diet acquired a Feed Conversion Rate (FCR) of $1.0 - 1.17$ in certain farming systems [60]. FCR is the increase in lobster weight per unit of feed given. In commercial production, an FCR of 1.5 is documented [27] which is slightly higher, although the feed had the same chemical composition. Solely fed fresh mussels, the dry weight FCR was 5.9 [12]. This is for

American lobster grown to $350g$, therefore, not completely comparable. Other feed sources have been tested, and feeding conspecifics to lobsters shows that lobster growth actually benefits from cannibalism, at least in the early stages of life [75], [60].

An important note on the diet is that most crustaceans process their food with their claws and mouths prior to ingestion [93]. This could make feed attributes different from what is favourable in the salmon industry, where the fish could swallow larger pellets. Feed pellets must not only be well formulated and processed but also bound in such a way that the integrity of the pellet is maintained and wastes are kept to a minimum. For this reason, a small pellet of only a couple of millimetres is provided to each individual [22]. In addition to growth considerations, accurate feeding is vital for water quality as it depends on suspended solids, especially in a closed system [12]. For a closed system, the need for accurate feeding is pointed out: *"A fully automated farming concept requires a formulated feed that can be portioned in exact amounts to each lobster in each cage in order to avoid excessive feeding and feed waste. It is also important that the feed is resistant to the farming environment without dissolving too fast"* [60]. Excessive feeding could lead to uneaten feed waste and must be kept to a minimum to provide a high level of water quality. Feed waste could be consumed by bacteria that consume available oxygen and produce carbon dioxide. Feed waste could also sediment with faeces under cages and cause lethal levels of hydrogen sulphide (H_2S) to arise [64], [18]. Therefore, a system design should be able to remove the particular matter from the cages effectively.

2.2.7 Water quality requirements

Several pilot projects have been tested in closed land systems and estimates for optimal water quality parameters have been established. For an open system with an excessive level of seawater renewal, all of these parameters may not be of vital importance. On the other hand, for a land-based RAS, parameters such as ammonia might be paramount.

Temperature [°C]	O_2 [mg/L]	CO_2 [mg/L]	pH -	Salinity ‰	TAN [mg/L]	$NO_2 - N$ [mg/L]	$NO_3 - N$ [mg/L]	Density [kg/m3]
18-20	>6	n.a	7.8-8.2	28-35	<0.3	n.a	n.a	n.a

Table 1: Water quality parameters observed at general conditions in RAS lobster farming

Source: [23]

Table 1 states that the temperature for lobster farming is between $18 - 20°C$. Farming at these temperatures is significantly beneficial because of the increase in growth rates, which reduces the overall production time. Salinity should be maintained between $28 - 35‰$. The lobster is a marine species and the recommended salinities are based on this. The oxygen content should be above a saturation of 80%, which corresponds to $> 6mg/L$ at the suggested farming temperature. The ability of water to rapidly dissolve oxygen decreases at increasing temperatures. It stands in contrast to the oxygen requirement in lobsters, which is strongly related to metabolism and increases with temperature [51]. This effect is ironically called nature's joke on aquaculture. There is abundant oxygen at low water temperatures when metabolism restricts the need for oxygen, while oxygen availability is limited when needed at higher temperatures [7]. Special oxygenation devices are applied to provide sufficient oxygen levels in a closed system at elevated temperatures. However, oxygenation using supersaturated seawater should be handled carefully, as air bubbles could develop and block blood flow causing severe damage [27]. No explicit recommendation was found for CO_2 levels in lobster farming during the literature review.

In a RAS, ammonia concentration is the most likely water quality limiting factor for lobster farming [60], [23]. Ammonia is the main metabolic waste product and is denoted NH_3. Ammonia is in equilibrium with ammonium, denoted NH_4^+, which together makes up Total Ammonia Nitrogen (TAN). The ratio between NH_3 and NH_4^+ depends on the pH [64], [2].

Although ammonia is the most toxic compound in TAN, the literature review has provided water quality requirements as prescribed in TAN. However, ammonia levels could be determined by knowing the pH [64]. The level of TAN in lobster farming operations is recorded at around $0.3mgTAN/L$ [12], [23]. Although optimal levels of nitrite and nitrate have not been established in farming, acceptable levels of nitrite and nitrate in the short term could be $5mg/L$ or $100mg/L$, respectively [27].

In addition, excretion rates for TAN and CO_2 for different sizes of lobsters, as well as oxygen consumption, have been estimated [31]. It should be noted that the results for CO_2 are not a regression result, but the production of CO_2 was stated to be $1,5-2$ times the consumption of O_2 in the experiments. CO_2 is albeit included, and here modelled to be $1.75x$ the consumption of O_2. The parameter CO_2 is included because it is stated to be a limiting factor in intensive production where the present biomass exceeds $> 40\frac{kg}{m^3}$ [31].

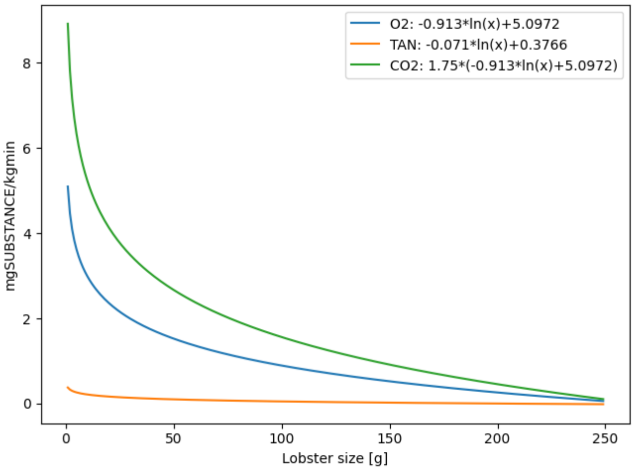


Figure 10: Excretion and consumption rates for O2, TAN and CO2 for different lobster sizes

Source: Modified from [31]

The excretion and consumption values in Figure 10 can be used to calculate the capacities of the required components in an RAS. These components may include pump capacity, biofilter size, tank volumes, and more. Assessing the tank as a control volume, where the presence of lobsters influences the concentration of substances described as a finite amount per volume (e.g., TAN, O_2, and CO_2), the objective is to achieve equilibrium between the lobster production rates and the decrease rates facilitated by the biofilter and degasser [66]. This would return estimates for water exchange needs and estimates for different component capacities. As ammonia is described as the most influential excretion substance, a model of ammonia concentration was established during the project work and the results are applied in the Appendix A. However, the output depends on the load on the system, which is related to the number of lobsters farmed and the specific cage layouts. The load of the system is also determined by the feeding pattern [18]. Therefore, the results are of little relevance before these are determined.

2.3 The lobster cage

A definition for the optimal farming tank was provided by the scientists *Aiken and Waddy*: *" The ideal tank for farming lobsters individually would be inexpensive to construct and operate and simple to maintain. It would be self-cleaning, use space in three dimensions, conserve water, and permit access to the livestock for inspection and feeding"* [2]. In addition to that, there are additional requirements that a cage should meet to ensure good growth. The growth of lobsters is influenced not only by the water quality but also by the physical dimensions of the cages. This aspect will be explained and discussed in more detail here.

2.3.1 Spatial requirements

If not provided sufficient cage space, the growth would be negatively influenced in terms of reduced length increments upon molting as well as decreased molting frequency and survival, and the cage size is the second most important consideration after water quality [2]. An examination of cage size and the effects that this has on growth is carried out [60]. The hypothesis was that the spatial needs for each lobster were given as:

$$A = (aTL)^2 \tag{1}$$

which was the result of [78]. The latter also found that the area factor a was in the range of $a \in < 1, 2 >$. This area corresponds to a cage that spans between 1 and 2 times the total length of the lobster (TL) in length and width. In the trials, the values ranged from $a \in < 0.85, 1.23 >$, and linear growth rates were found within all test cases. Thus, it was concluded that growth restriction was not observed and that the European lobster is less susceptible to growth restriction than the American lobster. However, it is noted that these results are based on smaller individuals and that similar trials should also be conducted for larger juveniles and adults [60]. These results have not been found; however, similar trials have concluded that cage width should not be less than lobster TL [90]. In other words, the cage should not be shorter or narrower than the lobster itself.

Lobster size (mm CL)	Age (months)	Area of container (cm^2)
5-10	1	25
11-25	4	115
26-40	12	310
41-60	24	620
61-85	30	1058

Table 2: Suggested container floor areas for individual confined clawed lobsters

Source: [93]

In Table 2 suggested cage areas for individually confined lobsters are presented. This table uses carapace length as a length measurement. It is also reported that the shape of the cage has not been shown to impact growth considering different geometries, such as circular, rectangular, and triangular cages. However, odd geometries would probably be expensive to construct, making rectangular or square geometries preferable from a production point of view.

2.3.2 Stocking densities

Stocking densities is linked to the lobsters spatial requirements, and in order to sustain growth the stocking densities is important to consider. Despite the absence of a suggested stocking density, as described in Table 1, there are some recommendations. Considering the plate-sized lobster at $22cm$, the lobster would have a CL of approximately $60-65mm$ using a coherence between the TL and the CL of $CL = 0.3512TL$ [60]. Having $1058cm^2$ available, as recommended in Table 2, this implies that $a \approx 1.5$ for the largest lobsters, using Equation 1. Using the ratio between CL and weight given in [60], stating that $weight = 0.0003CL^{3.1522}$ and the suggested stocking densities of [93] results in the following table to estimate stocking densities up to plate-sized lobsters:

Lobster size [mm CL]	Weight (mean)[g]	Individuals per m^2	Corresponding biomass $[kg/m^2]$
5-10	0.2	400	0.08
11-25	3	87	0.26
26-40	18	32	0.58
41-60	70	16	1.12
61-85	224	9	2.02

Table 3: Floor areas and corresponding biomass

Source: Modified from Table 2 and [60] and [93]

These estimates are for individually confined lobsters and provide insight into the lobster's spatial needs. However, studies have also been carried out on communally farmed lobsters. Research on cheliped immobilized lobsters, at a size corresponding to $50-81mm$ CL and farmed communally, suggests a maximum stocking density of $1.0kg/m^2$, whereas $0.8kg/m^2$ is closer to optimal growth and survival [3]. This was for lobsters provided with sufficient shelter and stocked at a similar size to avoid hierarchies.

All the spatial requirements mentioned earlier have been limited to a two-dimensional (2D) plane. The literature review did not uncover any recommendations for spatial requirements in the vertical direction. However, using three-dimensional space, stocking densities could be increased to $45\frac{kg}{m^3}$ for portion size lobsters [27]. Since these are individually confined, this could indirectly say something about the height provided. Using Table 3, $45\frac{kg}{m^3}/2.02\frac{kg}{m^2} \approx 22.3$ would be the number of cages that must be stacked in the vertical direction. This only leaves $100/22.3 \approx 4.5cm$ water depth available for each lobster: whether this is enough water to submerge the lobster is questioned. Therefore, it is reasonable to assume that the actual stocking densities in farming differs from Table 3, highlighting an uncertainty in the established stocking densities.

2.3.3 Substrate

A simple solution in cage design would be to construct several cages with the same attributes, i.e., the same material is used to cover the walls, ceiling and floor of the cage. However, having only a plastic surrounding could result in morphological growth anomalies - being exposed to shell sand at stage V is necessary for the lobster to grow a crusher claw [61], [55], [60]. In practical farming, when lobsters are farmed in a plastic environment throughout the stage, they will develop two scissor claws. The size of the floor mesh is also essential. If the mesh size is too coarse, the lobster's walking legs could slip between the slits on the floor, which might be unfavorable in terms of stress. Another theory is that having a hold-fast, where the lobster could pinch and hold on to something, could facilitate the molting process [36].

2.3.4 Hydrodynamic limitations

When the lobster is exposed to currents and wave surges that exceed a certain point, it will lose control of its antennas and its ability to walk, and in the worst case, it may even tumble and slip downstream. For lobster adolescents ($50mm$ CL) control of the antennae and walking could be impaired at as low a current as $10-15cm/s$. On both rock and gravel substrates, some lobsters are observed to slip downstream at currents from $21-43cm/s$. In a wave surge, where the drag force oscillates, and posture against the force is impossible, it is argued that the movement threshold could be even lower [62]. The need for shelter against such challenging situations is thus stressed to maintain welfare in such an environment.

2.3.5 Shelter

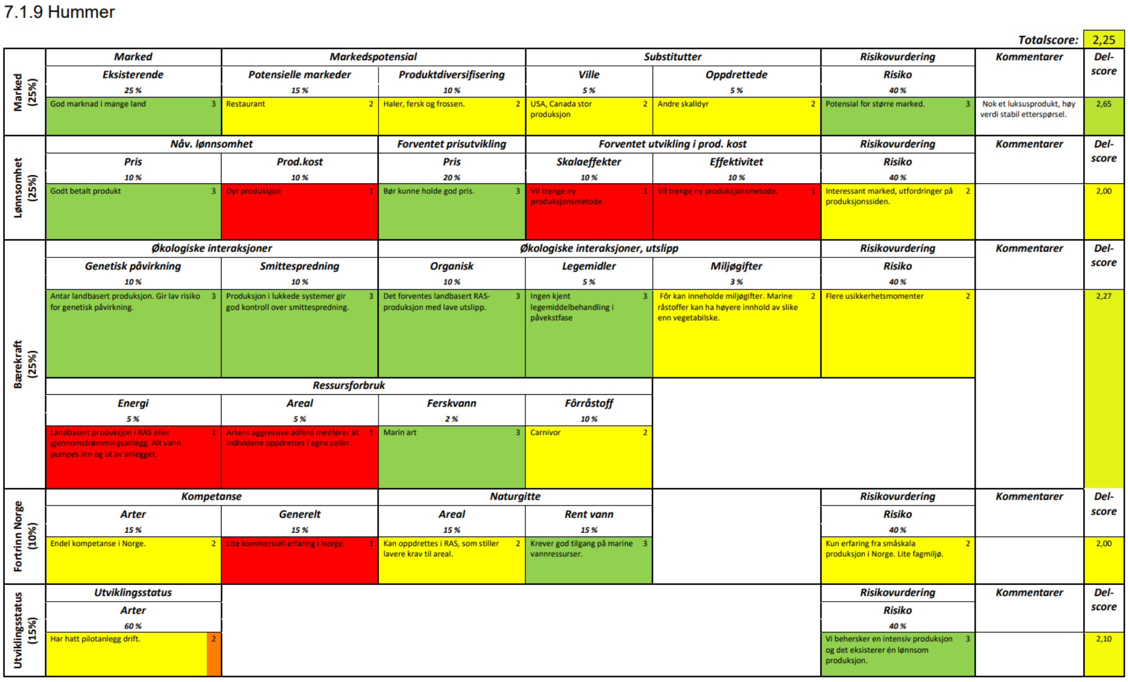
Separate cages arguably provide shelter from conspecifics and do not appear to be a focus area in European lobster farming. However, in the communal farming of western rock lobster, the presence of shelters has increased survival rates [57]. Here, both mesh and brick shelters were tested. No differences in growth rates were observed, but there were significant differences in survival rates, with the following recommendation for mesh shelters. A shelter could not only be beneficial to provide shelter from conspecifics, but also in the likelihood of experiencing currents and waves affecting the hydrodynamic limitations of the lobster, especially for a sea-based concept.

2.4 Development, status and main challenges in lobster farming

At the beginning of this millennium, it was possible to read about the lack of success in commercializing lobster farming as a self-sustaining and economically viable industry, despite several decades of efforts. The reasons then were identified as the lack of suitable technology and production methods in the form of systems that a) reduced the number of employees, b) were not very capital intensive, and c) could ensure sufficiently consistent and high water quality in each cage [29]. The operational and capital costs of complex land-based systems were enormous compared to the simpler systems used in other commercially viable aquaculture operations [2]. The economics of farming was also challenged due to the increase in lobster landings, which steadily satisfied market demands in the early 2000s [21], which can also be seen in Figure 3. The problems included not only the very high cost of the physical farm installation, but also the quality of the lobster feed. Consequently, the future of intensive farming depended on the advent of cost-effective diets and system designs [93].

In 2013, the knowledge base was declared to be broad enough to initiate industrial-scale farming, where scalable farming methods had been tested out and were deemed ready for upscaling [30]. However, the high investment costs of building a farm with a viable production volume efficiently thresholded the number of start-up companies to scale up and start industrial farming. Thus, getting capital access to build a production facility able to produce a viable volume of lobsters was reported to be the main issue in 2013 [30].

In 2019, lobster production in Norway was approximately 8 tonnes [87]. The status of lobster farming was now transitioning from pilot to upscaling, where scaleable production systems existed, and the species was nearing the point of commercialisation. The key challenges in lobster farming were pointed out to be a) feed and feed development for the larval phase, b) the bacteria *Leucatrix minor* which could cause great lethalities, and c) production techniques and methods to avoid predation [4].



7.1.9 Hummer

Totalscore: 2,25

	Marked	**Markedspotensial**		**Substitutter**		**Risikovurdering**	**Kommentarer**	**Del-score**
	Eksisterende 25 %	**Potensielle markeder** 15 %	**Produktdiversifisering** 10 %	**Ville** 5 %	**Oppdrettede** 5 %	**Risiko** 40 %		
Marked (25%)	God marknad i mange land 3	Restaurant 2	Haler, fersk og frossen. 2	USA, Canada stor produksjon 2	Andre skalldyr 2	Potensial for større marked. 3	Nok et luksusprodukt, høy verdi stabil etterspørsel.	2,65
	Nåv. lønnsomhet		**Forventet prisutvikling**	**Forventet utvikling i prod. kost**		**Risikovurdering**	**Kommentarer**	**Del-score**
	Pris 10 %	**Prod.kost** 10 %	**Pris** 20 %	**Skalaeffekter** 10 %	**Effektivitet** 10 %	**Risiko** 40 %		
Lønnsomhet (25%)	Godt betalt produkt 3	Dyr produksjon 1	Bør kunne holde god pris. 3	Vil trenge ny produksjonsmetode. 1	Vil trenge ny produksjonsmetode. 1	Interessant marked, utfordringer på produksjonssiden. 2		2,00
	Økologiske interaksjoner		**Økologiske interaksjoner, utslipp**			**Risikovurdering**	**Kommentarer**	**Del-score**
	Genetisk påvirkning 10 %	**Smittespredning** 10 %	**Organisk** 10 %	**Legemidler** 5 %	**Miljøgifter** 3 %	**Risiko** 40 %		
Bærekraft (25%)	Antar landbasert produksjon. Gir lav risiko for genetisk påvirkning. 3	Produksjon i lukkede systemer gir god kontroll over smittespredning. 3	Det forventes landbasert RAS-produksjon med lave utslipp. 3	Ingen kjent legemiddelbehandling i påvekstfase 3	Fôr kan inneholde miljøgifter. Marine råstoffer kan ha høyere innhold av slike enn vegetabilske. 2	Flere usikkerhetsmomenter 2		2,27
	Ressursforbruk							
	Energi 5 %	**Areal** 5 %	**Ferskvann** 2 %	**Fôrråstoff** 10 %				
	Landbasert produksjon i RAS eller gjennomstrømmingsanlegg. Alt vann pumpes inn og ut av anlegget. 1	Artens aggressive adferd medfører at individene oppdrettes i egne celler. 1	Marin art 3	Carnivor 2				
	Kompetanse		**Naturgitte**			**Risikovurdering**	**Kommentarer**	**Del-score**
	Arter 15 %	**Generelt** 15 %	**Areal** 15 %	**Rent vann** 15 %		**Risiko** 40 %		
Fortrinn Norge (10%)	Endel kompetanse i Norge. 2	Lite kommersiell erfaring i Norge. 1	Kan oppdrettes i RAS, som stiller lavere krav til areal. 2	Krever god tilgang på marine vannressurser. 3		Kun erfaring fra småskala produksjon i Norge. Lite fagmiljø. 2		2,00
	Utviklingsstatus					**Risikovurdering**	**Kommentarer**	**Del-score**
	Arter 60 %					**Risiko** 40 %		
Utviklingsstatus (15%)	Har hatt pilotanlegg drift. 2					Vi behersker en intensiv produksjon og det eksisterer én lønnsom produksjon. 3		2,10

Figure 11: Akvaplan Nivas evaluation of farming European lobster

Source: [4]

In Figure 11, the lobster is evaluated as a farmed species. The evaluation shows a greater market potential where lobsters are of high value and have a strong demand. However, the high production costs and challenges of scale and efficiency are highlighted and it is suggested that a new production method is likely needed, caused by the high energy and area demands. This is stated alongside the fact that there is a profitable production of lobsters.

In 2021, there were still significant knowledge gaps and challenges to be addressed for the expansion of aquaculture production. A primary focus should be to improve the quality and quantity of juvenile lobsters in a more cost-effective manner, where cannibalism is still a key bottleneck. Wild-caught lobster females are currently used as farming broodstock and only around 10% overall survival is present within a state-of-the-art farming system [26]. It is further explained that it is technically feasible to create separate physical rearing systems, but the amount of individual-based husbandry operations probably makes this approach unviable (per 2021) [55].

In the fall of 2022, a pilot farm produced 2,000 plate sized lobsters [84]. With its modular and scalable design, and with the philosophy of *"if one cage works, one million cages work"* [72], the farm aims for efficient up-scaling and expansion. Construction of an MNOK 650 farm is intended to begin in Q1 2023 [22]. It will be interesting to see what experiences and knowledge follow from the introduction of industrial-scale farming. However, it should not completely eliminate the reasons to investigate new solutions in lobster farming. These will be explored here through the creation of a docile lobster.

3 Possible farm designs

This section is not a definitive solution to the optimal configuration of a cage system. Instead, it is a discussion of how the previously described requirements of a lobster farm could be synthesised into conceptual designs. Further, it should be noted that due to the lack of industrialization, finding a state-of-the-art method has been difficult, where the state-of-the-art actor seem to have tried multiple intensive individual farming techniques in the last couple of decades, such as in [29], [27], [71].

The cannibalistic behaviour of lobster makes it necessary to separate each individual in farming [48], [23], [27], [56], which has made previous efforts to produce area-efficient farming systems difficult. There are many farming systems adapted for individual lobster farming. The sorting of stage IV lobsters and individually growing them either to juveniles for sea-ranching purposes [48], or plate size (250g) [60], [27] or fishery size (450g) [12] has been embodied in different farming concepts. Additional concept proposals have also been found for both on- and offshore farming [90], from which Concepts I and II are adapted.

3.1 Farming methods

First, the life cycle of lobsters described in previous sections can be contextualised within the lobster production sequence.

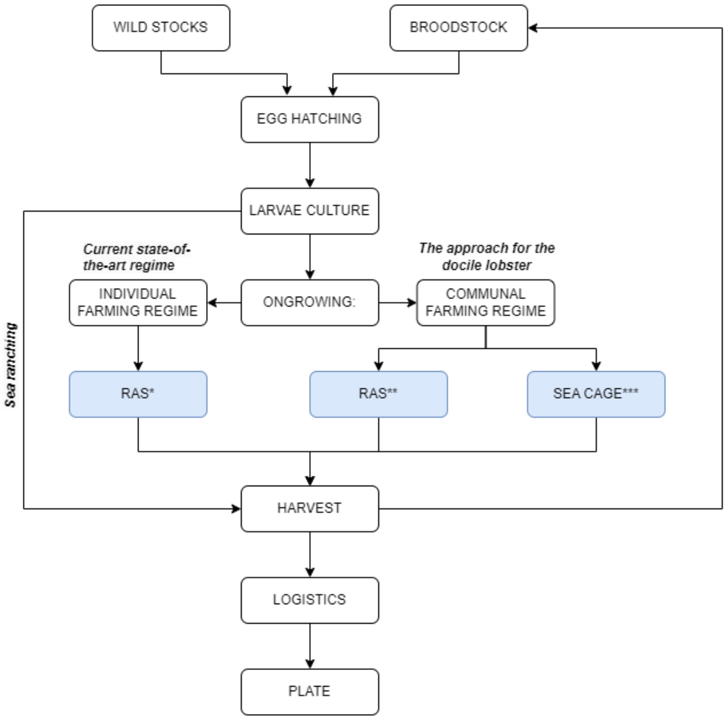


Figure 12: Production sequences in intensive lobster farming

Figure 12 depicts different sequences and methods of lobster production. Sea ranching is also presented here to demonstrate its relation to the production process. The blue squares represent the chosen farming regimes, that is, the focus area for the comparative analysis. Since larval culture is assumed to be similar across the concepts, an assumption that industrial-scale production would likely involve vertically integrated lobster hatcheries and nurseries responsible for producing juveniles for on-growing, similar to existing solutions for smolt in salmon production. In other words, the upcoming work will be based on successful larval rearing, focusing on the various on-growing options.

3.1.1 Individual farming

Due to the inherent territorial and cannibalistic behavior of the lobster, it is necessary to farm each lobster individually. This is achieved in most farming systems using separate cages from stage IV / V until harvest. For purposes of providing sufficient areas during different phases of growth, cage swaps are necessary.

However, there should be room to explore possibilities to mitigate interactions between lobsters, since fighting and the possibility of cannibalism occur first when lobsters get the possibility of interacting with each other.

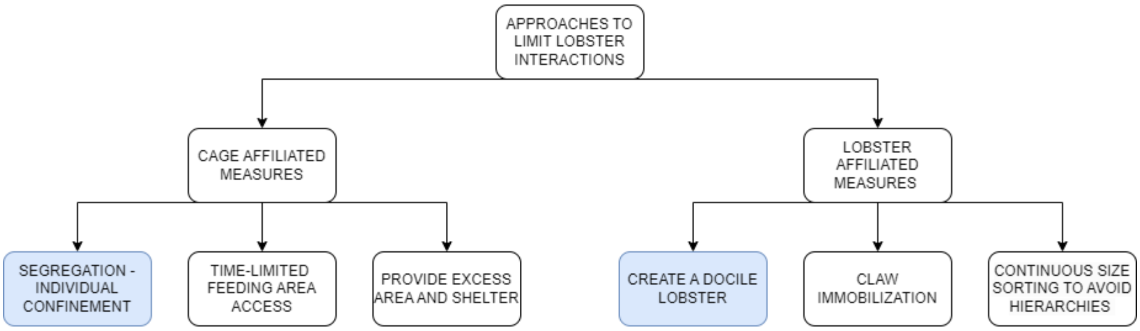


Figure 13: A selection of measures to mitigate encounters and interactions between lobsters. The blue squares depict the different measures focused further on.

Figure 13 shows measures intended to mitigate interactions between lobsters. Some of these measures have been tried in practical farming. Providing additional area and shelter would further lower the stocking densities, and challenge area efficiency, which is stated to be a key challenge in farming. Excess area and shelter is thus left out here, even though this measure could be beneficial in clawed lobster farming [92]. Claw binding, using rubber bands, would be necessary for each individual for each molt. If a commercial farm were to be between 100.000 – 1.000.000 individuals [60], and there are 20 molts for each individual for which the occurrence of molts is somewhat arbitrarily, it would be very laborious to monitor and bind claws. Additionally, littering bands in the cage environment could become a challenge. A continuous size sorting to avoid hierarchies is probably only viable in conjunction with other measures, such as claw-binding or sufficient shelter and space [3]. Crippling the claw by removing half of the claw is left out as an option due to animal welfare aspects. Other controversial measures, such as eyestalk ablation, are also excluded due to animal welfare considerations. Using time-limited feed access, where lobsters would have a time window to access the feeding area and then retreat to the shelter, is a novel idea proposed in this thesis. However, as time-limited feed access would involve keeping the lobsters individually most of the time, ultimately using more space than conventional individual farming, this is also left out.

It is not critically ruled out that some of the excluded measures could be part of future farming systems, but the most promising of the listed techniques appears to be individual farming and the creation of a docile lobster. Several techniques have also been carried out in practical farming, where the current state-of-the-art method uses individual confinement, indirectly demonstrating the feasibility of this measure.

3.1.2 Communal farming

The lobster's inherent aggressive and cannibalistic nature makes them unfit to be farmed in the same enclosure without taking measures such as in Figure 13. However, some farming systems use communal farming early in the farming process. A three-phase communal farming from stage IV is suggested for six months until $20mm$ CL, with corresponding loss of cannibalism up to 60% [90]. The loss is argued to be acceptable because production costs up to this point are low and a communal farming system is cheaper and less complex to operate and maintain. Despite animal welfare issues in such a system, lobster growth benefits from cannibalism, as previously mentioned in Section 2.2.6.

As described in Section 2.2.2, there are significant growth variations within a single culture. After 2 months of communal farming, the size difference between the smallest and the largest lobster in a single culture could be up to 3 times. Variable growth rates challenge farming operations because the largest lobsters develop faster and become dominant to the smaller lobsters. Consequently, the food intake of smaller lobsters is restricted. Regular size grading, where lobsters are stocked with other lobsters of the same size, has the greatest impact in preventing monopolisation of food resources [2], [92]. It is not clear whether the effect of food monopolisation could be eliminated in aquaculture by selective breeding resulting in uniform growth, but if the effect of feed monopolisation due to individual growth differences is present, it could be counteracted by regular size grading.

3.1.3 The docile lobster

A docile lobster would be a lobster that would be compliant or even gregarious toward conspecifics, making it possible to farm collectively without mortalities caused by fighting and cannibalism. This work does not answer whether creating a docile lobster is possible. Instead, it seeks to describe what the differences in the farming system could be.

Steps towards creating a docile lobster are made. Software capable of determining behaviour from posture estimation [82] and video analysis tracking lobsters in real time, as well as being able to determine the outcome of conflicts [80], [81] would be the foundation for robotic handling for selection purposes. The technology for behaviour analysis functions as desired and future efforts include implementing a laser to euthanise the most aggressive larvae. This technique aims to eliminate individuals possessing aggressive tendencies from a culture. Effectively, this creates a culture that bets on the genetics of the biological losers from nature's point of view. Long-term, after generations of breeding, this is thought to shift the normal-distributed aggression levels in the population toward a more docile lobster [36].

To obtain a foundation for the comparison, the theoretical docile lobster is compared with the tropical spiny lobster. Spiny lobster has several of the desired attributes of a docile lobster, which are a) tolerance to high stocking density, b) communal living without cannibalism, c) acceptance of pelleted feed, and d) strong market demand [76]. In the wild, spiny lobsters are seen to be gregarious, sharing shelters and migrating in groups, and are well cultured at larger densities [92]. There is commercial farming of different species of spiny lobster, where growth takes place in both land-based holding systems and sea cages [11]. There are some key differences between the European lobster and the different species of spiny lobster, such as the spiny lobster does not have a set of anterior chelipeds, as it is a clawless lobster. Its physical possibilities for physical confrontation are thus questioned. Spiny lobsters grow much faster at tropical water temperatures in the range between $25-30$°C [76]. However, the spiny lobster has a more complex and prolonged larval phase than the European lobster.

The farming practices employed during the growth phase of spiny lobster can be outlined as follows [11]: In a sea-based cage, as in Figure 23, the larvae in $10-50g$ are set up to $30/m^2$ and are manually stocked in groups of similar size on a regular basis during the growth phase. At sizes $200g$ and $500g$, they are typically stocked at $5/m^2$ and $2/m^2$, respectively. These numbers correspond to a stocking density of approximately $1kg/m^2$ throughout the growth phase, which lasts approximately 18-20 months. During the time in the sea, wild algae and biofouling organisms grow in the cages. Spiny lobsters eat some of the biofouling, but periodically cage cleaning is needed. Emptying of feed wastes and molted shells are also necessary. Despite its gregarious behaviour, cases of cannibalism are reported, especially during molting, when lobsters are vulnerable. Regular stocking in similar sizes and providing shelter are measures implemented to mitigate cannibalism [11]. Healthy lobsters can be stored at $1.0-1.25kg/m^2$ after being restocked in similar size groups, where $20g$ should be the maximum weight difference in size between the smallest and the largest lobsters [76]. However, there is a great variance in the stocking densities of different spiny lobsters of different sizes, as presented in [57], [76], [24]. For some species of lobsters, stocking densities seem to be significantly higher than $1\frac{kg}{m2}$, given its size. However, increasing stocking densities appear to reduce overall survival and growth. In the farming of mud spiny lobsters, the most common causes of death for lobster in cages were dying during molting or being consumed by other conspecifics in cages immediately after molting [24]. For western rock lobsters, cannibalism was also the most common cause of death, where lobsters were the most vulnerable during molting [57].

A central question is how docile the lobster could become and thus at which stocking densities lobster growth and survival are ensured. If the creation of a docile lobster becomes comparable to some species of spiny lobster, the suggested stocking density at plate size could be $\frac{1kg}{m^2}$, which was also the stocking density for cheliped immobilised lobster. However, stocking densities could also be significantly higher, as in other species of lobster. A brief examination of spatial requirements is needed. Another stocking density could possibly be derived from the physical area in which each lobster resides. It is given by the following geometrical considerations:

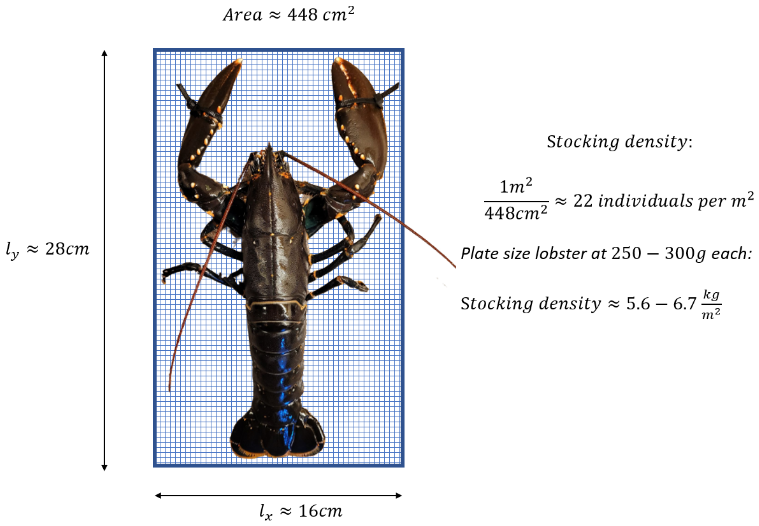
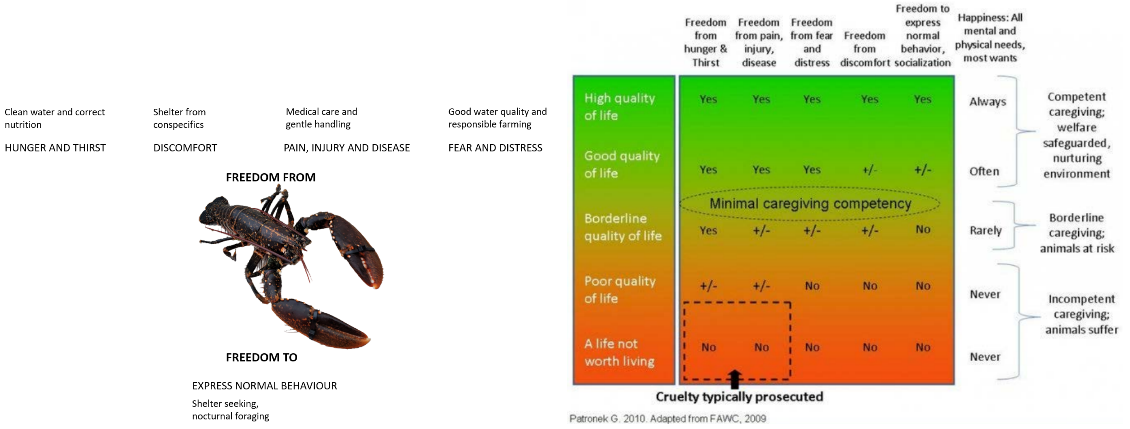


Figure 14: Stocking density given by the area the lobster physically resides

Figure 14 shows the area in which one lobster physically resides and the corresponding stocking density if all the space is considered used. Here, the stocking density is between $5.6 - 6.7\frac{kg}{m^2}$. It should be noted that this is from a fishery obtained $25.5cm$ TL, and a proportional morphological coherence is assumed between this lobster and the plate-sized lobster. This stocking density would act as an upper limit if it were assumed that there are no intraspecific interactions that limit growth up to this point. In order to provide a basis for comparing the docile lobster, the two stocking densities will be used to discuss the docile lobster farming potential. Namely, they will be referred to as low density (LD, $1\frac{kg}{m2}$) and high density (HD, $6\frac{kg}{m2}$). The theoretical production yield for clawed and spiny lobsters is approximately $12.8\frac{mt}{ha}$ and $22\frac{mt}{ha}$, respectively [93]. This further leads to the assumption that it is highly possible to increase the production capacity by introducing a docile lobster, but it appears challenging to determine in advance.

3.2 Animal welfare and legislative matters

Animal welfare is essential to ensure the health and well-being of the animals. A healthy production stock would also benefit the farmer, where better quality and production rates could be achieved. Having sufficient animal welfare could also reduce costs related to veterinarian visits and treatments. A simple definition of animal welfare is that *”the animal is not to suffer unnecessary”*, which is regulated by the animal welfare act. Another more formulated definition of welfare is the *Five Degrees of Freedom* [73].



	Freedom from hunger & Thirst	Freedom from pain, injury, disease	Freedom from fear and distress	Freedom from discomfort	Freedom to express normal behavior, socialization	Happiness: All mental and physical needs, most wants	
High quality of life	Yes	Yes	Yes	Yes	Yes	Always	Competent caregiving; welfare safeguarded, nurturing environment
Good quality of life	Yes	Yes	Yes	+/-	+/-	Often	
Borderline quality of life	Yes	+/-	+/-	+/-	No	Rarely	Borderline caregiving; animals at risk
Poor quality of life	+/-	+/-	No	No	No	Never	Incompetent caregiving; animals suffer
A life not worth living	No	No	No	No	No	Never	

Figure 15: Five degrees of freedom and corresponding measures (left), and classification system (right)

Source: [79]

Figure 15 shows the five degrees of freedom specified for lobster aquaculture. Freedoms from hunger, thirst, discomfort, pain, injury, fear, and distress could be solved, provided the measures on the left are implemented. Providing a cage layout that reduces lobster stress and provide a continuous, high-quality water supply are some of the engineering measures that could be used to ensure the welfare of farming and will be focused further on in this thesis.

During the last century of lobster farming, only a few outbreaks of disease have occurred [60], [23]. However, several lobster diseases and parasites might challenge intensive farming. These are extensively documented in [83] and [93] and will not be covered here. Medical care and monitoring of disease levels, and responsible farming are disputable to accommodate the requirements in this dimension of welfare. The main question raised is to what degree a confined space limits the lobster's ability to express normal behavior in the form of foraging and mobility. Most certainly, this dimension of welfare is best-maintained farming docile lobsters. On the other hand, it could be argued that the lobster is naturally territorial, seeking shelter and being stationar, and that individual confinement provides these attributes. In any case, it could be argued that lobster welfare is maintained above or at the level of borderline caregiving, according to Figure 15.

Other legislative matters must be included in the establishment of a lobster farm. These include (in Norwegian): a) Akvakulturloven, b) Tildelingsforskriften andre arter, c) Plan- og bygningsloven,

d) Forurensningsloven, e) Naturmangfoldsloven, f) Etableringsforskriften, g) Dyrevelferdsloven, h) Akvakulturdrifts-forskriften [4]. These are left out of the scope of the solution space of this thesis. Whether shellfish legally falls under the term fish is unanswered, but a floating fish farm should be able to fulfill the requirements given by NS9415, and a RAS should fulfill the requirements of NS9416.

3.3 Application of cybernetical methods in farming

In order to lower production costs, increase profit margins, and be economically viable, a technical system is thought to pertain a larger degree of automation to remove costs related to labour. Implementing automated systems has also been a focus area for several decades, and possible applications of various applications in lobster farming have been described as early as the 1980s [48], [9], [10]. Automation is crucial for handling many individual confined lobsters [30]. Therefore, the possibilities for implementing cybernetical methods are explored.

Cybernetics uses methods for instrumenting and monitoring systems and, through feedback, uses the information to influence the system toward a desired state. This is often facilitated using robotics, which is intended to assist humans in tasks considered *dull, dirty, dangerous, difficult and/or dear* [44].

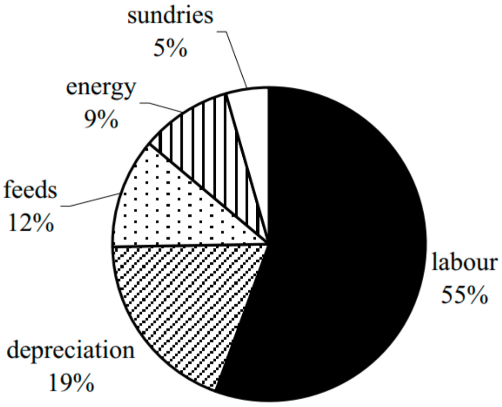


Figure 16: Operation costs for a lobster hatchery/nursery producing 5.000-30.000 juveniles annually

Source: [93]

Figure 16 illustrates the operating expenses of a generalized lobster hatchery / nursery sourced from 1990-2000, when manual labor was standard practice. Similar numbers for a on-growing facility are not found in the literature review and are probably nonexistent [93]. Although Figure 16 does not depict grow-out costs, it is assumed to give an impression of how vital automation of husbandry could be to decrease operational costs. For example, 6-7 full-time workers were needed to annually produce 120.000 juvenile lobsters in the 1980s for sea ranching purposes [48]. Here, monitoring, feeding, and sorting were done manually. Given that manual labor could result in such a significant portion of expenditure as in Figure 16, and considering the narrow profit margins due to high farming costs, there are reasons to explore ways to reduce the costs related to manual labor. This is hypothesized to be achieved through automation.

3.3.1 Automation of husbandry operations

Husbandry operations are activities related to the management of lobsters in farming. Focusing on the on-growing phase from stage IV/V to harvest, husbandry operations are presumably the following:

Husbandry operation	**Comment**
Sorting or placing stage IV/V lobsters	Lobsters are placed in their farming environment for on-growing.
Frequent, regular feeding	Depending on the system (individual or communal farming), feed is provided individually or communally to the lobsters. Feeding should not compromise water quality, and molting lobsters should therefore not be fed
Cage swapping*	During on-growing in individual cells, using the least number of transfers between cages during on-growing is important [93], where 2 swaps are the lowest recorded [23]. The reasons for swapping are to provide the correct cage dimension to sustain growth.
Cage cleaning	Even though the cage hydrodynamics should attain a self-cleaning effect, and the fact that lobsters feed on some of the bio-fouling, the cage would probably need the removal of bacterial slime and similar substances regularly
Dead lobster removal	With an average survival of 80% in the on-growing phase [93], removal of dead lobsters is probably necessary to preserve high water quality
Monitoring and controlling	The water quality should be within the values in Table 1. Monitoring possible diseases, biomass control, behavior, and welfare are also important to act quickly when necessary and control the farm environment.
Harvesting	Having control over molting frequencies could potentially be beneficial to assess which animals are hard-shelled at a given time, to harvest animals of highest quality
Handling for different purposes	For possible future purposes, such as vaccination against diseases
Grading of similar size lobsters**	If faster-growing individuals, i.e., larger individuals, acquire first access to the food source and monopolizes the feed resources, regular grading at the same sizes could remove hierarchies and provide distribution of food to all lobsters.

Table 4: Husbandry operations in a lobster farm. *Specific for individual farming. **Possible outcomes for a docile lobster, if comparable to spiny lobster aquaculture

Automation seems to have been the focus of farming for quite some time, and several of the above mentioned husbandry operations are already documented to be fully automated in lobster farming [60], [27], [30]. In-house hatchery solutions are established and robotics capable of sorting larvae and then placing them in separate confinements exist, as well as robotics for individual feeding and harvesting [27]. There is monitoring using artificial intelligence and computer vision systems used to classify and grade lobsters [72]. It is not clear whether there are systems for the removal of dead lobsters to this date, but it was mentioned as a future field of work in 2013 [30]. An approach to achieve this is the concept of precision fish farming.

3.3.2 Precision Shellfish Farming

The main aim of the Precision Fish Farming (PFF) concept is to improve the accuracy, precision, and repeatability of farming operations by continuous and autonomous biomass monitoring to reduce dependence on manual labor and subjective evaluations [47].

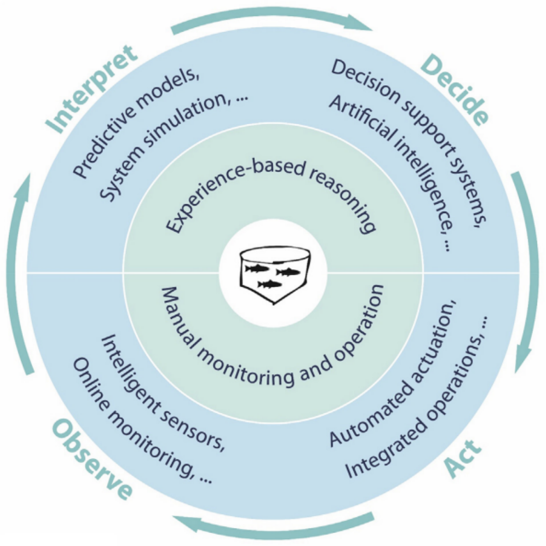


Figure 17: The Precision Fish Farm concept

Source: [47]

Figure 17 shows how cybernetic methods can be applied to move from manual work based on experience to automated operations. Although PFF is based on finfish farming, it provides a generic framework that could be extended to shellfish farming using *Precision Aquaculture* [46]. The PFF concept is subdivided into four tasks: observe, interpret, decide, and act.

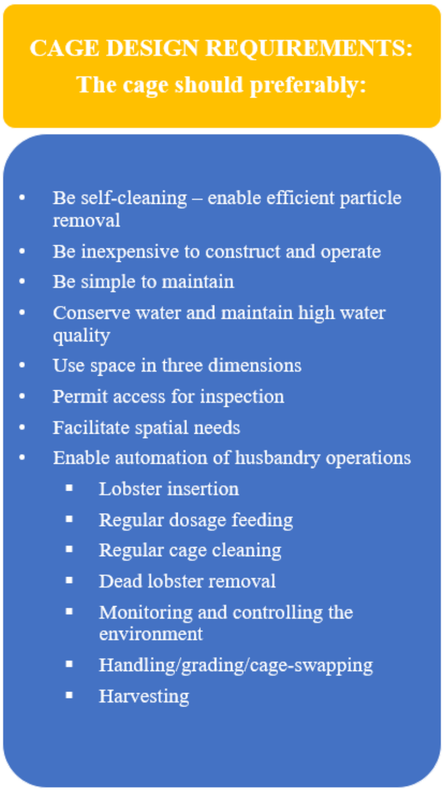
Automated feeding provides a relevant example in which the application of Precision Fish Farming (PFF) can be explored. It should be noted that this is already being developed in lobster farming, but it is included to describe how the PFF concepts could be used in automating tasks. First, observations of the lobsters are carried out using a camera setup. The stationary, benthic behaviour of the lobster arguably makes it easier to trace each individual compared to other species, such as salmon. The monitoring is further simplified if the lobsters are individually confined, making it easier to achieve an individual focus in farming. The data captured by the camera is interpreted in an image processing programme by means of software on a computer. Information could also be stored and represented as historical data in a base case, making the basis for a digital twin. The digital twin could be used in future decision-making, acting as a digital representation of the farm. The digital representation could be used in simulation and model testing. Combined with AI, more accurate growth and molting models could be established for different farming conditions, providing a powerful decision support tool. A type of actuation must be present to physically enact control of the farming system. For feeding, physical interaction is enabled using a feed dispenser. A robotic arm, an actuator, can handle tasks such as operating lobsters directly. Specifically, the actuator can reach into the tank to remove dead lobsters or harvest them. When harvesting, the actuator can selectively choose only lobsters far from molting, using historical data or information from the digital twin, resulting in the withdrawal of the highest quality animals. The same actuator could fit a rotatable brush that is used in clean cage meshes to sustain the necessary water flow. Using the four steps, *observe, interpret, decide, act* provided in the PFF framework, it makes it possible to introduce automation and control over a physical farm.

3.3.3 System attributes accommodating cybernetical control

It is uncertain what future systems will require regarding the system design to implement the husbandry described above. With the rapid pace of technological development, there may be opportunities in the future for robotics, such as snake robots that can handle the varied husbandry described above. Regardless, here are some thoughts on how a system design should meet the cybernetics control methods that enable automation, given the current technology development. A camera (hardware) and a code (software) comprise the components needed for computer vision systems. To provide camera clarity, a background that provides contrast and fewer disturbances between the camera and the surveillance object is likely to work best; the water surface and its angle can also be disturbing because of light reflections. A camera angle presented directly from above will likely perform better in such a case. Additionally, a consistent distance between the camera and the individual lobsters would make it easier to determine the size of each lobster, using the distance as a reference. Furthermore, it is likely easier to monitor and control animals that are already physically separated. The shellfish, which is more or less stationary, will be easier to monitor in this regard [46]. Instead of tagging each animal with an appearance code, it is sufficient to keep track of each individual's cage number. Monitoring in an environment where shelters are provided is likely to introduce difficulties - it could be difficult to monitor a lobster that is not observable to the camera systems. Heated seawater provides a harsh environment for the equipment. If a dry camera setup is required, as used in [27], [82], [80] and [81], it would seem beneficial to use a relatively shallow tank to monitor the lobster. Particles throughout the water layer would probably not entail unclear visibility due to turbidity. A relatively shallow and easily observable cage is, because of this, arguably a system easier to automate.

Although it would arguably be easier to implement the PFF framework in a highly controlled land-based facility, possibilities for the automation of a sea-based cage should also be discussed, i.e., for Concept 3. For a sea-based farm, there are several technologies for monitoring and cage cleaning [44]. There appear to be future possibilities to construct robotics capable of handling lobsters, but how this would affect stress levels has not been elucidated in the literature review and should be conducted before creating automated handling robotics. However, a lobster with its exoskeleton would like to be more robust in handling than a finfish with a delicate mucus layer [45].

3.4 Functional requirements



CAGE DESIGN REQUIREMENTS:
The cage should preferably:

- Be self-cleaning – enable efficient particle removal
- Be inexpensive to construct and operate
- Be simple to maintain
- Conserve water and maintain high water quality
- Use space in three dimensions
- Permit access for inspection
- Facilitate spatial needs
- Enable automation of husbandry operations
    - Lobster insertion
    - Regular dosage feeding
    - Regular cage cleaning
    - Dead lobster removal
    - Monitoring and controlling the environment
    - Handling/grading/cage-swapping
    - Harvesting

Figure 18: A summary of previously discussed cage requirements for individual confinement

Figure 18 summarises the cage requirements previously discussed for the individual confinement of lobsters in a figure. It aims to be a framework for future efforts to create new cage designs.

3.4.1 Functional requirements for the docile lobster

The most significant advantage of a docile lobster is presumably the advantage of not having a physical separation between individuals in the cages, which results in a significantly less complex system. A less complex system would likely result in a technical farming system that is less capital-intensive and solve the problem of achieving profitable farming at a lower production capacity.

However, as there is probably no empirical database in which to validate these assumptions, the approach must be qualitative.

There is lobster farming in relatively inexpensive floating sea cages for tropical spiny lobsters, but this is in Asian countries where manual labour is cheaper and more widespread. More than 80% of the production costs could be traced to feed and seed (larvae for growing) [11]. Although actual costs have not been discovered and there is a theoretically viable possibility of farming a docile lobster using more manual methods, this is not considered in this work due to the high costs that manual labour represents, as in Figure 16. Here, the success of a docile lobster will likely depend on the opportunities to automate most of the husbandry operations, as is the cage in individual farming. Several of the requirements of individual farming should presumably also be present in communal docile lobster farming, such as the cage's ability to be self-cleaning, inexpensive in operation and construction, simple to maintain, maintain high water quality at all times, permit access for inspection, and enabling automation of husbandry operations.

The key differences are presumably the stocking densities at which the docile lobster could be farmed. These are deduced to be between $1\frac{kg}{m^2}$ and $6\frac{kg}{m^2}$ at plate size. Further simplifications following the introduction of the spiny lobster would presumably be the removal of the need for individual feeding and the need for cage swapping. However, if the docile lobster could be comparable to the spiny lobster, regular restocking could occur regularly. Exactly how the physical rearing system for a docile lobster is not suggested and is described here similarly to individual farming, excluding the physical separations. Using space in three dimensions will here be assumed important in a docile lobster farm, as the docile lobster would still be benthic and only be able to use the bottom area of the water column.

3.5 RAS environment

This section is included primarily to discuss differences between the concepts later, and a detailed elaboration on RAS technologies is not the objective. However, the components of the system and their intended use are described to discuss how different farming technologies impact key farming criteria.

RAS is the abbreviated form for Recirculating Aquaculture System. A RAS differs from a flow-through system (FTS) by applying different water treatment steps. In a RAS, the water in the culture tank is removed and treated to such an extent that the water can be reused. For a flow-through system, the water is used once and then transported out of the facility. A key advantage of lobster farming in these systems is the ability to use heated seawater used to promote rapid growth at increased temperatures, and obtain stable optimum conditions, as well as to provide high water quality and biosecurity [55]. Inherently, it keeps predators physically away from the cage environment. Lobster RAS, or more frequently flow-through systems, for growth [27], is a technology that has been tested in the field and shows its technical applicability. On the other hand, the introduction of a RAS could have negative impacts, such as increased stocking intensity resulting in increased risk of disease and the requirement that ozone, pH and alkalinity be optimised for molting [55]. An RAS also sets knowledge requirements for the operators of the farm, given the more complex biological and chemical processes that occur within the system and what to do in the event of unforeseen happenings. Another drawback of an RAS compared to an FTS is that pathogens that cause disease have the ability to recirculate with the system, and therefore disease outbreaks could possibly be more common in an RAS compared to an FTS. However, an RAS has been shown to provide a more stable environment and increased survival than an FTS [30].

RAS water treatment consists of the treatment of the intake water and the treatment of the recirculation. Intake water treatment typically consists of mechanical filtration to remove solids (such as sand filters or drum filters) and disinfection (ozone/UV) to kill bacteria and viruses. It is beneficial to have the water inlet below the thermocline of the sea to control the temperature of the water inlet [64]. The recirculating water treatment steps are mainly there to manage toxic metabolites and to ensure that the water used for farming meets the water quality requirements. The rates at which toxic metabolites TAN and CO_2 are excreted by lobsters are described in Figure 10. Different components are adapted to remove different substances. Solids, such as faeces and feed waste, are most commonly facilitated using a drum filter [18]. The treatment of water is not limited to the removal of solids, but also to the manipulation of the levels of dissolved gases. Removal of gases such as CO_2 is necessary, as well as the addition of oxygen, to maintain the necessary levels. The removal of gases such as N_2 depends on the level of recirculation [42]. If recirculation is high, a denitrification process could help remove nitrogen from systems [64].

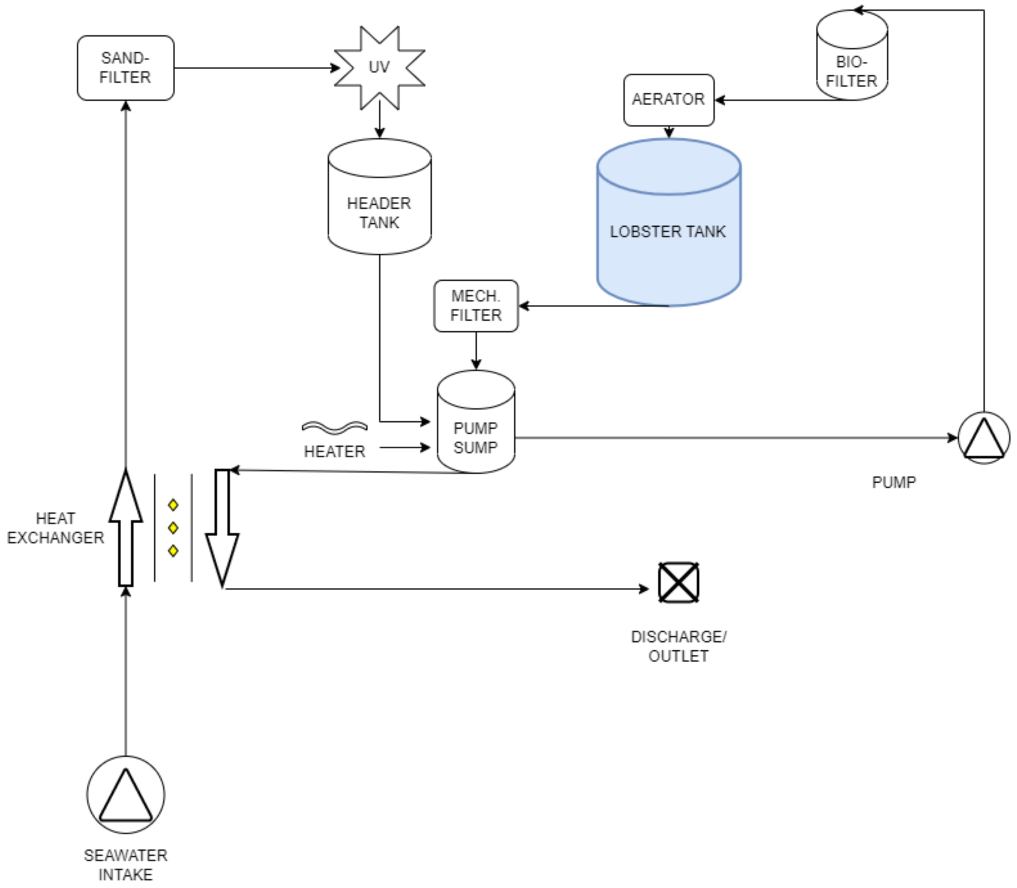


Figure 19: A suggested principal layout for a lobster RAS for on-growing purposes

A schematic representation of a principal lobster RAS layout is depicted in Figure 19, and the components are briefly discussed to highlight how a land-based lobster could provide and maintain high water quality and environmental control. It should be noted that not all relevant steps are included. For example, a kind of buffer addition should also be present.

At seawater intake, new seawater is pumped from the sea and, through a mechanical filter, solid particles up to a certain size are removed. Mechanical filters could be a sand filter, drum filter, or chamber filter press, given the size of the solid and the preferred level of removal, at the expense of operating costs. A mechanical filter efficiently removes small particles that can provide shelter for microbes and pathogens and thus increases the efficiency of potential UV disinfection. UV disinfection works by sending ultraviolet radiation that destroys the DNA of the organism, making it difficult for them to reproduce.

The header tank is filled with filtered seawater and acts as a reservoir for new water, increasing the stability of the water supply. Having the header tank placed high on the farm would still make water available to the farm components during a pump failure due to lift height. The water is directed to the pump sump from the header tank, where a heater warms the seawater to optimal temperature. As direct heating using electricity is costly, using waste heat (Norwegian: *spillvarme*) would be beneficial in reducing costs. This has been used in larvae rearing systems [48], and in current flow-through systems [71].

The primary function of the biofilter is to convert ammonia to less harmful substances. A biofilter could be a self-cleaning moving bed biofilter that uses a filter medium in which a biofilm grows. Inside the biofilm, different bacteria grow. Shortly explained, NH_4^+ are transformed into NO_2^- by *nitrosomonas* bacterias and further into NO_3^- by *nitrobacter* bacterias. This is much less lethal and could be present in a higher concentration, removed with excess water. In high-reuse RAS, a further denitrification process could transform the substances into nitrogen gas and degass them out of the system [64]. This is how TAN is handled in an RAS.

An aerator removes dissolved gases that must be removed in the RAS, such as CO_2. This could be combined with a biofilter in a so-called *rislefilter*. Oxygenation devices that add oxygen to the water are also present to ensure the correct levels of oxygen. In the system layout, various pumps and pipes deliver the desired amount at a given time.

As the RAS layout is often different among the RAS suppliers [42], and some components may also be excluded given the species, there is not only a single design that could be applied. In lobster farming, some treatment steps are advantageously left out. Examples of these are the use of disinfection methods: Norwegian Lobster Farm does not use ozone and UV [26]. Ozone could produce harmful bromates in saltwater. UV has been shown to limit the survival of lobster larvae, and, without using disinfection methods, a stable bacterial culture was established and was shown to perform better in larval survival than for a flow-through system [8]. However, it is not clear to what extent a stable microbiota benefits the farming environment during ongrowing of larger individuals.

The blue element in Figure 19 is the lobster tanks and cages themselves and the main difference between Concepts 1 and 2. The main difference is whether the animals are farmed individually or communally. However, there are several cage arrangements that have been tried in lobster farming and, therefore, the cage layout should be discussed. In farming, the separation between two-dimensional and three-dimensional systems seems to be a way to discuss farming systems. The following is a brief description of selected 2D and 3D configurations.

3.6 Cage arrangements

Several methods have been established in farming, but low survival rates and automation challenges have led to the abandonment of several methods in individual farming [29]. Some farming systems use a circular two-dimensional farming environment, where each lobster is placed in a separate cage in a shared tank, as in [48]. Stacking lobsters purely in a 2D plane, given the stocking densities discussed above, would occupy vast land areas and increase land costs. Therefore, the focus is on systems that use space more efficiently. The proposal for an ideal cage also underlines that the ideal cage *use space in three dimensions.* To use space in three dimensions and increase production yield per ground square metre, two different approaches are presented in the form of a layered 2D configuration and a 3D cage configuration. In the 2D layered configuration, multiple 2D stacking patterns are introduced vertically, resembling a warehouse rack. This system, known as a *flushing tray system*, enables efficient use of space per floor area. Each level has a separate water supply, ensuring individualised water circulation to a small amount of lobster per time. On the other hand, the 3D cage configuration involves submerging all cages in a single water volume. Known as a *deep tank system*, this approach could increase biomass per water volume. For a visual representation that shows the distinctions between these two configurations, the following figure is provided.

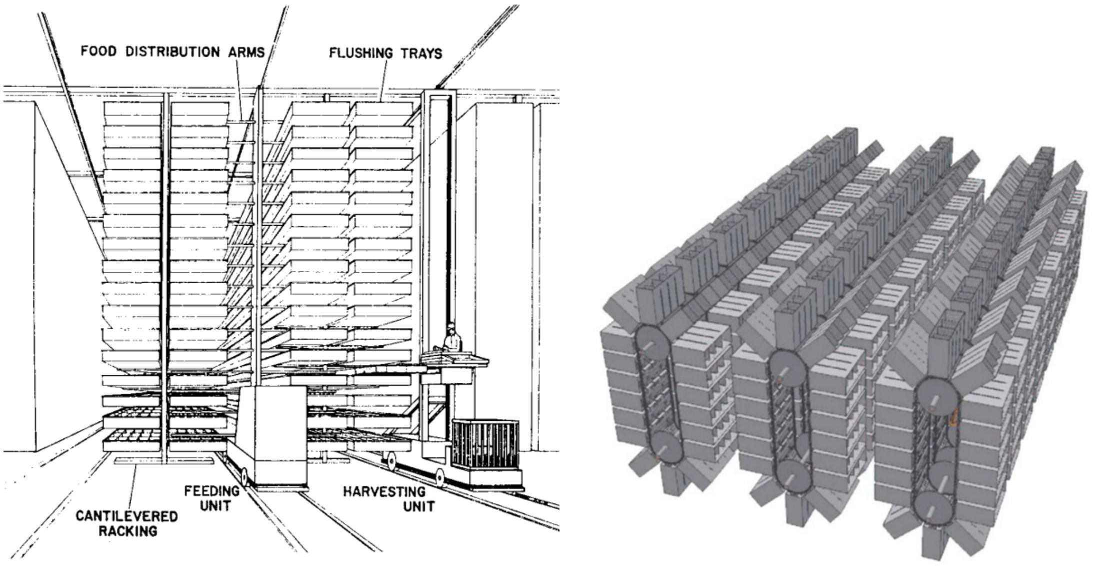


Figure 20: Two lobster farm layouts utilizing space in three dimensions. Left: a layered 2D configuration (*flushing trays*). Right: a submerged rotational 3D cage configuration (*deep tank).*

Source: Left: [90], right: [27]

Figure 19 exemplifies the two concepts that increase production per ground area. The figure on the left, showing the flushing tray, is self-cleaning by having a meshed bottom in each separate cage that allows the faeces to settle below the cage and be ”flushed” away regularly when needed. Dissolved substances in the water are effectively removed as they trickle down between the lobster cages due to the height difference between the cages. Combining a meshed bottom and trickling allows for the efficient removal of dissolved and solid materials. The spacing between the trays ensures visual access to each lobster, and an easily accessible flushing tray facilitates inspections and maintenance. The installation cost of this setup is not specified.

The figure on the right represents a rotating unit that serves multiple functions. In the upper position, it feeds and monitors the lobsters as they eat during their descent. In the bottom position, the unit facilitates self-cleaning by allowing the uneaten food and faeces to fall out of the cage. While this configuration efficiently utilises space in three dimensions, monitoring is limited to the top side, as the cameras are mounted there.

In a brief comparison between the flushing tray and the deep tank, the flushing tray offers a simple, modular design that can be easily extended in height and width and is scalable. On the other hand, a rotating deep tank introduces a more complex structure with rotation mechanisms that may be susceptible to wear and tear in a corrosive heated saltwater environment. Maintenance of the rotating unit could require removing it from the water, and a broken rotation mechanism could potentially cause severe problems, making the feed unavailable to lobsters. Although the literature review only reports automation facilitation in the rotating deep tank, the flushing tray is assumed to be easier to monitor due to its simpler design and accessibility. Thus, considering the need for easy maintenance, inspection possibilities, and automation of husbandry operations, it is chosen to further explore possibilities in a flushing tray system for the docile lobster, based on the discussion on the aforementioned points.

3.7 New ideas vs. adaptation of existing ideas

The establishment of rough sketches of completely new farming systems was attempted to meet the design requirements. Still, the uncertainty they introduce regarding performance compared to existing systems makes them difficult to compare. Combined with the advice that it is often beneficial to explore ways of transferring knowledge and experiences rather than starting from scratch [93], the comparison focusses on existing systems. Furthermore, the strict functional requirements in Figure 18 probably limit the number of systems that can meet these strict criteria. As a result, further work is based on adapting existing farming systems using recent technological advances. The idea became using the flushing tray system described by [90] and modernising it by introducing cybernetical robotics. Notably, in the latter part of the thesis work, it became clear that striking similarities existed between the aforementioned flushing tray and ”the new” state-of-the-art solution, as found in [71].

3.7.1 Concept I presentation

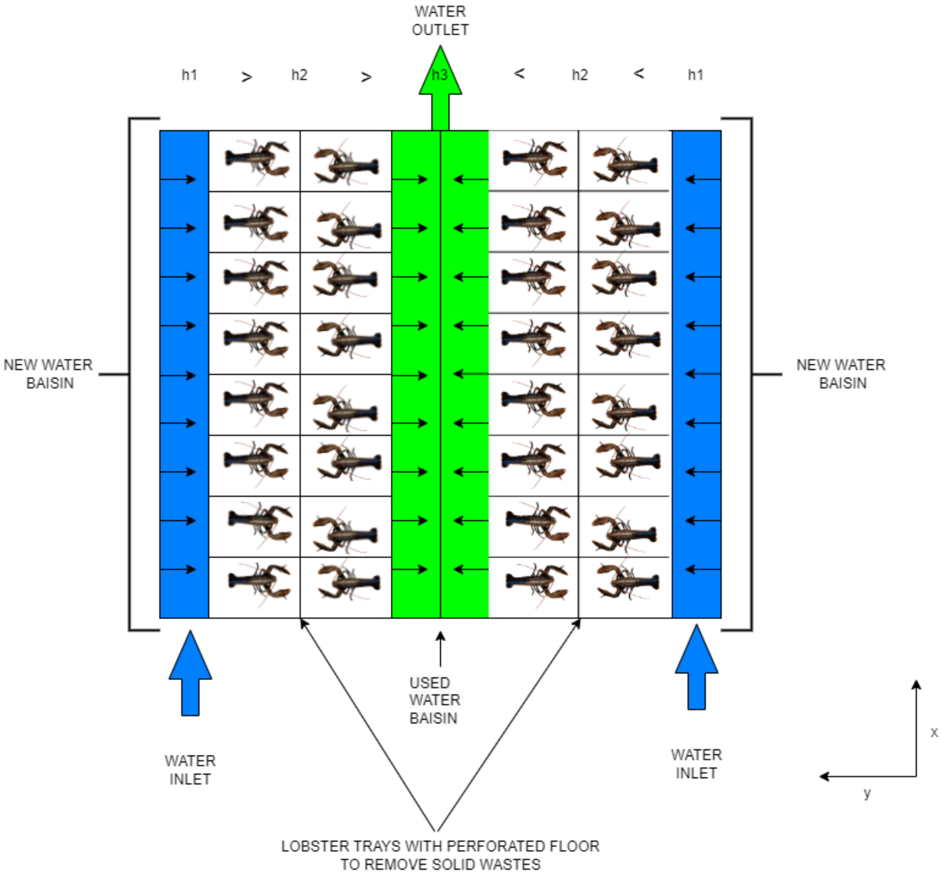


Figure 21: Concept 1. A preliminary individual farming system using a flushing tray

Figure 21 shows a tray in a flushing system. In this system, each lobster has its own cage, and because the water flow is perpendicular to the cage orientation, the number of lobsters downstream can be controlled to a smaller quantity. This allows for the prevention of disease transmission among a large number of individuals. Flow-through systems, in this regard, offer an advantage over RAS as they ensure that pathogens in the water are removed from the system instead of being recycled. The size of each lobster gives the area requirements and could be chosen according to Table 2. During the ongrowing phase, changing cages similar to existing systems may be necessary to maintain animal welfare.

3.7.2 Concept II presentation

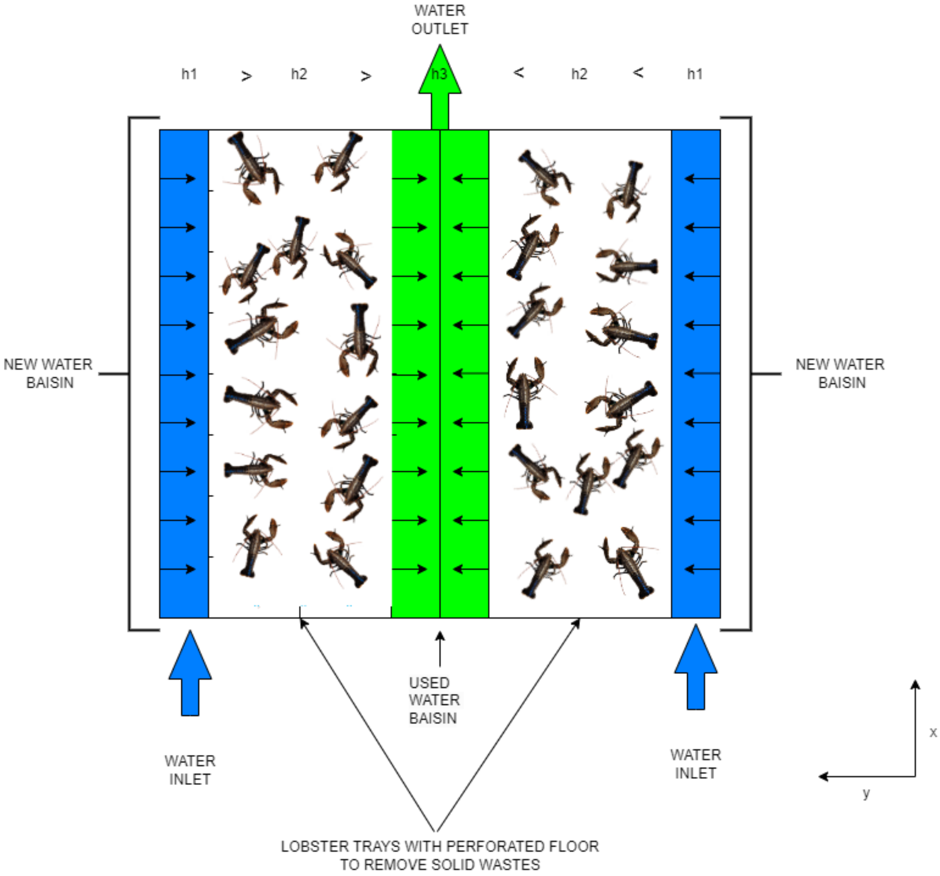


Figure 22: Concept 2. A preliminary communal farming system using a flushing tray

Concept 2 is very similar to Concept 1, except that there are no separate confinements and the system should fulfil the functional requirements discussed for the docile lobster in Section 3.4.1. The docile lobster system is introduced into a flushing tray to increase yields per ground area.

3.8 Sea environment

Some reasons for investigating a sea-based farming system are the opportunity to take advantage of lower water treatment and pumping costs and the building of a less capital-demanding farming system. On the other hand, control over environmental and predator control could be more difficult in a sea-based solution, as well as more challenging inspection, feeding, and maintenance. Structural aspects of the ability of the system to withstand environmental loads, such as waves and currents, must be met, but are left out of the scope of this work. The determination of temperature and other water quality parameters is mainly interchangeable by choosing the location prior to installation. Given the requirements for water quality and hydrodynamic limitations, a sea-based farming site should be carefully selected. As the docile lobster is assumed to be comparable to the spiny lobster, it naturally falls to explore the farming systems used in commercial spiny lobster aquaculture.

3.8.1 Concept III presentation

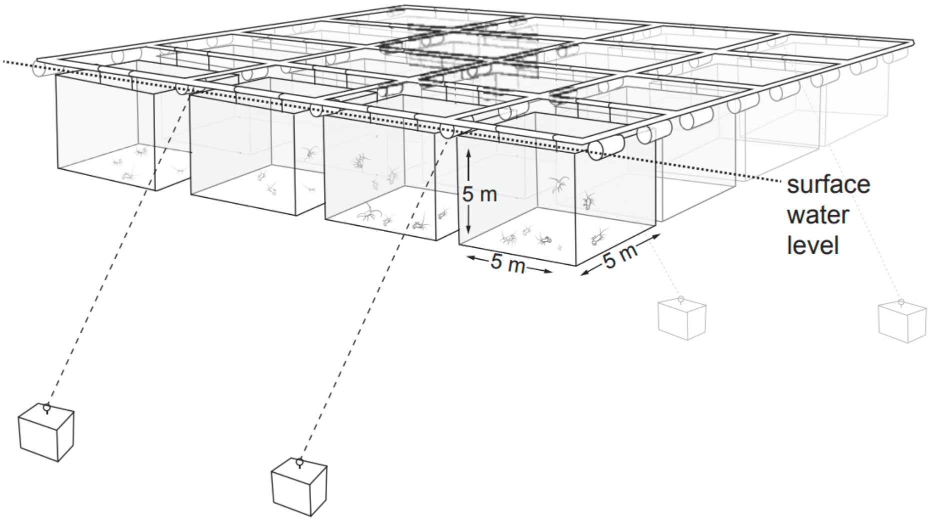


Figure 23: Typical layout of sea-based spiny lobster on-growing net cages

Source: [63]

Figure 23 illustrates a generic design used in the sea-based farming of spiny lobster. The system consists mainly of cubical net cages with flotation devices in a shared frame with a common mooring system. The cubic cages here have sides of 5 m each.

4 Concept comparison

Although several elements between the different concepts have been highlighted in the previous sections, certain elements between the concepts have not yet been addressed. These will here be part of a concept study for the sea-based concept, which aims to estimate different important criteria in farming, such as production time and the feasibility of increasing the biomass. Additionally, an estimation of production costs in hypothetical farming concepts is examined.

4.1 Establishing a basis for the comparison

4.1.1 Estimating production time

Growth rate, and thus the production time, depends on several factors, including ambient temperature, feeding intensity, and available space, as described in the biology chapter. The latter two are arguably possible to approach in a system design process. However, the ambient temperature in an open-sea-based system is little influential after choosing a farming location. Therefore, the focus is on temperature to estimate the production time in the sea. Although no explicit in-detail growth models accounting for different temperatures and environmental considerations for the European lobster were found in the literature review, an accumulative degree model will here be established to attempt to quantify production time. The model sums up daily contributions for different locations for the year. If a linear growth rate is valid, as is the case for the American lobster between $8 - 25°C$, the accumulated degree days for the different locations could provide a rough estimate of the production time.

To achieve this, the surface temperature forecast data are obtained from Copernicus, the European Union Earth Observation Program [32]. The data provided areforecast data for the time period between November 1st 2021 and October 31, 2022. It is collected for the same geographical area where the lobster is naturally present, which is depicted in Figure 4. The representativity of the one-year data set and its validity compared to other years is not elaborated. However, the results should reflect general weather conditions and describe seasonal differences. First, to compare Copernicus data with actual measurements, raw data are collected from the Havforskningsinstituttets research centre at Flødevigen and compared with Copernicus data at the same geographical location. Some key differences exist, such that Copernicus uses a rough geospatial grid and provides forecast data every 6. th hours compared to Havforskningsinstituttets actual measurements taken every minute throughout the year.

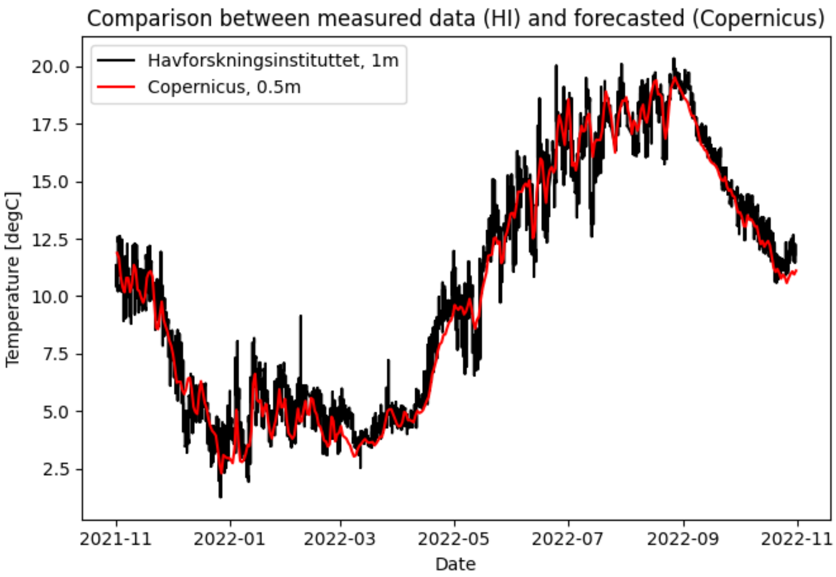


Figure 24: Temperatures comparison between Copernicus and HI

Source: [32], [50]

The Copernicus temperatures in Figure 24 seem to follow the trend of measured temperatures given by the raw Havforskningsinstituttet data, and the daily contributions for this location seem to fit quite well. Since the Copernicus data provide information on several other locations and not only at a measurement station, the Copernicus data are utilised further. However, the temperature data is not given as valid for other locations as in Flødevigen. A visualisation of the Copernicus data is done by generation of a GIF through a Python code. Each picture frame is provided for each day throughout the year. Some snapshots are provided here to show the results for the different seasons.

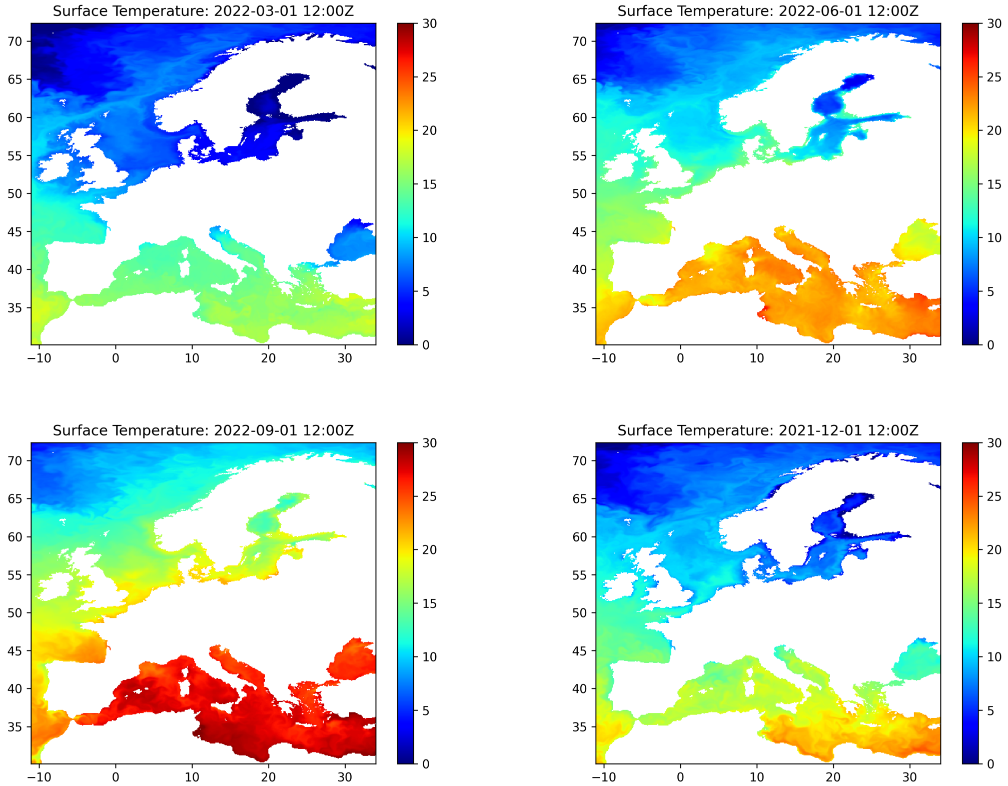


Figure 25: Surface temperature for given dates, where the colorbar expresses temperature in $[°C]$ for the given coordinates

As seen in Figure 25, the temperature in the surface area is seen above the upper threshold of $25°C$ in the Mediterranean area in the summer, while the surface temperature is below the lower threshold of $5°C$ in winter in the northern parts of Europe. Furthermore, a set of locations could be determined to further evaluate different farming locations. Here, three locations are chosen to illustrate variations in surface temperatures.

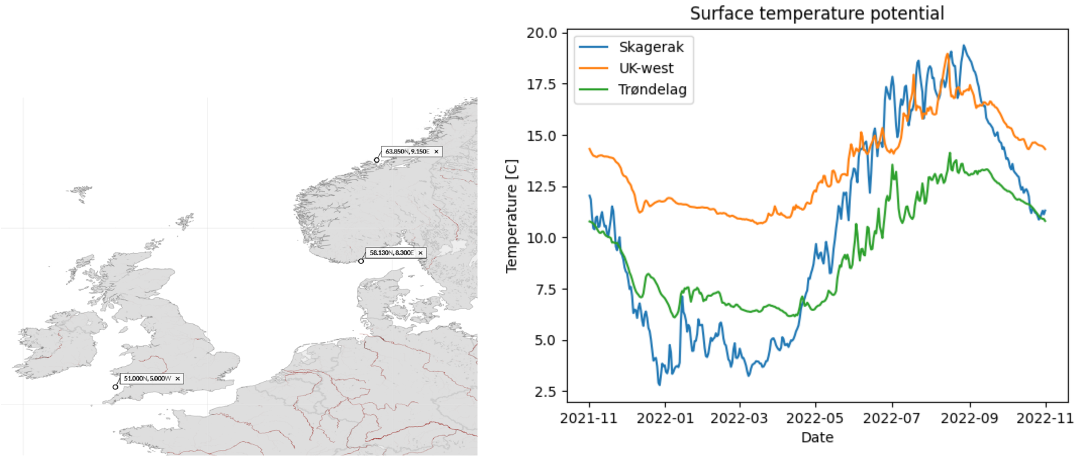


Figure 26: Three different locations and surface temperatures for the same time period as in Figure 25

Figures 25 and 26 show that surface temperatures vary throughout the year for all locations but to different extents. As mentioned in Section 2.2.5, it would take approximately 17.000 degree days for the larvae to grow to a portion-sized lobster under a certain farming regime. Assuming a linear coherence between growth and temperature, the area under each plot would depict degree days and again the time needed to reach plate-sized product - or at least an estimate of the mean average of the lobsters as in Figure 8. The significant variance in growth probably makes this approach a rough estimate at best.

Location	Degree days (DD) above 8°C	DD between $5 - 8$°C	Avg. DD	Avg. grow-out in years
Skagerak	3068	360	3250	5.2-5.4
Trøndelag	2340	1083	2882	5.9-7.2
UK-west	4945	0	4945	3.4-3.4
RAS at $20°C$	7300.0	0	7300	2.3-2.3

Table 5: Degree day potential and estimated growth time to reach 17.000 degree days for locations given in Figure 26

Table 5 summarizes the individual temperature contributions for different days and calculates the potential degree days and the corresponding mean grow-out time. Growth is assumed to be proportional to temperatures ranging from 8 to $25°C$. The growth potential for temperatures between $5 - 8°C$ is not explicitly described, but is here included as negligible for growth (lower left value for mean grow-out time) and as half the growth potential (upper value for mean grow-out time). When combining both these contributions for temperatures between $5 - 8°C$ and above $8°C$, the average degree days are determined. The average degree days are then used to estimate the grow-out time.

Given the individual growth of lobster and a mean sea-based farming time of 5.3 years, and a proportional difference in grow-out times as in a RAS as in Figure 8, the production time in the sea could be between 3.3 and 8.0 years for the different individuals, making the results inconclusive. It is not clear and more research is needed. This approach is very uncertain and would, at best, be very rough. The results show that the production time in the sea would be significantly longer in colder seawater than in heated RAS, and that Norway could have a competitive drawback compared to other European nations with warmer and more stable temperatures.

4.1.2 Water quality in sea-based cages

Being confined, lobsters cannot escape unfavorable conditions such as hypoxia. The cage layout design should maintain adequate dissolved oxygen levels at any time to sustain animal welfare. The clustering of cages could lead to the depletion of available oxygen, especially downstream in the enclosure. Unlike farming in a RAS where pump delivery and biofilter capacity could be modified, a sea-based environment is little adaptable. The feasibility of increasing the apparent biomass of lobsters for the docile lobster is, for this reason, conducted, as well as to create an estimation for what size a conceptual sea-based lobster farming plant (Concept III) could behold. The intended usage of the model is to be used in future decision making. For these reasons an approach considering downstream effects of accumulated substances such as carbon dioxide and TAN as well as oxygen depletion is taken. A transportation model is used to describe the transport of substances similar to [5] and [6]. Here, a transport equation in the form of the advection-diffusion equation, i.e., a partial differential equation (PDE), is solved to model oxygen levels in salmon sea cages.

The advection-diffusion equation is numerically solved to estimate the amount of different substances present in the environment. It describes the transportation of a quantity within a physical system and is expressed by the following equation:

$$\frac{\partial c}{\partial t} = \nabla(Cv) + \nabla\kappa\nabla C = C_{sources} - C_{sinks} \tag{2}$$

Equation 2 states that the concentration change as a function of time is dependent on an advective and a diffusive term, as well as the presence of sources and sinks. Their physical explanations are described as the more stable part of the current (advection), and the diffusive term could be seen to account for the mixing of turbulence of sea water. The sources and sinks represent the lobster production of TAN and CO_2 (source) and the consumption of O_2 (sink).

Symbol	Unit	Description
Δx	[m]	Cell size in x direction
Δy	[m]	Cell size in y direction
Δz	[m]	Cell size in z direction
Δt	[s]	time step increment
N rows	#	Number of cages arranged in x direction
N columns	#	Number of cages arranged in y direction
Cagesize	[m]	Cage side size, square
Cagespacing	[m]	Distance between cages
m	#	Number of cells in x direction
n	#	Number of cells in y direction
o	#	Number of cells in z direction
c[i,j,k]	[mgC/L]	Concentration of substance C in cell (i, j, k)
Substance	-	Either TAN, O2 or CO2
u	[mgC/Ls]	Production/consumption rate of substance C in cage
Biomass	$[kg/m^2]$	Present biomass in the cages per m^2, per discretization $[m^3]$
Lobster size	[g]	Lobster size in grams per individual
Ambient value	[mgC/L]	Initial concentration of substance C in ambient water
V_x	[m/s]	Current velocity in x-direction
V_y	[m/s]	Current velocity in y-direction
V_z	[m/s]	Sinking/floating speed in z-direction
κ	$[m^2/s]$	Diffusion rate

Table 6: Parameters used in the model, with units and description

The simulation of the model uses the different parameters found in Table 6. From Equation 2, it follows that:

$$\frac{\partial c}{\partial t} = v_x \frac{\partial c}{\partial x} + v_y \frac{\partial c}{\partial y} + (v_z + u_z) \frac{\partial c}{\partial z} + \nabla \kappa \nabla C = C_{sources} - C_{sinks} \tag{3}$$

where

$$\nabla \kappa \nabla C = \frac{\partial}{\partial x}(\kappa_x \frac{\partial}{\partial x} c) + \frac{\partial}{\partial y}(\kappa_y \frac{\partial}{\partial y} c) + \frac{\partial}{\partial z}(\kappa_z \frac{\partial}{\partial z} c) \tag{4}$$

Here, κ (kappa) is the diffusion coefficient, which is the mixing rate between neighbouring cells. For a specific substance, it is difficult to estimate the diffusion coefficient without experimental measurements. This fact should be emphasised thoroughly. Furthermore, the diffusion coefficient κ varies significantly depending on the substance being focused on (e.g., pellets / gas molecules). In the model, the modelled diffusion accounts for turbulence related to flow conditions rather than molecular diffusion. For oxygen, $\kappa = 10(v_x^2 + v_y^2)$ was shown to be a reasonable estimate for oxygen [5], which is then used for the substances here as well. It is also assumed that κ is omnidirectional, that is, constant and similar in all directions, so $\kappa_x = \kappa_y = \kappa_z = \kappa$. With such an assumption, specifically that κ_z is equal to those in the vertical plane, it was indirectly stated that there is no solid floor in the cage bottom. At the same time, it is said that the substances have neutral buoyancy, i.e., they are neither floating nor sinking. Therefore, uz is eliminated.

The new assumption for κ simplifies the governing equation into the following equation:

$$\frac{\partial c}{\partial t} + v_x \frac{\partial c}{\partial x} + v_y \frac{\partial c}{\partial y} + v_z \frac{\partial c}{\partial z} + \kappa(\frac{\partial^2}{\partial x^2} c + \frac{\partial^2}{\partial y^2} c + \frac{\partial^2}{\partial z^2} c) = u \tag{5}$$

Equation 5 is then solved for each discretized cell in the spatial domain for each time increment dt.

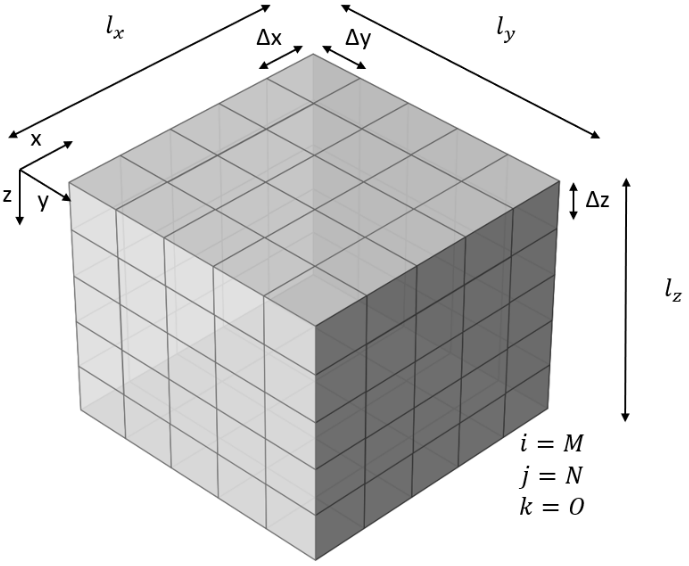


Figure 27: The discretized domain

Figure 27 shows the discretized domain. Within certain cells, the lobster cages are stated to be within. Here, a production or reduction u is stated to be present:

$$\dot{c}_{[i,j,k]} = fA + fD + u \tag{6}$$

where

$$fA = v_x \frac{c_{[i,j,k]}}{\Delta x} + v_y \frac{c_{[i,j,k]}}{\Delta y} + v_z \frac{c_{[i,j,k]}}{\Delta z} - (\frac{v_x}{\Delta x} + \frac{v_y}{\Delta y} + \frac{v_z}{\Delta z}) \cdot c_{[i,j,k]}$$

$$\begin{aligned} fD = \kappa(& \frac{c_{[i+1,j,k]} - 2c_{[i,j,k]} + c_{[i-1,j,k]}}{\Delta x^2} \\ & + \frac{c_{[i,j+1,k]} - 2c_{[i,j,k]} + c_{[i,j-1,k]}}{\Delta y^2} \\ & + \frac{c_{[i,j,k+1]} - 2c_{[i,j,k]} + c_{[i,j,k-1]}}{\Delta z^2}) \end{aligned}$$

and u is given as TAN or CO_2 production or O_2 consumption. No measures for aeration or degassing imply that there is no source and sink in the same physical instance. This implies that the investigated variable could be modelled by the same variable u where the value could be interchanged, with the sign as the direction in or out of the system. An example for u as consumption is provided for O_2:

$$
\begin{aligned}
u_{O_2} &= consumption[\frac{mgO_2}{kgmin}] \cdot biomass[\frac{kg}{m^3}] \cdot \frac{1}{60} \cdot \frac{1}{1000}[\frac{m^3}{L}] \\
u_{O_2} &= 2[\frac{mgO_2}{kgmin}] \cdot 7[\frac{kg}{m^3}] \cdot \frac{1}{60} \cdot \frac{1}{1000}[\frac{m^3}{L}] \\
u_{O_2} &= 0.000\overline{233}[\frac{mgO_2}{L \cdot s}]
\end{aligned}
\tag{7}
$$

Further model simplifications are applied. The sea-based farming system that makes up Concept III is examined. Although the Python script could input a variety of different cage configurations, the input of cages in rows and columns is modelled to correspond to the system described for spiny lobster farming, described in Figure 23, where 4x4 cages of 5 m each are used. Additionally, all lobsters are modelled to be evenly distributed throughout the cage environment at the cell layer corresponding to the cage bottom. This means that lobsters are assumed to be uniformly distributed in a volume corresponding to the discretization size dz. The simulation solution is thus sensitive to the chosen cell discretization. Furthermore, lobsters are assumed plate size (250 g each) and follow the consumption and excretion rates shown in Figure 10. Time-dependent excretion peaks as a result of feeding are not modelled. Furthermore, the current in these cases is modelled to be constantly $V_x = 5cm/s$, which should be within the hydrodynamic limitations of the lobster and provided by the choice of location. There are no shelters in the cages and there are no interactions between the cages and water flow.

Initially, the ambient levels of dissolved substances are stated to be zero for the substances produced. Although substances could exist prior to simulation, the relative difference would be the same, and the solution could later be scaled. This could also be the case for consumption, but for oxygen, the following composition is utilized:

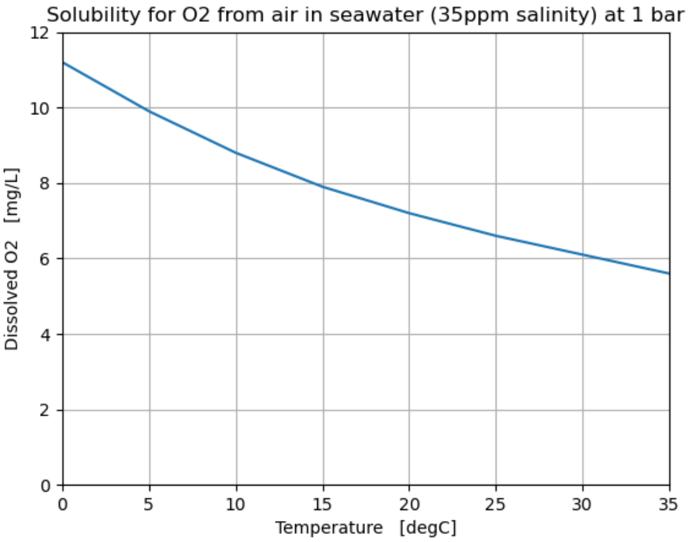


Figure 28: Oxygen solubility for seawater for different temperatures

Source: Modified from [34]

At 20°C, this is approximately 7 mg/L, which is a conservative estimate, given the information on metabolism and solubility described in the literature review. All cells in the domain are then initially set to this value. Then the model is simulated until steady state is reached.

At the outermost cell boundaries, the cell at the ”north” and ”south” sides are stated to be far enough away to act as sinks in the system. The ”east” side, which is located on the downstream side, has the boundary conditions that the outermost cell is set to be the second outermost cell, representing a continuous flow out of the system.

The results for water quality in sea-based cages

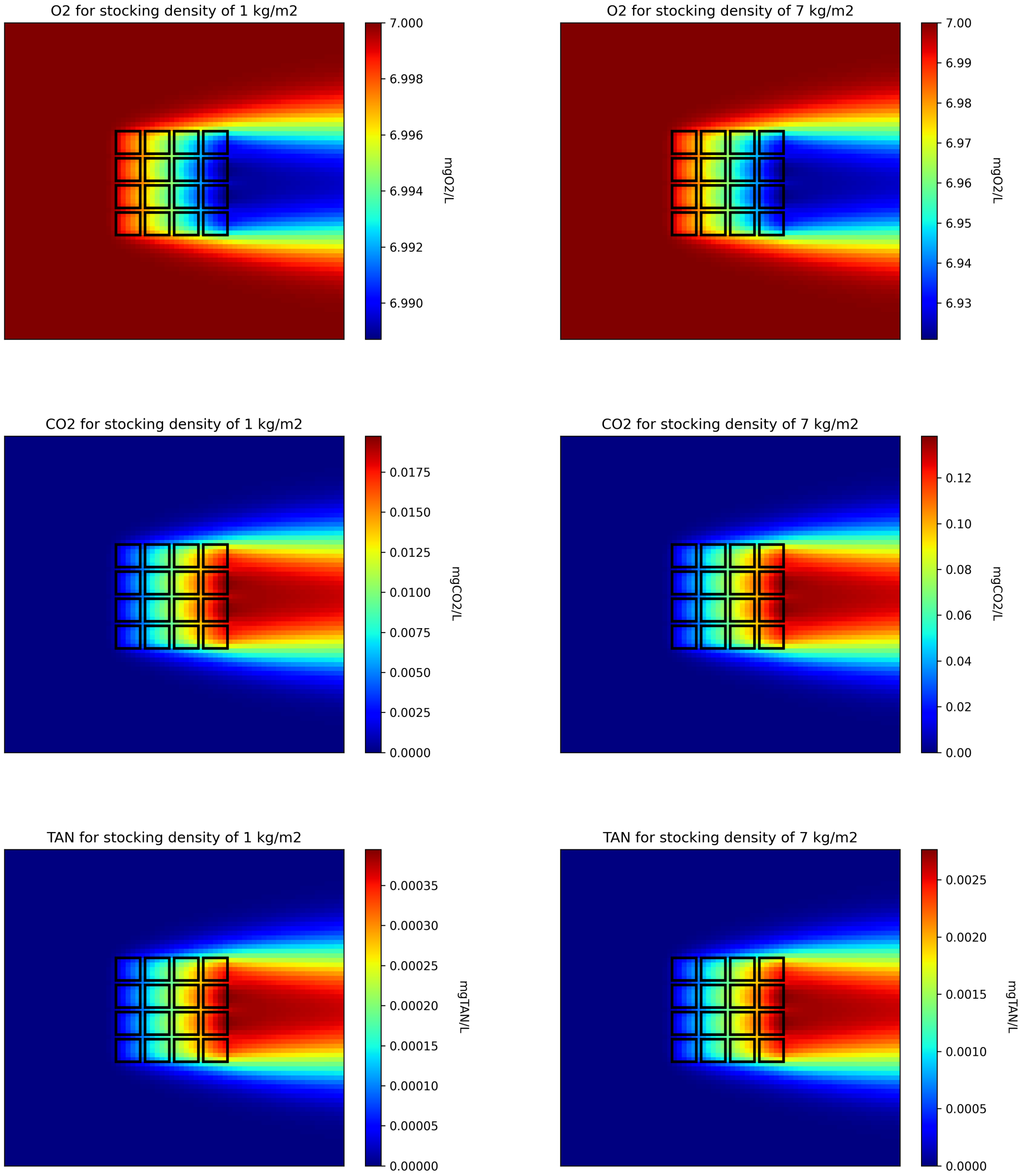


Figure 29: Estimated dissolved substances for two biomasses at steady-state: 1kg/m2 (left) and 7 kg/m2 (right), at 5cm/s current speed.

Based on the observations in Figure 29, it appears that increasing the biomass of the docile lobster would not immediately pose a threat to the selected water quality parameters described in Table 1.

4.2 Risk and uncertainty in farming

The concept of risk could be defined as the answers to 1) what can go wrong, 2) what would the consequences be, and 3) at what frequency is something going wrong? [77]. A risk assessment is often based on a probability or frequency distribution and is thus measurable to a certain degree and could be used in future assessments. Uncertainty is related to risk, but it is fundamentally different. It would be used in settings where there is no historical data that can be used to estimate future states [16]. Uncertainty would be more appropriate in this context due to the lack of industrialisation and historical data. However, the two concepts will be used interchangeably to describe and pinpoint generic risks and uncertainties in farming for the different concepts. In lobster farming, there are different concepts of risk. The risk could be related to different aspects of farming, such as the market risk, biological risk, and technical risk.

The market risk is explained by the fact that because lobsters are luxury food items, sales are exposed to market recessions. When the market is strong, sales and demand are accordingly robust. In the event of a market recession, demand and sale prices could collapse disproportionately, and the farmer is not guaranteed the ability to sell at profitable prices [93]. Not directly related to the market, but to the investment in a farm, there is further risk. During development and production, the gained experiences could potentially create the need to update or change farm components [16], again affecting costs.

The biological risk includes outbreaks of diseases that could lead to mass deaths on the farm. Disease outbreaks could lead to a situation where all animals present must be euthanized and the environment thoroughly cleaned or even fallowed for a long time. Attaining high control over the farm environment by real-time monitoring of relevant water quality parameters, as well as having the know-how and contingency plans to make corrective measures, would reduce the likelihood of accumulation of metabolites above lethal threshold levels. Compared to other species, such as salmon, lobsters have much higher tolerance to variations within their farm environment and could survive for several days in a moist environment. *Lobsters handles better land than bad water* [84], highlighting that the response time in lobster farming is days compared to minutes in fish farming. In addition, some lobsters are oxygen regulators and can adjust their metabolism at very low oxygen levels [76]. If the European lobster has this ability, it was not explicitly found in the literature review. However, the biological risk incurred by stopping the water supply is arguably lower than that of other species.

The biological risk could also be mitigated by making choices about a farming concept. For example, increased stocking densities amplifies the disease vector [60], as well as having more animals in the same water volume [71], ultimately increasing the risk of diseases. Furthermore, if the likelihood of disease outbreaks is influenced by the time the lobsters are exposed to diseases, which would be the ongrowing time, it is believed that extending the duration of lobster farming could raise the potential for such outbreaks. Using a flow-through system would arguably offer better control than an RAS, as bacteria and pathogens would not be recirculated and introduced to the other lobsters in the tank system. The ability of the systems to segregate a smaller number of animals would reduce the consequence if a disease outbreak occurs. Instead of a large plant using a common deep-tank system, several modular systems could be built nearby and use different water intakes. This would probably mitigate the consequences of disease outbreaks at the expense of increased construction and production costs. Determining the risk profile, which describes how willing stakeholders are to take risks, is an active choice that relevant stakeholders must consider prior to the construction of a lobster farm. A low risk profile would come with a higher installation and operation cost, and with a lower earning potential compared to a higher risk profile.

Technical risk is related to the probability and frequency with which technical failures occur. In a RAS, this would primarily be related to farm components, such as pumps, filters, etc., leading to downtime. The technical risk could also be mitigated by introducing redundant pumps or backup systems in the event of pump failure. This would come at an increased cost, which again depends on the risk profile of the farmer. For the sea-based concept, there are other risk elements. Environmental conditions, such as waves and currents, will affect the farm and could lead to structural failures. For sea-based fish farming in flexible nets, a hole in the net is the most common escape mechanism [43]. With fewer safety barriers between the farm and the environment, the risk of affecting wild populations is increased for the sea-based system. This will likely also be the other way around, where wild animals, such as birds, otters, and seals, could possibly enter the farm.

However, analysing these risks and uncertainties will probably be inaccurate in the real world. Assessments aimed at quantifying and managing risk are not given to focus on the correct factors. In innovation processes such as lobster farming, critical success factors will not be known beforehand but discovered during development, making a theoretic risk analysis less valuable [30].

In summary, several risks and uncertainties affect farming, but they are hard to quantify in advance and, due to a lack of historical data, an analysis would probably have limited value. Furthermore, measures against risk could be taken and depend on the associated risk profile of the farming system. Due to these challenges, the risk is inherently included in other evaluation criteria later on.

4.3 Estimating production costs

The economy of an industry is a direct measure of its productivity, quality of products and its ability to cope with influence upon the environment [9]. Furthermore, the economic situation in which the high costs involved in capital intensive farming systems present a significant challenge in upscaling farming operations. Ultimately, the economy will serve as a crucial factor in determining the feasibility and success of a farming concept. Although economic estimates, in the best case, will be very coarse because of the lack of empirical data, a brief cost comparison will be conducted to compare the concepts.

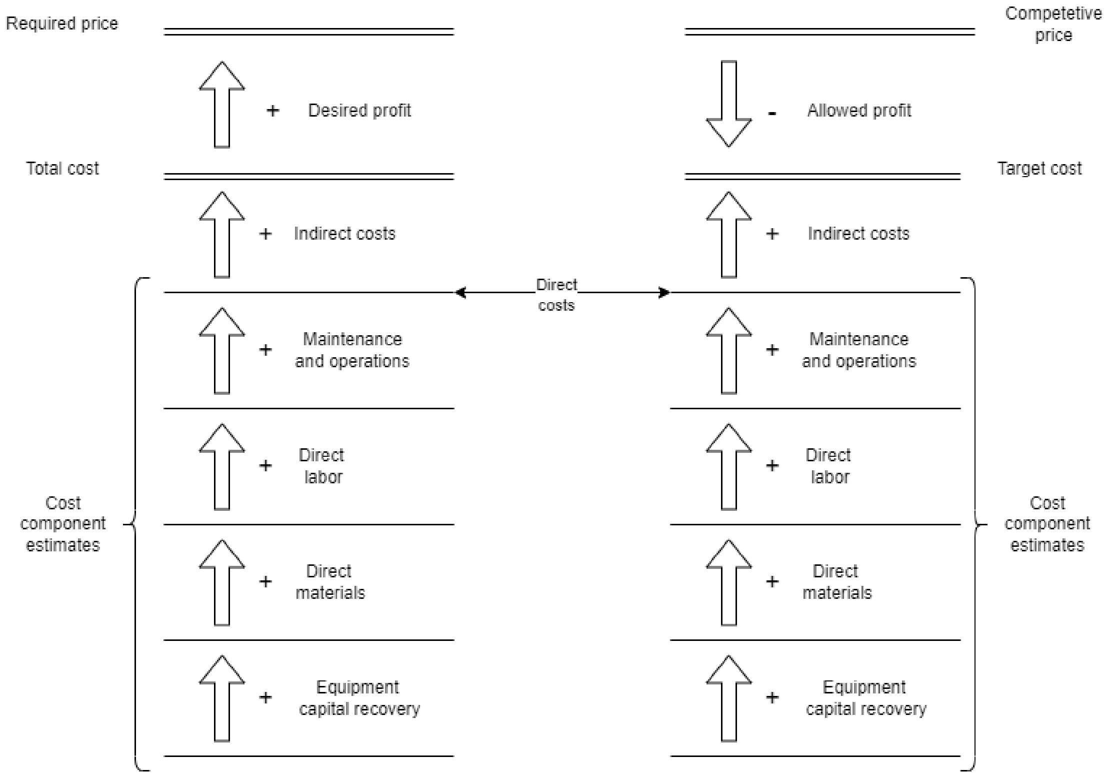


Figure 30: Bottom-Up (left) and Top-Down approaches used for cost estimation

Source: [17]

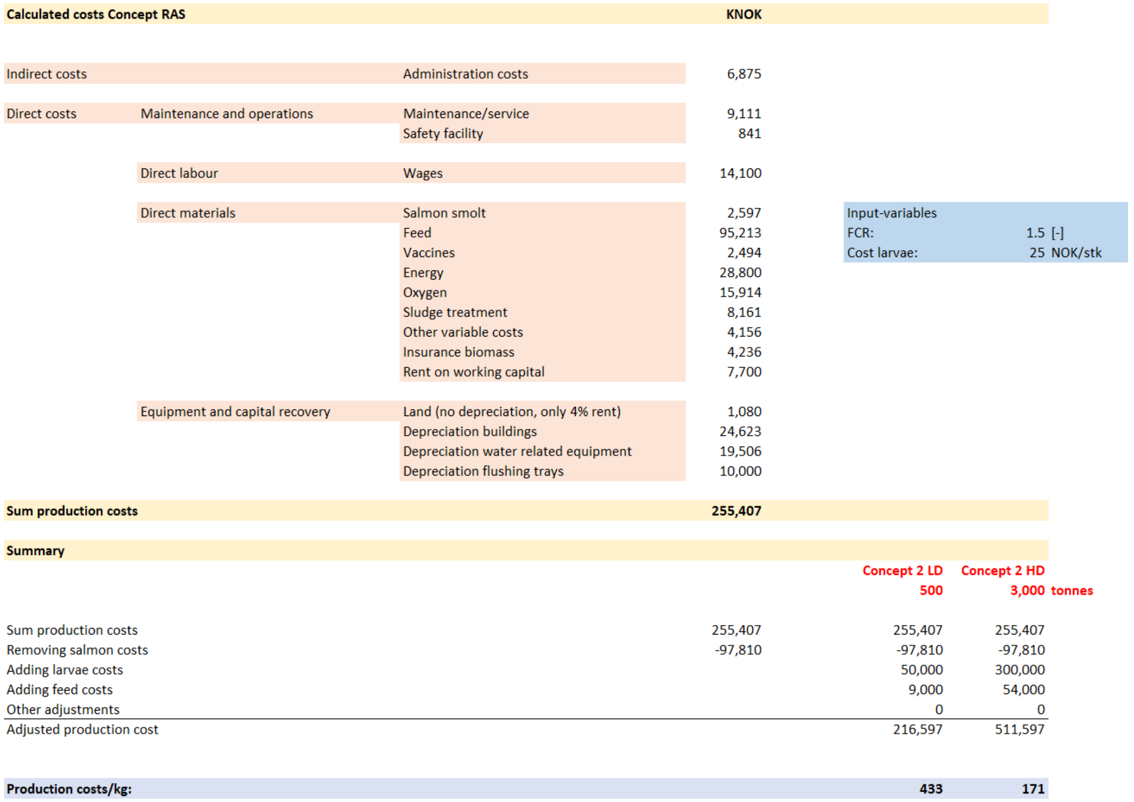
Figure 30 presents two approaches to cost estimation, typically used in different stages of planning. The top-down approach is best applied in the early stages of the design, where price estimates are used to establish the target costs [17]. The top-down approach will here be used to establish an estimate of the target costs, which here is the production cost, for the different concepts. Here, a market for plate-sized lobsters that achieve NOK $500/kg$ will be assumed, according to the findings in Section 2.1.1.

4.3.1 RAS costs

A RAS facility is not a standard item, and the cost of RAS building depends on the demands of each customer, the specific farming location, and the degree of automation and recirculation [16]. The specific needs of the species would also be reflected in the investment. The basis for the cost comparison is established from numbers related to salmon farming, implying that some adjustments are likely needed, as the presence of flushing trays is expected to be a significant differentiating factor when comparing lobster farming with salmon farming in tanks. In this case, no estimate of the price of these flushing trays has been found, leaving the flushing tray cost currently unknown.

Since cost estimates are specifically for the salmon industry, the costs undergo certain modifications before being used. The only estimate of the cost of a land-based lobster farming system is found in [22], where investment costs were MNOK 650 for an annual production capacity of 1000 tonnes. This facility is probably the only one of its kind in the world. The investment cost is, compared to a salmon RAS of similar size as in [16], approximately $5-6$ times higher per tonne produced, which is likely to be attributed to decreased shellfish stocking densities compared to finfish. To account for variations in yield, the costs are scaled based on the production capacity of the system. In other words, the physical size of the farm is the same, but the amount of lobster able to be produced in the same amount of space is changed according to the relative change in production yield. Individual-based farming (Concept 1) is assumed to have a stocking density of $2\frac{kg}{m^2}$, which is supported by the findings of the literature review deduced in Table 3. The cost-to-yield ratio from the provided dataset is then adjusted according to this ratio and used to evaluate Concept 2. In terms of total cost, Concept 2 LD (Low Density, $1\frac{kg}{m^2}$) would have half the production capacity (500 tons), while Concept 2 HD (High Density, $6\frac{kg}{m^2}$) would have three times the production per unit of floor area (3000 tons) compared to individual-based RAS.

The costs provided are found in Tables 1 and 9 in [16], and are applied in the Appendix B. Costs are first arranged accordingly in Figure 30, which leads to an estimate of the target cost. The depreciation cost for the flushing trays is set at MNOK 10, but may be subject to change if a more accurate estimate becomes available later. The costs specifically related to salmon, which are smolt and feed costs, are then replaced by lobster-related costs in the form of larvae and feed consumption. Lobster larvae costs was in 1996 1.5$/ per individual [65] which could be approximately NOK 25 per individual today. Since survival of 100% is assumed, the number of larvae is set accordingly to be the production yield of the farm, where a plate size lobster is harvested $250g$ size (4 lobsters per kg). Furthermore, the feed consumption is set at 1.5 according to the literature review, and the feed price is set equal to that of the salmon found in [16].



Calculated costs Concept RAS			KNOK
Indirect costs		Administration costs	6,875
Direct costs	Maintenance and operations	Maintenance/service	9,111
		Safety facility	841
	Direct labour	Wages	14,100
	Direct materials	Salmon smolt	2,597
		Feed	95,213
		Vaccines	2,494
		Energy	28,800
		Oxygen	15,914
		Sludge treatment	8,161
		Other variable costs	4,156
		Insurance biomass	4,236
		Rent on working capital	7,700
	Equipment and capital recovery	Land (no depreciation, only 4% rent)	1,080
		Depreciation buildings	24,623
		Depreciation water related equipment	19,506
		Depreciation flushing trays	10,000
Sum production costs			**255,407**

Input-variables		
FCR:	1.5	[-]
Cost larvae:	25	NOK/stk

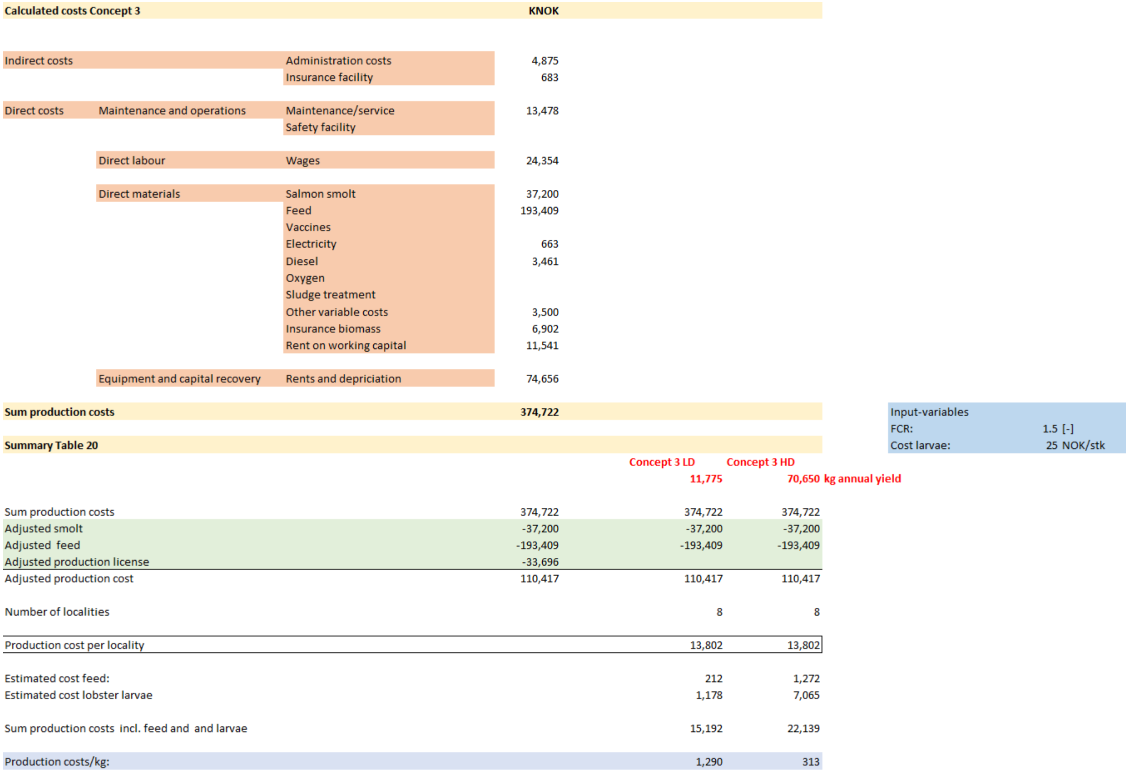
Summary				
		Concept 2 LD	Concept 2 HD	
		500	3,000	tonnes
Sum production costs	255,407	255,407	255,407	
Removing salmon costs	-97,810	-97,810	-97,810	
Adding larvae costs		50,000	300,000	
Adding feed costs		9,000	54,000	
Other adjustments		0	0	
Adjusted production cost		216,597	511,597	
Production costs/kg:		**433**	**171**	

Figure 31: Estimated investment and production costs for Concept 2

In Figure 31, it seems that production costs would be approximately NOK $433/kg$ for a stocking density of $1\frac{kg}{m^2}$ and NOK $171/kg$ for a stocking density of $6\frac{kg}{m^2}$. As these numbers are from 2018, the production costs could now be NOK $515/kg$ and NOK $203,50/kg$ scaled to the net present value [86]. The result also indicates that production costs are dependent on production volumes and are decreased when a higher yield is present. The yield is again linked to stocking densities, so this indirectly implies that production costs diminish for an increased stocking density.

4.3.2 Sea based costs

Firstly, it is important to note that the evaluation outlined here deviates from the specific concept that uses 4x4 cubical cages measuring 5 m each, shown in Figure 23. Instead, the deductions are derived from a salmon production facility. Concept 3, similar to RAS, incorporates similar assumptions such as 100% survival rate, larval cost, and utilisation of the same FCR and feed costs. Additionally, total costs are determined by substituting salmon-specific costs for lobster-related costs. The costs of salmon production are found in Tables 12 and 20 in [16], which are placed in the Appendix B. Some costs, such as the production licence, are excluded. The yields are set to be proportional to the available cage bottom area, which is a significant difference between the flushing trays and the sea-based farm. Instead of being placed in vertical trays, it is assumed that the lobsters are evenly distributed on the cage floor and that the yield is proportional to the floor area. The numerical basis provided is for a location that has 6 conventional gravity cages with a diameter of $50m$ each, giving a total area of $11780m^2$ in total. The two stocking densities lead to two different yields of $11781kg$ and $70686kg$ for low and high densities, respectively, which should be noted to be significantly lower than RAS. Similarly to RAS, the costs are grouped according to Figure 30.



Calculated costs Concept 3			KNOK
Indirect costs		Administration costs	4,875
		Insurance facility	683
Direct costs	Maintenance and operations	Maintenance/service	13,478
		Safety facility	
	Direct labour	Wages	24,354
	Direct materials	Salmon smolt	37,200
		Feed	193,409
		Vaccines	
		Electricity	663
		Diesel	3,461
		Oxygen	
		Sludge treatment	
		Other variable costs	3,500
		Insurance biomass	6,902
		Rent on working capital	11,541
	Equipment and capital recovery	Rents and depriciation	74,656
Sum production costs			**374,722**

Input-variables	
FCR:	1.5 [-]
Cost larvae:	25 NOK/stk

Summary Table 20		Concept 3 LD	Concept 3 HD
		11,775	70,650 kg annual yield
Sum production costs	374,722	374,722	374,722
Adjusted smolt	-37,200	-37,200	-37,200
Adjusted feed	-193,409	-193,409	-193,409
Adjusted production license	-33,696		
Adjusted production cost	110,417	110,417	110,417
Number of localities		8	8
Production cost per locality		13,802	13,802
Estimated cost feed:		212	1,272
Estimated cost lobster larvae		1,178	7,065
Sum production costs incl. feed and and larvae		15,192	22,139
Production costs/kg:		1,290	313

Figure 32: Estimated production costs for sea-based lobster farming

In Figure 32, it seems that production costs would be approximately NOK $1290/kg$ for a stocking density of $1\frac{kg}{m^2}$ and NOK $313/kg$ for a stocking density of $6\frac{kg}{m^2}$. Scaling to the net present value, an increase would be NOK $1570/kg$ and NOK $381/kg$, respectively [86]. Since similar assumptions are made for both the sea-based concept and the land-based concept, comparable outcomes regarding the evaluation of yields and stocking densities are also evident in this case.

4.4 Establishing evaluation criteria

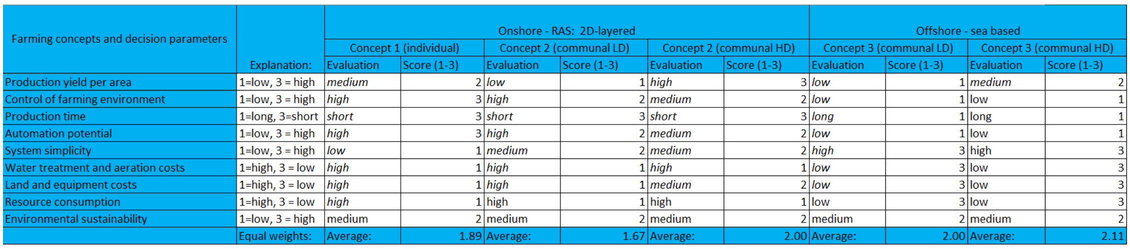
The following evaluation criteria are established by understanding the information gathered from the literature review and the results described above. A special emphasis should be placed on the work of *Van Olst etal 1977* [90], which lists important design parameters and how different farming systems compare. However, there is no guarantee that the decision parameters listed below will cover all relevant information, but the decision parameters are broad and will inherently cover key aspects relevant to the success of lobster farming.

Evaluation criteria	**Findings in previous sections**
PRODUCTION YIELD PER AREA is important in establishing area-efficient farming systems, which is a challenge in farming [4]. Higher production yield is linked to increased revenues and cash flows, as well as lowering production costs per kg. Because the production yield is linked to stocking density, the stocking density acts as a measure of area utilization	At plate size, the results of the thesis have shown that the recommended stocking densities could be $2.0\frac{kg}{m^2}$ using individual confinement (Concept 1). For docile lobsters, a relatively low stocking density of $1\frac{kg}{m^2}$, is used in the farming of some species of spiny lobster (Low Density). This is compared to spatial needs, which lead to a stocking density of approximately $6\frac{kg}{m^2}$ (High Density). Flushing trays provide multiple layers, increasing yields compared with the sea based farm which only uses one layer of space.
CONTROL OF FARMING ENVIRONMENT is important to maintain optimal conditions in which growth and health are best taken care of. This, in turn, can contribute to increased yield and product quality, which can improve profitability. Having control over the environment is also believed to reduce biological risk, as it is conceivable that having control over the environment will reduce the risk of disease outbreaks. Control over predators is also important to protect lobsters from predation.	Introducing an RAS, makes the farmer in greater control over the farming environment. Several components of the system help maintain the desired water quality. (Concepts 1-2) Furthermore, farming in individual modules with a lower number of animals present in the same water volume (reducing consequences), or farming in an flow-through system (reducing frequency), mitigates risk of disease outbreaks. The control over the farming environment is somewhat unclear in communal farming, but are set to be medium for Concept 2. Land placement inherently deals with predators such as seals, otters, and birds, and to a certain extent with disease-inducing pathogens through intake water control. Therefore, a sea-based farming system leaves less control of the farming environment (Concept 3).
PRODUCTION TIME is important for several reasons. It is related to the production yield, where more animals can be farmed in the same amount of time. Production time is also related to risk. If farming is prolonged, disease outbreaks could be more likely, especially in combination with low environmental control. The need for necessary maintenance would presumably also increase, as would the increase in biofouling and the incured costs of removing it.	Farming time in constant $18-20°C$ has an average production time of 2 years [26], (concepts 1-2), while preliminary results indicate that in Norwegian waters the production time is likely to increase, with an average of more than 5 years (concept 3). However, this could probably be significantly lower when choosing a better farming location, and the on-growing time is also dependent on several other parameters (feed, space, interaction effects, etc.).
AUTOMATION POTENTIAL is argued to be important to reduce the operational costs related to farming. It also aims to improve precision and repeatability in farming. Automation has been the focus of individual farming for the last decades, and most of the husbandry operations are automated in state-of-the-art systems. For a land-based RAS, the need to stock lobsters in the vertical direction (several layers) is presumed a necessity, making automation relevant also for the docile lobster to increase production yields.	In a land-based system, automation is probably easiest implemented using flushing trays, which is the basis for Concepts 1-2. Automation is further simplified by having individual separation (concept 1). Some husbandry operations may be excluded from communal farming, such as individual feeding. However, other possible operations (such as regular classification and size grading) may require automation, leading to a medium automation potential. In sea-based systems, systems already exist for monitoring and cage cleaning, but due to deeper, flexible net cages, it is arguably harder to monitor and automate several husbandry operations (Concept 3).

Evaluation criteria	Findings in previous sections
SYSTEM SIMPLICITY is, in opposition to complexity, believed to reduce initial farm costs due to the elimination of the need for individual confinement, as well as introduce a simpler farm environment that would be easier to monitor, maintain and operate.	Communal farming excludes the need for confinements and will introduce a simpler farming environment (Concepts 2-3). However, as land based farming of docile lobsters are assumed in flushing trays (concept 2), the needs for sophisticated technologies arguably makes the system more complex than the floating net sea based cages (concept 3).
WATER TREATMENT AND AERATION COSTS consumes resources in the form of energy and contributes to production-costs. This criterion is also indirectly linked to farm environment control and system simplicity, as well as environmental sustainability.	A RAS involves a great deal of water treatment (concepts 1-2), compared to a sea-based cage where currents ensure water renewal.
LAND AND EQUIPMENT COST needed to be invested in construction seems to make up for a substantial part of the capital needed to start up a land-based lobster farm, and getting access to capital has been a problem for upscaling.	A floating sea-based net cage system could, compared to a RAS, have an investment cost of 1:10 if comparable to the salmon industry [53], and approximated at MNOK 50 and 500, respectively. An economic investigation comparing the costs found in salmon farming also deduces these results.
RESOURCE CONSUMPTION is here related to the use of non-returnable goods, specially focusing on power consumption and material use. This criteria is linked to water treatments and aeration costs, but also building materials needed to build a farm.	The RAS would require more energy for various components such as heaters, pumps, filters, and aerators, to maintain optimal water conditions. This could to a certain degree be mitigated using effluent heated water from other industries, using flow-through systems. As the RAS is built of concrete and steel, compared to simpler plastic ring and nets for the sea based concept, the resource consumption is arguably higher for the RAS.
ENVIRONMENTAL SUSTAINABILITY assesses the long-term effects, including landscape alterations and the pollution such as feces and feed wastes released into the nature	Building a land-based RAS would likely be built near seawater, and the essential groundwork required in construction could have irreversible consequences on the natural environment. On the other hand, controlling the waste stream and use the wastes as f.ex fertilizer would increase this dimension of sustainability. Thus, concepts 1-2 are stated to have a medium impact. Having no control over the waste stream, the sea based concept 3 also scores medium.

Table 7: Decision-making parameters chosen in comparison between Concept 1-3

Given the considerable uncertainties surrounding the ranking of the different systems, a rating scale ranging from low to high is provided to assess their relative performance. The information obtained from Table 7 is assigned a value based on its intended performance and organised into a matrix presented in the form of a spreadsheet:



Farming concepts and decision parameters		Onshore - RAS: 2D-layered						Offshore - sea based			
		Concept 1 (individual)		Concept 2 (communal LD)		Concept 2 (communal HD)		Concept 3 (communal LD)		Concept 3 (communal HD)	
	Explanation:	Evaluation	Score (1-3)	Evaluation	Score (1-3)	Evaluation	Score (1-3)	Evaluation	Score (1-3)	Evaluation	Score (1-3)
Production yield per area	1=low, 3 = high	*medium*	2	*low*	1	*high*	3	*low*	1	*medium*	2
Control of farming environment	1=low, 3 = high	*high*	3	*high*	2	*medium*	2	*low*	1	low	1
Production time	1=long, 3=short	*short*	3	*short*	3	*short*	3	*long*	1	long	1
Automation potential	1=low, 3 = high	*high*	3	*high*	2	*medium*	2	*low*	1	low	1
System simplicity	1=low, 3 = high	*low*	1	*medium*	2	*medium*	2	*high*	3	high	3
Water treatment and aeration costs	1=high, 3 = low	*high*	1	*high*	1	*high*	1	*low*	3	low	3
Land and equipment costs	1=high, 3 = low	*high*	1	*high*	1	*medium*	2	*low*	3	low	3
Resource consumption	1=high, 3 = low	*high*	1	high	1	high	1	low	3	low	3
Environmental sustainability	1=low, 3 = high	medium	2	medium	2	medium	2	medium	2	medium	2
	Equal weights:	Average:	1.89	Average:	1.67	Average:	2.00	Average:	2.00	Average:	2.11

Figure 33: Equal weighing amongst evalutation criteria

Figure 33 shows to what degree the previously described parameters are met for the three concepts, where the communal farming concepts are evaluated for low and high densities. It could be seen that docile lobster farming systems with high stocking density score higher. The results could also be presented as a radar chart. Here, only the lines for the high density are included to improve the readability.

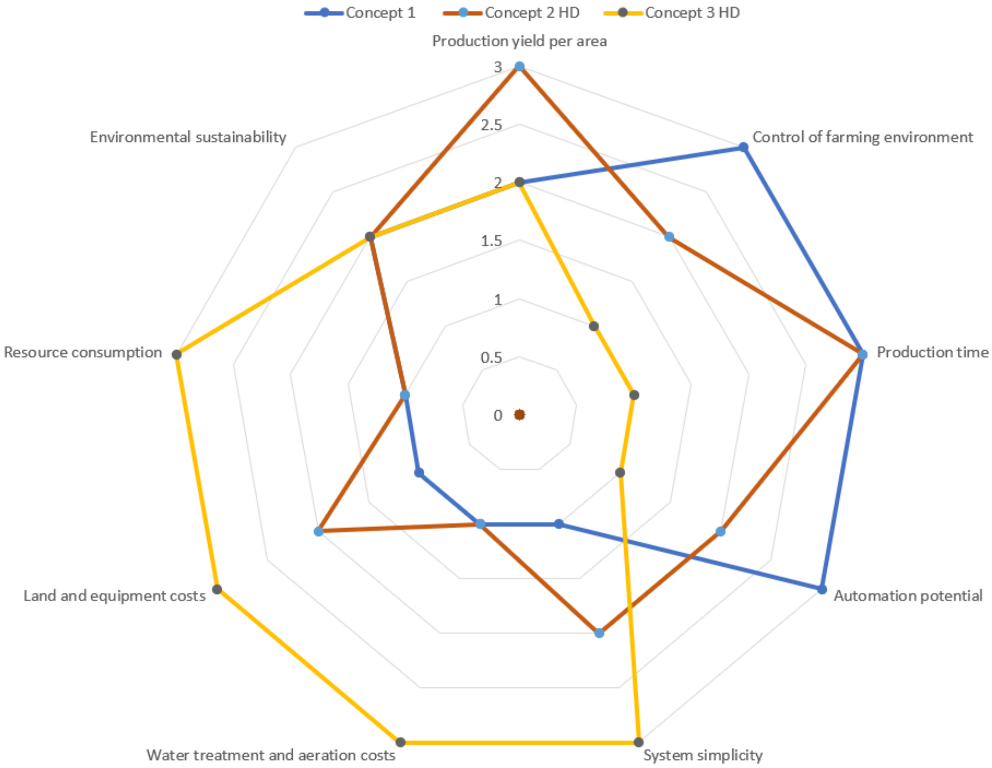


Figure 34: Radar chart of given evaluation criteria. Inner values score low, outer values score high

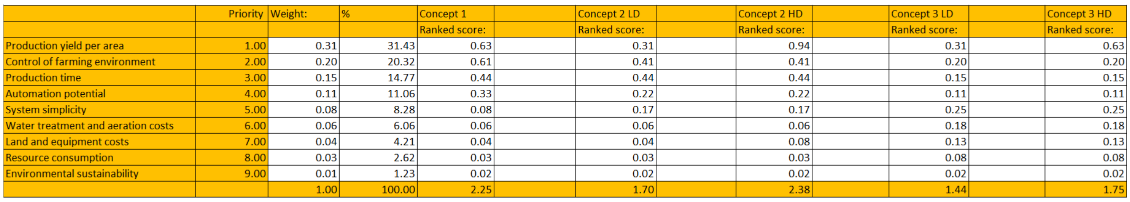
Figure 34 shows a radar chart for the three concepts and represents the same information as in Figure 33 more graphically. From the comparison presented in Figure 34, it is evident that none of the concepts attain high scores across all criteria, but the different concepts score better on the different criteria.

4.4.1 Ranking of farming systems

Rank Order Centroids *ROC* is a method to weight a set of criteria. It is a quick and easy way used in decision making [33]. A list of criteria is ranked in order of importance and then weighted accordingly to the ranking. In this case, it should be noted that what is important depends on the different stakeholders. However, since the importance described in this work is the challenge of reaching viable farming without significant upscaling, revenue-affecting criteria such as *Production Yield Per Area* is prioritised first and weighted the most. The criteria ranked in the order they are presented.

$$W_i = \frac{1}{M} \cdot \Sigma_{n=i}^{M} \frac{1}{n} \tag{8}$$

Equation 8 provides the individual weighing W_i for each criterion i in a set of M elements. Applying this weighting method to the listed decision criteria, the following results are obtained for the given priorities:



	Priority	Weight:	%	Concept 1		Concept 2 LD		Concept 2 HD		Concept 3 LD		Concept 3 HD
				Ranked score:		Ranked score:		Ranked score:		Ranked score:		Ranked score:
Production yield per area	1.00	0.31	31.43	0.63		0.31		0.94		0.31		0.63
Control of farming environment	2.00	0.20	20.32	0.61		0.41		0.41		0.20		0.20
Production time	3.00	0.15	14.77	0.44		0.44		0.44		0.15		0.15
Automation potential	4.00	0.11	11.06	0.33		0.22		0.22		0.11		0.11
System simplicity	5.00	0.08	8.28	0.08		0.17		0.17		0.25		0.25
Water treatment and aeration costs	6.00	0.06	6.06	0.06		0.06		0.06		0.18		0.18
Land and equipment costs	7.00	0.04	4.21	0.04		0.04		0.08		0.13		0.13
Resource consumption	8.00	0.03	2.62	0.03		0.03		0.03		0.08		0.08
Environmental sustainability	9.00	0.01	1.23	0.02		0.02		0.02		0.02		0.02
		1.00	100.00	2.25		1.70		2.38		1.44		1.75

Figure 35: Different weighing amongst evaluation criteria using the ROC method

Combining the results of Figures 33 and 35, results in the following:

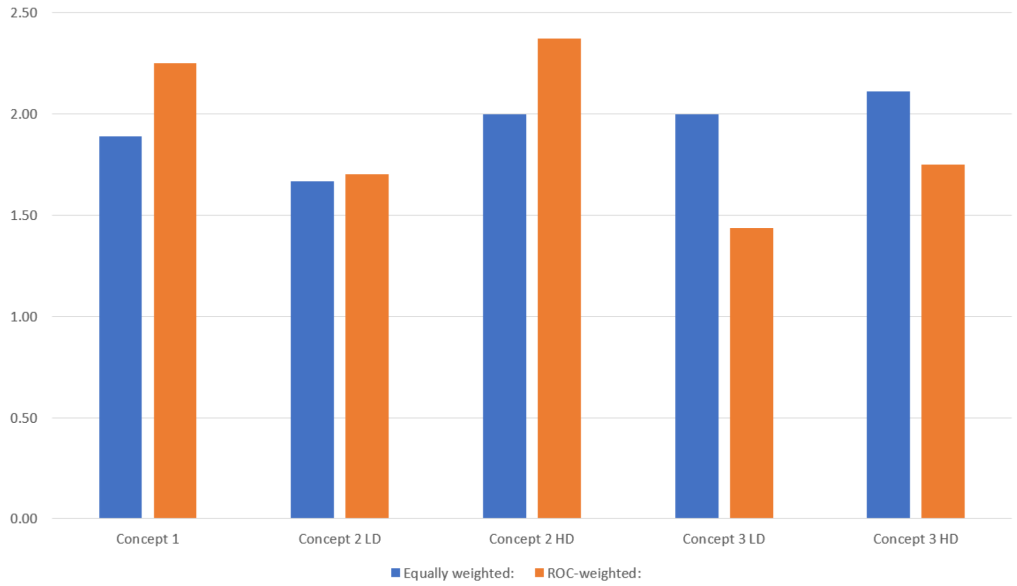


Figure 36: Comparison of concepts using different weighing methods

From Figure 36, it could be seen that from the evaluation criteria given, concept 3 HD scores marginally better in the equal weighting (blue bars), whereas concept 2 HD is better when given certain weights to the different criteria using the ROC method (orange bars). It could further be seen that the results differ significantly between the weighting methods, which is especially observable in concept 3 LD, and that, in general, the systems with the high density of communal farming introduce a increase in desired performance. Given equal weight, the sea-based concept is suggested to perform best, but the sea-based concepts are thought to perform worse when a main focus is given to the criteria weighted most in the ROC method, which ultimately makes the results hard to interpret. However, Concept 2 HD stands out as the only concept that marginally outperforms conventional individual farming (Concept 1) using both weighting methods. As the radar diagram in Figure 34 indicates, no concept excels in all criteria combined, and the results are therefore dependent on the chosen focus of the comparison.

5 Discussion, conclusive remarks and further work

Although the results, particularly the results obtained from the comparative evaluation, are derived from a discussion on the concept's intended performance, the outcome of the results and limitations are here discussed. Furthermore, the limitations of the different models and suggested areas of improvement is also discussed.

5.1 Discussion of the comparison

According to the results of Figure 36, it is not ultimately given that the docile lobster would outperform the conventional individual confined lobster based on the comparison criteria chosen. From the results, the stocking density of the docile lobster appears to be the most influential factor in determining its potential benefits, and it represents the main distinction between the high-density and low-density in concepts 2 and 3. Further, a recommendation would be hard to derive from the results, as the concept 3 HD concept performs best given equal weighting, whereas concept 2 HD is suggested to perform better if yields, control of farming environment, and production time are more important. This effect is highlighted by the ROC results, which favour those criteria. As a result, it could be stated, that the better concept is dependent on which attributes are focussed on, and that such a comparison has a limited value. However, it seems very promising for the docile lobster farmed at higher densities, and further work should be conducted to find how the different systems would score in the criteria.

The selection of the decision criteria in this study is based on the importance attributed to key aspects of farming. However, different parties involved may prioritise different criteria. For example, investors may prioritise yield and production time to maximise profits, while government agencies may focus on environmental impacts and social acceptance. A comprehensive comparison should consider criteria based on the participation of all relevant stakeholders, including farmers, government, investors, and local residents. The focus here has been on mainly considering certain aspects of farming, but several other criteria have been indirectly described. For example, biological risk falls under both the "control of the farming environment" and the "production time" criteria. Other important parameters, such as animal welfare, seem to be left out. This is because no indicators of how welfare would be connected to the different systems were found. It could arguably be partly interconnected with the control of the environment, where the engineering measures are to provide sufficient water quality and spatial requirements to sustain animal welfare. According to Hinchcliffe et al. 2022, [55], the development of welfare indicators and methods to monitor these is mentioned as a future field of work. Adding knowledge such as this would help in a more detailed decision-making process.

Furthermore, the evaluation is presented on a very coarse scale from low to high using three grades, making it difficult to distinguish the different concepts. The concepts may become more similar than they might be. However, increasing the resolution, for example, from 1-10, would not make sense because the uncertainty of the intended performance is too high. Therefore, more knowledge would help differentiate farming concepts with respect to their performance.

The use of the ROC should be discussed. In this specific context, evaluation criteria are prioritised to identify a more viable farming system, and an attempt is made to sort them accordingly. It can be argued that the use of ROC introduces bias by assigning different weights to the criteria. The lowest-ranked criteria are effectively left out using this method, having only a weighting of 1%. In contrast, it may also help to focus on the more crucial criteria necessary to achieve viable farming and give this more weight in comparison. The ROC could also be used to rank the criteria for which there is a more solid foundation, reducing uncertainties in the results by excluding criteria that rely on less robust foundations. ROC is included in this work, but the results should be interpreted critically. The use of another model, for example, the analytical hierarchy process, could lead to different results, depending on which evaluation criteria are the most weighted. The use of weighting methods should then be used as a tool in decision making, not as a solution to find the correct concept.

In comparison, it is generally easier to obtain precise answers for parameters that can be quantified, such as production costs. However, in this comparison, production costs are excluded because they vary significantly between sea-based and land-based farming due to differences in production yield. The disparity in production yield between sea-based low density (11 tonnes) and land-based high density (3000 tons) has a direct impact on production costs. Therefore, the costs associated with production are indirectly addressed through criteria such as ”land and equipment costs”, ”water treatment and aeration costs”, and ”resource consumption.”

As a short summary of the comparison, there is no solid foundation on which to state that one system would perform significantly better than the other, given a set of criteria and different weighting methods. However, there appear to be indices that a docile lobster farmed at a higher stocking density would perform better than conventional individual farming, which should be further examined.

5.2 Model limitations and improvements

5.2.1 Estimating production time

The accumulative degree day model suggests that the locations chosen with colder seawater would require a longer farming time compared to a recirculating aquaculture system (RAS) that maintains optimal farming temperatures. This extended duration of farming raises concerns about the feasibility of intensive sea-based farming as a viable solution, particularly in colder temperate waters along the Norwegian coast. However, applying the model to other locations shows more promising results with reduced production time, and a recommendation for sea-based docile lobster farming would be to consider locations beyond Norway.

The degree day model itself has some limitations. The linear growth between $8 - 25°C$ and the inhibition below $5°C$ is implemented, but the contributions between $5 - 8°C$ are unclear. It was attempted to obtain a data base to compare the accumulated degree days with actual growth curves. When talking to different actors in the industry, it became clear that these numbers were either not available or not existent, ultimately making it difficult to validate the results. As no clear indication of how growth is affected between $5 - 8°C$, the assumption of no growth and half the growth rate between $5 - 8°C$ was included to elucidate the uncertainty of growth between these temperatures and give a rough estimate which could later be used when data is acquired. Furthermore, it should be noted that brief temperature fluctuations are not present in the model because of the daily updates in temperature, which could also lead to uncertainties for the accumulated degree days.

A set of three locations were chosen to investigate differences at different places, but could easily be adapted to other locations. The results range significantly in the Troendelag location, where the temperature is between $5 - 8°C$ for a greater part of the year compared to the other locations, and thus the estimation of growth time is more inaccurate, given the assumptions. The effect of distribution is excluded from the results, due to further unknowns. For a RAS, where lobsters as a mean have an on-growing time of 24 months, the fastest and slowest individuals grow at 18 and 36 months, respectively. If this distribution observed in the RAS were the case for sea-based farming, then production time could differ from 3.9 to 8.1 years at the Skagerrak location, and 4.4 to 10.8 years at the Troendelag location, and from 2.55 to 5.1 years at the location in the southwest of Britain. Accordingly, using the power of larger datasets, these extremal points would likely increase further and the time it takes for the last lobster to be sellable even longer. The results deduced here are founded on the basis that 17000 degree days are needed for a certain farming regime, given a pelleted feed. The pellet feed could efficiently reduce growth rates to only 50-80% of natural diets [28], which means that the intensive farming regime that provides a more suitable feed could significantly influence the production time. This could explain why the results are comparable to sea ranching, which takes 5-6 years from egg to recapture [30]. Other factors, such as genetics, play an important role in growth, which in turn affects the overall production time. Since feed and genetics are key considerations in farming, optimising these factors could potentially have a significant impact on reducing production time in the coming years. Thus, the contribution of the degree-day model is simply a presentation of different degree days at different locations, for a given year.

5.2.2 Water quality in sea-based cages

From the results of the concentration simulation, it does not appear to be a water quality-related issue to increase biomass to $6\frac{kg}{m^2}$ given an idealised steady water flow of 5cm/s using a simplified transportation equation considering the spiny lobster farm. However, several simplifications that affect the outcome must be addressed.

A primary limitation from a marine technical point of view would be the neglect of interference between the lobster cages and the water flow, and thus the wake effects. As the flow enters the cage, the velocity of the water decreases. The amount of velocity that is reduced depends on the solidity of the net. Solidity is the percentage of solid material (e.g., twine or rope) compared to the total area of a net structure. With increased solidity, a further reduction in water velocity is observed [15]. The necessary mesh size and solidity used in lobster farming is unclear and probably depends on the size of the larvae that are robust enough to be placed in the sea environment, so that they do not escape. In salmon farming, the solidity of the net typically induces a reduction corresponding to the velocity 80% at the back end of the net compared to the inlet. If a solidity similar to what is used within the salmon industry and a linear reduction between farming cages could be present, only $0.8^4 \approx 40\%$ of the current velocity would be present in the cages located downstream. Efforts to implement this into the simulation turned unsuccessful in this case and are mentioned as a future improvement of the model. However, one could raise the question of why there is not only one large cage instead of several small. If growth variations and regular stocking could be removed, then one large cage could probably be adequate to contain the lobsters. If this large cage had a low solidity, then the simulation would presumably return a ballpark estimate of the substance concentrations downstream. In addition, the chosen discretization also introduces uncertainty in the model. As the discretised cells are cubic, combined with the fact that the source and sinks are modelled to be uniformly distributed within each cell, the size of the cell would efficiently alter the concentration with the same present biomass. Additionally, the cage bottom is not given to be fixed in place at all times. The results provided use a $dx = dy = dz = 1m$, which is said to depict a situation with smaller bottom deformations. Having a smaller discretization, according to the Courant-Friedrich-Lewy criterion, would make the need for a smaller timestep and making the simulation more time consuming.

Another constraint is related to the underlying basis of the excretion and consumption rates. It appears that these rates are established on a limited number of lobsters, which were raised in a significantly different farming environment with heated seawater, likely due to higher metabolism. Furthermore, there were indications of potential stress among some of the lobsters, and significant variations were observed, with regression results that apparently do not fully capture the consumption patterns of larger individuals. Moreover, the simulation did not consider the peak feeding rates due to uncertainties associated with estimating them. If the outlined method is to be utilised further, it is important to estimate these variables more closely with the environmental conditions of an actual system.

The emphasis on water quality exclusively in the sea-based concept may appear somewhat imbalanced in a task that aims to compare a set of farming systems. However, this focus has been developed under the assumption that the water quality can be controlled and adjusted using the components available in the RAS environment, while the water quality is not easily modifiable in the sea environment. Exactly how the water streams in the flushing tray are is unknown. Considering the deep tank system, a simpler estimate was carried out in the project work and is applied in the Appendix A. Given the limited information available, it is difficult to directly compare water quality beyond established evaluation criteria.

5.2.3 Estimating production costs

The results of the cost estimation clearly demonstrate that increasing the stocking density leads to significantly lower production costs for both lobster farming concepts. While the costs of larvae and feed remain proportionate across different densities, the other costs are spread over a larger production volume, resulting in lower production costs per kg. This observation highlights the economies-of-scale effects associated with increased yield that result from increased stocking densities, and that a sufficient yield is needed to be profitable as a farmer.

Consequently, these findings provide strong motivation to further investigate the potential of the docile lobster. Given current assumptions, it is important to note that the direct costs of feed and larvae would not drop below $118kr/kg$, due to the minimum requirements of four larvae (4 plate-sized lobsters ($250g$ each)) and $1.5kg$ of feed per kg produced lobster. However, larvae production is addressed as a current challenge and improving the number and quality of juveniles is mentioned as a future field of work (Section 2.4). This is further linked to the potential of the docile lobster: if the docile lobster can effectively eliminate cannibalism, even during the pelagic phases, it opens up opportunities for both more cost-efficient and volumes of larvae, and thereby substantially reducing overall estimated production costs. For example, if robust larvae could be produced at a cost of NOK 5 per individual and then reared communally, the RAS facility at a high stocking density (Concept 2 HD) could achieve costs as low as NOK $91/kg$ according to the cost estimate in Figure 31. This further emphasises the potential benefits and motivation for exploring the potential of the docile lobster, which could be a significant improvement, perhaps even a game changer in the critical pelagic larval phases, where low survival is linked to cannibalism.

However, the economic comparison is also based on a set of assumptions and the results should be interpreted carefully. The estimation of production costs in this study is based on cost estimates obtained from the salmon industry, where it was possible to find relevant data on farm costs. Although the specific farming costs associated with salmon are excluded and substituted with lobster-specific costs in the different concepts, the assumption is made that the proportion of other costs remains relatively similar between lobster farming and salmon farming. It is important to note that this assumption indirectly implies a similarity in the operational and farming framework between lobster and salmon farming, which may not necessarily hold true. The results of the production time in sea-based farming indicate a longer duration of farming compared to salmon farming, which could take 24 months in the sea phase [67]. If the farming time could be reduced to this amount of time by providing optimal feed and improving genetics, the results for the costs obtained would align more closely with a realistic outcome. However, there is currently limited knowledge about other factors involved in lobster farming, such as the energy and labour requirements of the farming operations.

Another key difference between salmon and lobsters is the benthic nature of lobsters, which efficiently changes the farm environment from a 3D environment to a 2D environment, with a subsequent decrease in the production yield in a sea cage, making the lobster farming systems more sensitive to the available cage bottom area. To maximise yield, a floating lobster cage may need to incorporate different levels or layers where lobsters can reside. However, since the data source that provides production costs specifically for lobster farming is scarce, the discussion on production costs has been based on the available information for salmon cages.

5.3 Conclusive remarks

The primary objective of this thesis was to perform a technical investigation and comparison between a set of lobster farming systems to assess the impact the availability of a docile lobster would have on industrial-scale lobster farming. In Chapter 2, aspects of lobster biology that need to be taken into account independently of production technology were addressed. The two most important factors for lobster growth were found to be water quality and spatial requirements. In Chapter 3, the identified needs were translated into a set of functional requirements essential for a successful farming system. Additionally, various technical farming systems were described in detail. An investigation was conducted between different farming systems, resulting in a suggestion for two types of flushing trays, where one was for the communally farmed docile lobster. Subsequently, a comparison of these and a floating-sea-based farm was made in Chapter 4, where a set of evaluation criteria was established, which were intended to be sufficiently broad and cover key aspects relevant to the success of lobster farming. It became evident that the concepts excelled in different criteria and that no single concept outperformed the others. The evaluation used two different weighting methods, resulting in altered outcomes that indicated no clear superiority of any single concept when considering both methods simultaneously. However, the concepts involving docile lobsters at higher stocking densities generally showed improved performance. Other factors not directly considered in the comparison, such as production costs between the concepts, were investigated. Systems appear to be profitable at higher stocking densities, but their production yields differ significantly due to the spatial constraints, which is especially present in Concept 3. An accumulative degree-day model, which calculates the total degree days at different locations, is thought to give an estimate of the production time. It indicates a significant prolongation of production time in two locations in Norway compared to a RAS facility. The extended production time may render intensive sea-based farming impractical, and it may be more feasible to explore alternative locations outside of Norway. Yet, increasing the biomass of a sea-based farming system does not seem to pose a direct threat to water quality.

Determining the potential impact of the docile lobster has been a challenging task. Compared to some species of spiny lobster, which already has established commercial farming practises, the introduction of the docile lobster can possibly lead to the emergence of new husbandry operations, such as regular size grading. It should be noted that commercial spiny lobster aquaculture is heavily dependent on manual farming operations, which is assumed to require automation in a high-cost country such as Norway due to high labour expenses. Moreover, the comparison between stocking densities in spiny lobster farming and individual farming was not conclusive, further complicating the task of accurately identifying the specific advantages that could arise from the introduction of the docile lobster. It should also be expressed that the comparison focusses primarily on the ongrowing phase of farming, and does not cover all aspects of the farming process. Therefore, the full extent of the potential impact of the non-cannibalistic docile lobster is not captured in the comparison, and it is hypothesized that the introduction of docile lobsters could lead to a substantial improvement, possibly even a game-changing transformation, in the crucial pelagic larval phase where survival rates are limited to cannibalism and considered a major bottleneck in current lobster farming.

Through the discussion of production and investment costs, expected stocking densities, production time, and other critical aspects of farming, the information presented serves as a foundation for evaluating the potential impact of docile lobsters in different production concepts, thus answering the main objective. Although the analysis highlights the importance of cautious interpretation due to several underlying assumptions, it indicates that the availability of docile lobsters could potentially lead to substantial improvements in lobster farming. These improvements may vary depending on the specific production concept, which may not currently exist.

5.4 Key findings of this thesis - take-away points

Even though the models and results mentioned above have limitations, some general remarks can be made on behalf of the results:

- It is likely that the production time in the seas around Norway would be severely prolonged compared to farming in optimum temperatures in a RAS facility, which question marks the feasibility of intensive sea-based lobster farming in Norway
- It does not appear to be a water quality issue to increase biomass to $6\frac{kg}{m^2}$ given an idealised steady water flow of 5cm/s using a simplified transportation equation for a highly porous net.
- Increased yields within the farming system lead to decreased production costs per kg. This relationship is closely associated with the achievable stocking density and the available cage area. Therefore, if the stocking density is increased, as hypothesized with the introduction of docile lobsters, it would effectively lower production costs.

5.5 Recommendations for further work

As parts of the results suggest a potentially significant improvement in docile lobster farming, a natural starting point would be to investigate the feasibility of creating docile lobster, and subsequently verify what characteristics it would have. This approach would make it much easier to develop new farming systems that meet its specific needs. Moreover, it would establish a basis for assessing potential improvements compared to existing methods. As current solutions are now being scaled up to an industrial level, there is a possibility that insights into the success criteria for industrial-scale lobster farming will be gained and may indeed be transferable to docile lobsters as well, such as the establishment of welfare indicators, optimal feeds, etc.

Other areas have been highlighted as the way forward in individual-based lobster farming, such as improving the quality and quantity of lobster larvae. The latter could be an excellent task for the *Experts in Teamwork (EiT)* course given at NTNU, where a multidisciplinary group consisting of individuals with backgrounds in biology, technology, and economics could solve problems in lobster farming. An EiT group would probably also be well positioned to develop new concepts based on the requirements outlined in Figure 18.

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Appendices:

A Water quality in a deep tank RAS system

Flowchart

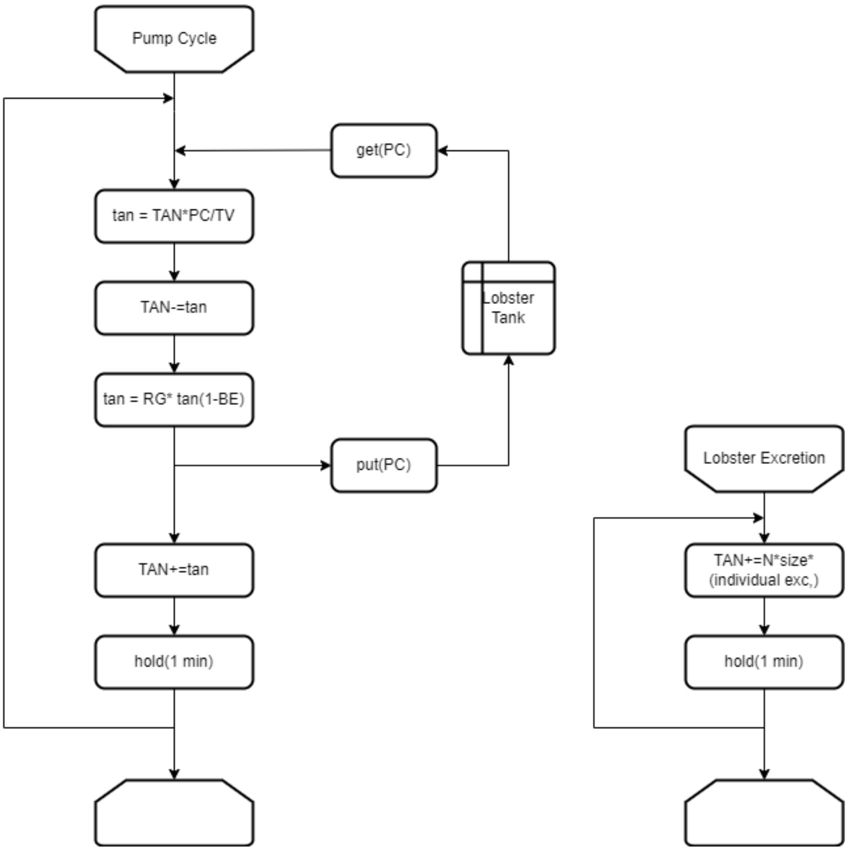


Figure 37: A flowchart for TAN.py

Parameter name	Abbreviation	Unit
Tank volume	TV	m3
Pump Capacity	PC	m3/min
# Lobsters	N	units
Lobster size	size	kg
Water reusage fraction	RG	%/100
Biofilter efficiency	BE	%/100
Simulation time	-	minutes

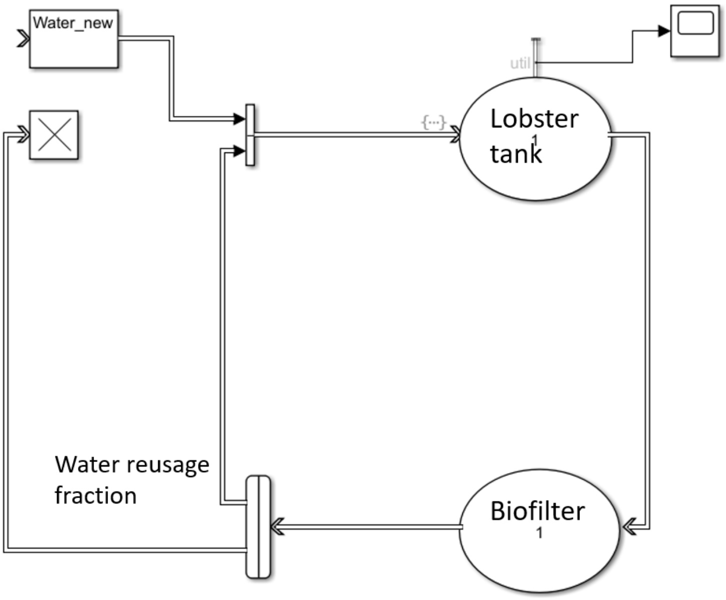


Figure 38: Model of a simplified RAS environment

Results for TAN accumulation for a given input

Parameter name	Value
Tank volume	625
Pump Capacity	10
# Lobsters	125.000
Lobster size	0.2
Water reusage fraction	0.99
Biofilter efficiency	0.5-0.7
Simulation time	10080

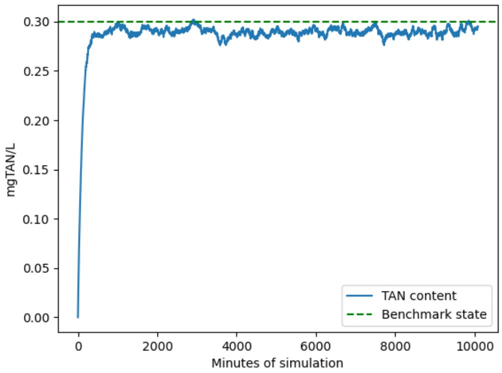
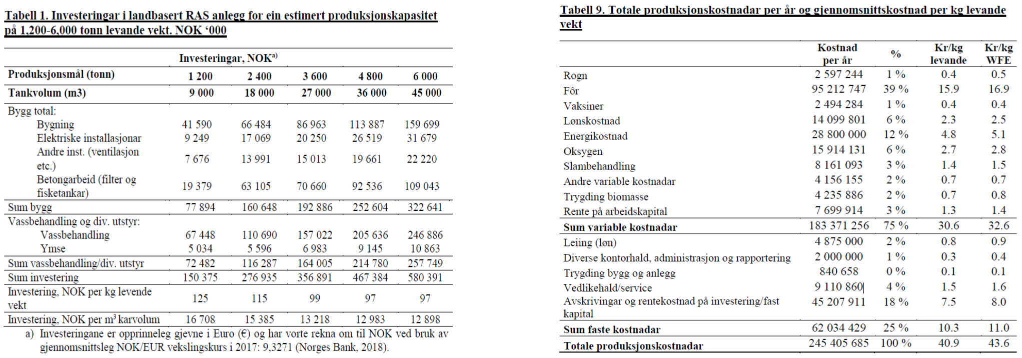


Figure 39: Simulation parameters and results

B Costs related to farming

B.1 Costs related to RAS farming



Tabell 1. Investeringar i landbasert RAS anlegg for ein estimert produksjonskapasitet på 1,200-6,000 tonn levande vekt. NOK ‘000

	Investeringar, NOK[a)]				
Produksjonsmål (tonn)	**1 200**	**2 400**	**3 600**	**4 800**	**6 000**
Tankvolum (m3)	**9 000**	**18 000**	**27 000**	**36 000**	**45 000**
Bygg total:					
Bygning	41 590	66 484	86 963	113 887	159 699
Elektriske installasjonar	9 249	17 069	20 250	26 519	31 679
Andre inst. (ventilasjon etc.)	7 676	13 991	15 013	19 661	22 220
Betongarbeid (filter og fisketankar)	19 379	63 105	70 660	92 536	109 043
Sum bygg	77 894	160 648	192 886	252 604	322 641
Vassbehandling og div. utstyr:					
Vassbehandling	67 448	110 690	157 022	205 636	246 886
Ymse	5 034	5 596	6 983	9 145	10 863
Sum vassbehandling/div. utstyr	72 482	116 287	164 005	214 780	257 749
Sum investering	150 375	276 935	356 891	467 384	580 391
Investering, NOK per kg levende vekt	125	115	99	97	97
Investering, NOK per m^3 karvolum	16 708	15 385	13 218	12 983	12 898

a) Investeringane er opprinneleg gjevne i Euro (€) og har vorte rekna om til NOK ved bruk av gjennomsnittsleg NOK/EUR vekslingskurs i 2017: 9,3271 (Norges Bank, 2018).

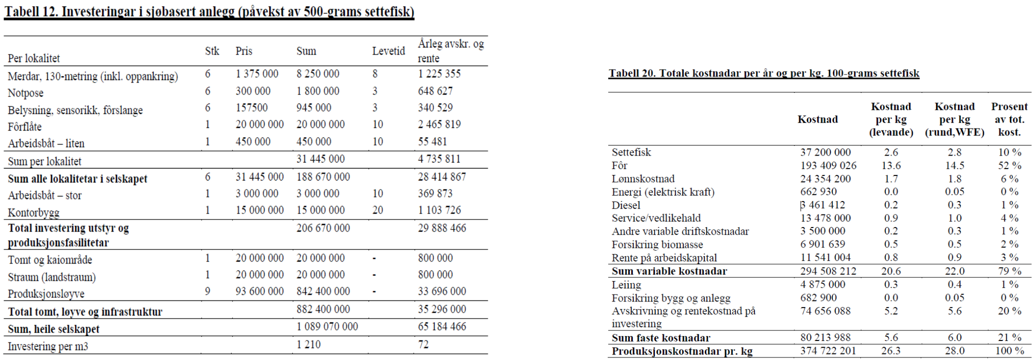
Tabell 9. Totale produksjonskostnadar per år og gjennomsnittskostnad per kg levande vekt

	Kostnad per år	%	Kr/kg levande	Kr/kg WFE
Rogn	2 597 244	1 %	0.4	0.5
Fôr	95 212 747	39 %	15.9	16.9
Vaksiner	2 494 284	1 %	0.4	0.4
Lønskostnad	14 099 801	6 %	2.3	2.5
Energikostnad	28 800 000	12 %	4.8	5.1
Oksygen	15 914 131	6 %	2.7	2.8
Slambehandling	8 161 093	3 %	1.4	1.5
Andre variable kostnadar	4 156 155	2 %	0.7	0.7
Trygding biomasse	4 235 886	2 %	0.7	0.8
Rente på arbeidskapital	7 699 914	3 %	1.3	1.4
Sum variable kostnadar	183 371 256	75 %	30.6	32.6
Leiing (løn)	4 875 000	2 %	0.8	0.9
Diverse kontorhald, administrasjon og rapportering	2 000 000	1 %	0.3	0.4
Trygding bygg og anlegg	840 658	0 %	0.1	0.1
Vedlikehald/service	9 110 860	4 %	1.5	1.6
Avskrivingar og rentekostnad på investering/fast kapital	45 207 911	18 %	7.5	8.0
Sum faste kostnadar	62 034 429	25 %	10.3	11.0
Totale produksjonskostnadar	245 405 685	100 %	40.9	43.6

Figure 40: Tabulated costs used in RAS cost estimation

Source: [16]

B.2 Costs related to sea-based farming



Tabell 12. Investeringar i sjøbasert anlegg (påvekst av 500-grams settefisk)

Per lokalitet	Stk	Pris	Sum	Levetid	Årleg avskr. og rente
Merdar, 130-metring (inkl. oppankring)	6	1 375 000	8 250 000	8	1 225 355
Notpose	6	300 000	1 800 000	3	648 627
Belysning, sensorikk, fôrslange	6	157500	945 000	3	340 529
Fôrflåte	1	20 000 000	20 000 000	10	2 465 819
Arbeidsbåt – liten	1	450 000	450 000	10	55 481
Sum per lokalitet			31 445 000		4 735 811
Sum alle lokalitetar i selskapet	6	31 445 000	188 670 000		28 414 867
Arbeidsbåt – stor	1	3 000 000	3 000 000	10	369 873
Kontorbygg	1	15 000 000	15 000 000	20	1 103 726
Total investering utstyr og produksjonsfasilitetar			206 670 000		29 888 466
Tomt og kaiområde	1	20 000 000	20 000 000	-	800 000
Straum (landstraum)	1	20 000 000	20 000 000	-	800 000
Produksjonsløyve	9	93 600 000	842 400 000	-	33 696 000
Total tomt, løyve og infrastruktur			882 400 000		35 296 000
Sum, heile selskapet			1 089 070 000		65 184 466
Investering per m3			1 210		72

Tabell 20. Totale kostnadar per år og per kg. 100-grams settefisk

	Kostnad	Kostnad per kg (levande)	Kostnad per kg (rund,WFE)	Prosent av tot. kost.
Settefisk	37 200 000	2.6	2.8	10 %
Fôr	193 409 026	13.6	14.5	52 %
Lønnskostnad	24 354 200	1.7	1.8	6 %
Energi (elektrisk kraft)	662 930	0.0	0.05	0 %
Diesel	3 461 412	0.2	0.3	1 %
Service/vedlikehald	13 478 000	0.9	1.0	4 %
Andre variable driftskostnadar	3 500 000	0.2	0.3	1 %
Forsikring biomasse	6 901 639	0.5	0.5	2 %
Rente på arbeidskapital	11 541 004	0.8	0.9	3 %
Sum variable kostnadar	294 508 212	20.6	22.0	79 %
Leiing	4 875 000	0.3	0.4	1 %
Forsikring bygg og anlegg	682 900	0.0	0.05	0 %
Avskrivning og rentekostnad på investering	74 656 088	5.2	5.6	20 %
Sum faste kostnadar	80 213 988	5.6	6.0	21 %
Produksjonskostnadar pr. kg	374 722 201	26.3	28.0	100 %

Figure 41: Tabulated costs used in sea farming cost estimation

Source: [16]

C Code for sea-based water quality

```python
import numpy as np
import matplotlib.pyplot as plt
from matplotlib.patches import Rectangle

# Defining the Environment class which primarily contains main system variables
class Environment:
    def __init__(self, vx, vy, vz, K, dx, dy, dz, dt, tmax, cagerow, cagecolumn, cagespacing, cagesize, biomass):
        self.vx = vx
        self.vy = vy
        self.vz = vz
        self.K = K
        self.dx = dx
        self.dy = dy
        self.dz = dz
        self.dt = dt
        self.tmax = tmax
        self.TAN_amb_val = 0  # mg/L
        self.CO2_amb_val = 0  # mg/L
        self.O2_amb_val = 7   # mg/L
        self.cagerow = cagerow
        self.cagecolumn = cagecolumn
        self.cagesize = int(cagesize / dx)  # making the cage as [n cells] instead of [m]
        self.cagespacing = int(cagespacing / dx)  # making the cage spacing as [n cells] instead of [m]
        self.biomass = biomass #kg/m2 stocking density
        gridsize = max(cagerow, cagecolumn) * (1 + cagesize) * 3  # variable grid domain
        self.mcell = int(gridsize / dx)  # grid cells in x direction, total domain
        self.ncell = int(gridsize / dy)  # grid cells in y direction, (quadratic total domain)
        self.ocell = 1


# Defining the Lobster class which contains values for lobster consumption/excretion
class Lobster:
    def __init__(self, biomass, lobstersize, EnvObj):
        dx = EnvObj.dx
        dy = EnvObj.dy
        dz = EnvObj.dz
        dt = EnvObj.dt
        self.biomass = biomass  # kg/m2
        self.size = lobstersize # g
        o2_consumption = 5.0972-0.913*np.log(self.size)  # mgO2/kgmin for larger juvenile lobster. DrengstigEtal2017
        tan_production = 0.3766-0.071*np.log(self.size)  # mgTAN/kgmin for larger juvenile lobster. DrengstigEtal2017
        # self.TAN = tan_production*biomass*((dt/60)*(dx*dy*dz/1)*(1/1000))   # mgTAN/Ls; This is for each cell discretized in space.
        self.TAN = tan_production * biomass * ((1 / 60) * (1 / 1000))*dx  # mgTAN/Ls; This is for each cell discretized in space.
        self.O2 = -o2_consumption * biomass * ((1 / 60) * (1 / 1000))*dx  # mgO2/Ls;  This is for each cell discretized in space.
        self.CO2 = self.O2 * (-1.75)  # mgCO2/Ls; Drengstig 2017.


# Defining the Cage class which is used to create objects that has the following attributes
class Cage:
```

```
    def __init__(self, start_x, start_y, EnvObj, xNum, yNum):
        self.start_x = start_x
        self.start_y = start_y
        self.cagesize = EnvObj.cagesize
        self.xNum = xNum
        self.yNum = yNum
        # self.cagespacing = cagespacing
        # TODO:add flowreduction corresponding to the solidity


# A function that returns a list of Cage objects.
def cageMaker(EnvObj):
    cageArr = []
    n_rows = EnvObj.cagerow
    n_columns = EnvObj.cagecolumn
    cagesize = EnvObj.cagesize
    cagespacing = EnvObj.cagespacing

    # This loops centeres the cage configuration into the center of the
    for i in range(n_rows):  # make a loop adding cage objects with cage attributes into the
    ↪   cage-array
        for j in range(n_columns):  # adding cages into figure center and evenly distributed
        ↪   considering nxm cages + spacing
            for k in range(cagesize):  # applying cage only in cagesize into the depth. This loops
            ↪   centeres the cage configuration!
                cageN = Cage(int((EnvObj.mcell / 2 - (cagesize * n_rows + (n_rows - 1) *
                ↪   cagespacing) / 2) + (cagesize + cagespacing) * i),
                             int((EnvObj.ncell / 2 - (cagesize * n_columns + (n_columns - 1) *
                             ↪   cagespacing) / 2 + (cagesize + cagespacing) * j)), EnvObj, i + 1,
                             ↪   j + 1)
                cageArr.append(cageN)

    return cageArr


# A simple code check, that checks the Courant Friedrichs Lewy criteria for stability
def stabilityChecker(EO):
    # TODO: make a separate function that checks for numerical stability
    cfl_x = (EO.vx) * EO.dt / EO.dx  # Courant{Friedrichs{Lewy stability, x direction
    cfl_y = (EO.vy) * EO.dt / EO.dy  # Courant{Friedrichs{Lewy stability, y direction
    cfl_z = (EO.vz) + EO.dt / EO.dy  # Courant{Friedrichs{Lewy stability, z direction
    cfl_K = (EO.K) * EO.dt / EO.dx ** 2
    cfl_abs = np.sqrt(cfl_y ** 2 + cfl_x ** 2 + cfl_K ** 2 + cfl_z ** 2)
    print('Courant{Friedrichs{Lewy, x: ', cfl_x, 'and Courant{Friedrichs{Lewy, y: ', cfl_y, 'cfl_K:
    ↪   ', cfl_K,
          'absolute: ', cfl_abs)
    if cfl_abs >= 0.6:
        print('MAKE CORRECTIVE MEASURES')

    return 0


# A function that saves the plot into selected folder
def plotSaver(c, lowerlim, upperlim, csize, CageArray, EnvObj, path, wq_var):
    fig, ax = plt.subplots()
    plt.pcolormesh(c.T[1:-2, 1:-2], cmap=plt.cm.jet)  # indexing cagesize depth; i.e max
    ↪   concentration where the lobsters are located
    # ax.set_xticks(np.arange(0, EnvObj.mcell, 10))
    # ax.set_xticklabels(['one', 'two', 'three', 'four, five, six, seven'])
    ax.set_xticks([])
```

```
    ax.set_yticks([])
    cb = plt.colorbar()  # makes a colorbar
    titlename = wq_var + f" for stocking density of {int(EnvObj.biomass)} kg/m2"
    plt.title(titlename)
    plt.clim(lowerlim, upperlim)  # lowlim, uplim
    cb.set_label(f"mg{wq_var}/L", rotation=270, labelpad=25)

    for cage_item in CageArray:  # cages only appearing into half the depth
        ax.add_patch(Rectangle((cage_item.start_x-1, cage_item.start_y-1), cage_item.cagesize,
        ↪   cage_item.cagesize,
                               facecolor='none',
                               linewidth=2, edgecolor='black'))
    #plt.show()
    plt.savefig(path
    ↪   +f"{wq_var}dxdydz{EnvObj.dx}m.dt{EnvObj.dt}s.tmax{EnvObj.tmax}s{EnvObj.cagesize}M.png",
    ↪   dpi=300)  # saves figure into plot simulation
    plt.close()

    return 0



# The function that does the simulation
def concentrationSim(EnvironmentObj, CageArray, LobsterObj, path, wqvar, case):
    cagesize = EnvironmentObj.cagesize
    dx = EnvironmentObj.dx
    dy = EnvironmentObj.dy
    dt = EnvironmentObj.dt

    tmax = EnvironmentObj.tmax

    if wqvar == "TAN":  # which water quality variable that is investigated
        U_var = LobsterObj.TAN
        ambient_value = EnvironmentObj.TAN_amb_val
    elif wqvar == "O2":
        U_var = LobsterObj.O2
        ambient_value = EnvironmentObj.O2_amb_val
    elif wqvar == "CO2":
        U_var = LobsterObj.CO2
        ambient_value = EnvironmentObj.CO2_amb_val
    else:
        pass

    vxAlt = EnvironmentObj.vx
    vyAlt = EnvironmentObj.vy
    K = EnvironmentObj.K

    m = EnvironmentObj.mcell  # grid cells in x direction, total domain
    n = EnvironmentObj.ncell  # grid cells in y direction, total domain

    stabilityChecker(EnvironmentObj)  # checks code for CFL criteria

    c = np.ones((m + 1, n + 1)) * ambient_value  # Sets all cells to ambient value initially



    # fA, fD = 0, 0  #Initiate the advection and the diffusion terms
    maxValArr = []  # storing max values to check for convergence and steady state in simulation,
    ↪   as well as colorbar max value
    minValArr = []  # storing min values to check for convergence and steady state in simulation,
    ↪   as well as colorbar min value
```

```python
    # xValArr = np.arange(0, (m-1)*(n-1)*(tmax/dt), 1) #time array for same dimension as max values
    ↪  for later plotting

    #timeStepChecker(dt, Re, h)

    # MAIN ITERATION LOOP
    for t_index in range(int(tmax / dt)):  # iteration through time domain
        if (100 * dt * t_index / (tmax)) % 10 == 0:
            print('Simulation: ', 100 * dt * t_index / (tmax), ' % complete')  # GIVES FEEDBACK ON
            ↪  SIMULATION PROGRESS

        for i in range(1, m):  # iteration for x size

            for j in range(1, n):  # iteration for y size

                cProd = 0


                c[i, 0] = ambient_value   # "South wall" of the domain
                c[i, -1] = ambient_value  # "North wall" of the domain
                c[0, j] = ambient_value   # "West wall" of the domain
                c[-1, j] = c[-2, j]       # "East wall" of the domain


                for cage_item in CageArray:  # Reassuring that consumption/production only happens
                ↪  inside the cage, at the cage bottom where the lobsters are located.
                    if cage_item.start_x <= i < (cage_item.start_x + cage_item.cagesize) and
                    ↪  cage_item.start_y <= j < (cage_item.start_y + cage_item.cagesize):
                        cProd = U_var
                    else:
                        pass


                vx = vxAlt
                vy = vyAlt

                fA = vx * (c[i - 1, j] / dx) + vy * (c[i, j - 1] / dy) - (vx / dx + vy / dy) * c[i,
                ↪  j]  # The advective term
                fD = K * ((c[i + 1, j] - 2 * c[i, j] + c[i - 1, j]) / (dx ** 2) + (c[i, j + 1] - 2
                ↪  * c[i, j] + c[i, j - 1]) / (dy ** 2))  # The diffusive term
                c[i, j] += (cProd + fA + fD) * dt

                maxValArr.append(np.amax(c))  # List of all max values
                minValArr.append(np.amin(c))


    lowlim = min(minValArr)
    uplim = max(maxValArr)
    plotSaver(c, lowlim, uplim, cagesize, CageArray, EnvironmentObj, path, wqvar)

    return 0


# The main function that initiates all variables and test cases
def main():
    # MISC VALUES
    path = "C:\\Users\\..."  # Where to save the results from the simulation

    # SEA AND CURRENT VALUES
    vx = 0.05  # current velocity in x direction; m/s
```

```
    vy = 0.0  # current velocity in y direction; m/s
    vz = 0.0  # current and sinking/floating velocity in z direction; m/s
    K = 10 * (vx ** 2 + vy ** 2)   # Kappa, diffusion coefficient; m2/s

    # TEMPORAL DISCRETIZATION VALUES
    dt = 0.5 # time step
    tmax = 15000 # seconds

    # SPATIAL DISCRETIZATION VALUES
    dx = 1  # m
    dy = 1  # m
    dz = 1  # m

    # LOBSTER VALUES
    biomass = 1  # kg/m3, however modelled to be on the bottom of the cage
    lobstersize = 250  # g per individual

    # CAGE VALUES
    cageRows = 4
    cageColumns = 4
    cageSize = 5
    cageSpacing = 1

    # INITIATE SIMULATION OBJECT 1
    EnvironmentObject = Environment(vx, vy, vz, K, dx, dy, dz, dt, tmax, cageRows, cageColumns,
    ↪  cageSpacing, cageSize, biomass)
    cageArray = cageMaker(EnvironmentObject)
    LobsterObject = Lobster(biomass, lobstersize, EnvironmentObject)
    concentrationSim(EnvironmentObject, cageArray, LobsterObject, path, "O2", "SEA")

    #INITIATE SIMULATION OBJECT 2
    EnvironmentObject2 = Environment(vx, vy, vz, K, dx, dy, dz, dt, tmax, cageRows, cageColumns,
    ↪  cageSpacing, cageSize, biomass)
    cageArray2 = cageMaker(EnvironmentObject2)
    LobsterObject2 = Lobster(biomass, lobstersize, EnvironmentObject2)
    concentrationSim(EnvironmentObject2, cageArray2, LobsterObject2, path, "CO2", "SEA")

    #INITIATE SIMULATION OBJECT 3
    EnvironmentObject3 = Environment(vx, vy, vz, K, dx, dy, dz, dt, tmax, cageRows, cageColumns,
    ↪  cageSpacing, cageSize, biomass)
    cageArray3 = cageMaker(EnvironmentObject3)
    LobsterObject3 = Lobster(biomass, lobstersize, EnvironmentObject3)
    concentrationSim(EnvironmentObject3, cageArray3, LobsterObject3, path, "TAN", "SEA")


main()
```

D Solution space for thesis work

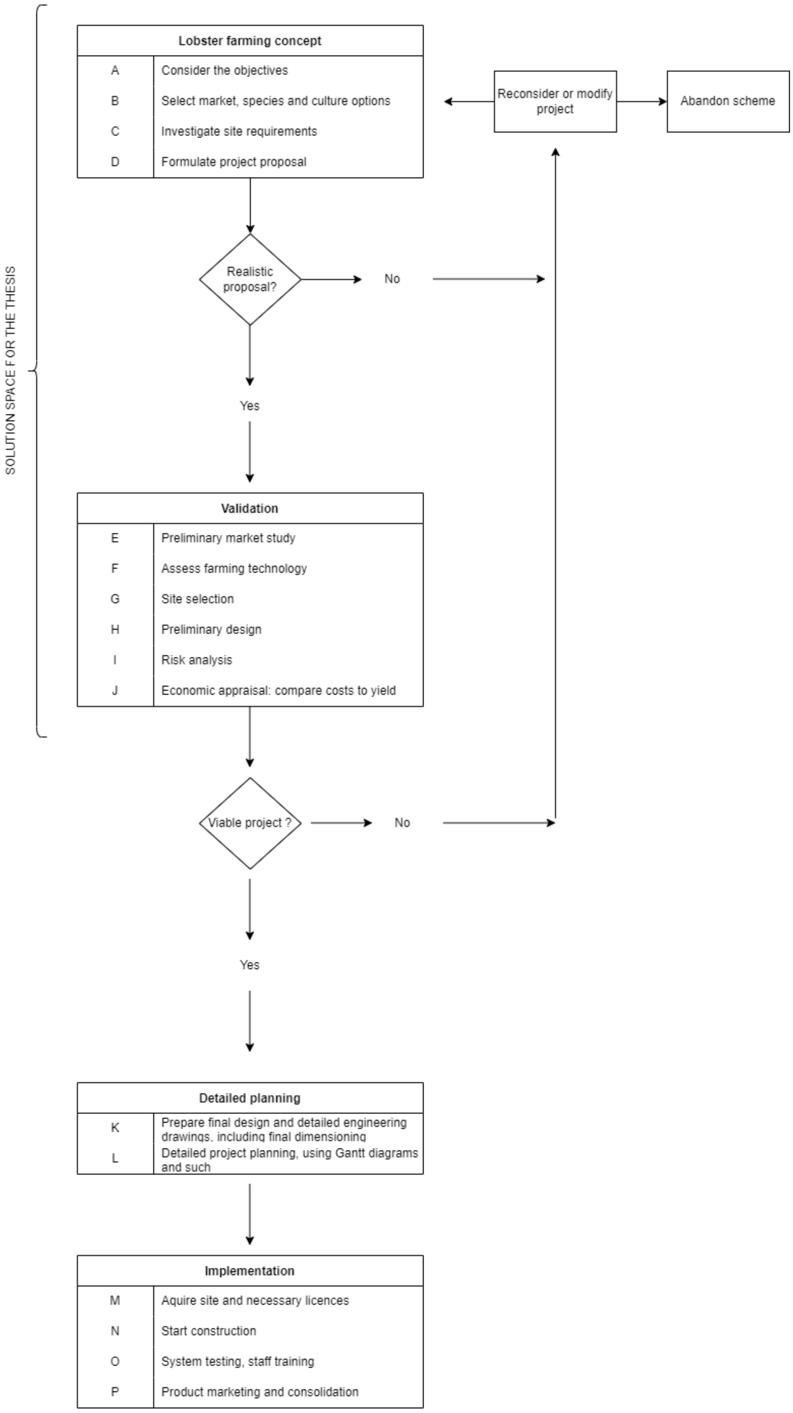


Figure 42: Solution space for the thesis work in a lobster farm project planning schedule

Source: Modified figure from [93]

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