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Report

Concept development for macroalgae seeding, deployment and harvesting

Development of new technology for industrial macroalgae cultivation

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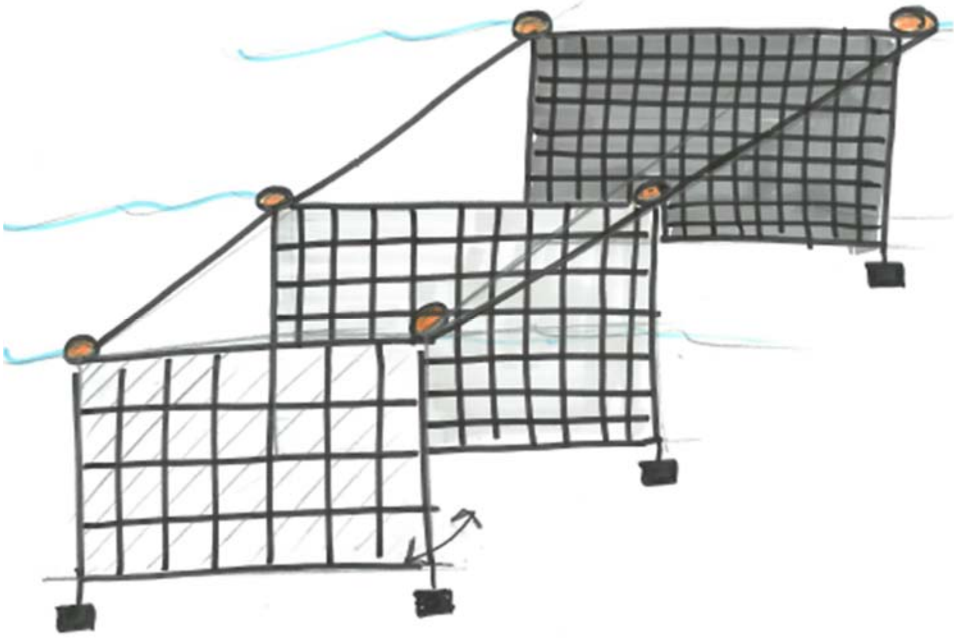

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ABSTRACT
This report is the result of SINTEF summer job "Development of new technology for industrial macroalgae cultivation. It is based on a report from Work Package 5 in MACROSEA, "State of the art", which covers seedling production, deployment and harvesting. It focuses on developing new technology for macroalgae cultivation and it is a design study that consist of different concepts. Design Thinking is heavily used in this process, all solutions I have been able to think of, advantages, disadvantages and further questions are considered and reviewed here. It is likely that a successful industrial scale farming concept could include an automated spraying process of a gel containing seedlings, which can be applied to a 2D substrate. It can be combined with a custom-made vessel with integrated processing equipment, and ROV or AUV technology.

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Background

MACROSEA is a four year lasting project with the goal to develop a knowledge platform for industrial scale macroalgae cultivation. The current R&D strategy for the marine sector in Norway, HAV21, recommends to "develop technologies for cultivation and harvest of macroalgae at industrial scale". MACROSEA will deliver fundamental knowledge on macroalgae production biology and technology for sea farm design, enabling industrial production of biomass at different climatic, ecological and physical regimes representative for the Norwegian coastline.

This task focuses on macroalgae seedling, deployment and harvest technology. Requirements and bottlenecks for industrial scale seedling production systems should be addressed. Traditionally, macroalgae production consists of a laboratory phase and a sea phase. In the laboratory, seedlings are grown on a string substrate, which later is spun onto a thicker rope before deployment in the sea. After the growth phase, seaweed at a size of 1-1.5 m are harvested by manually processing the ropes. Existing processes and methods for seedling production and seeding of substrates is industrially underdeveloped and labor intensive, and in need of development and automation. Both production systems and instrumentation should be developed with emphasis on efficient production of high quality, robust seedlings.

Introduction to process used for developing new technology

The Design Thinking process is a methodology, which can be used for product development and in general for solving problems. It focuses on involving the human element and user of a product and develops a solution through a non-linear and iterative process that includes the following steps; empathy, define, ideate, prototype and testing. It is a holistic way of thinking and it relies on fundamentally understanding the needs of the user and defining the real problem. Each of the steps (or phases) mentioned above includes a series of tools; techniques and exercises. It is closely connected to the Hasso Plattner Institute of Design at Stanford.[1]

Empathy: In order to fully understand a problem you need to understand your user. This is done by empathising with the user and immersing yourself in the user's situation. It is the foundation for a human-centred design process.

Define: Defining the problem through a statement called point-of-view (POV) gives clarity and focus on the real problem. It consists of user, needs and insight (the challenge).

Ideate: Using the POV it is time to come up with solutions to the problem through idea generation, going as broad, far and wild as you possibly could with your ideas.

Prototype: Another way of ideating is prototyping, creating simple models for easy communication of your ideas, failing quickly and cheaply (and thereby succeeding sooner), and testing possibilities.

Testing: Testing your prototypes and ideas at an early stage gives a quick indication of what works and what does not, which enables you to spend your time more efficiently. It will help you refine your solutions and understand your user.

[1] See "An Introduction to Design Thinking PROCESS GUIDE" for a further introduction to Design Thinking. https://dschool.stanford.edu/sandbox/groups/designresources/wiki/36873/attachments/74b3d/ModeGuideBOOTCAMP2010L.pdf

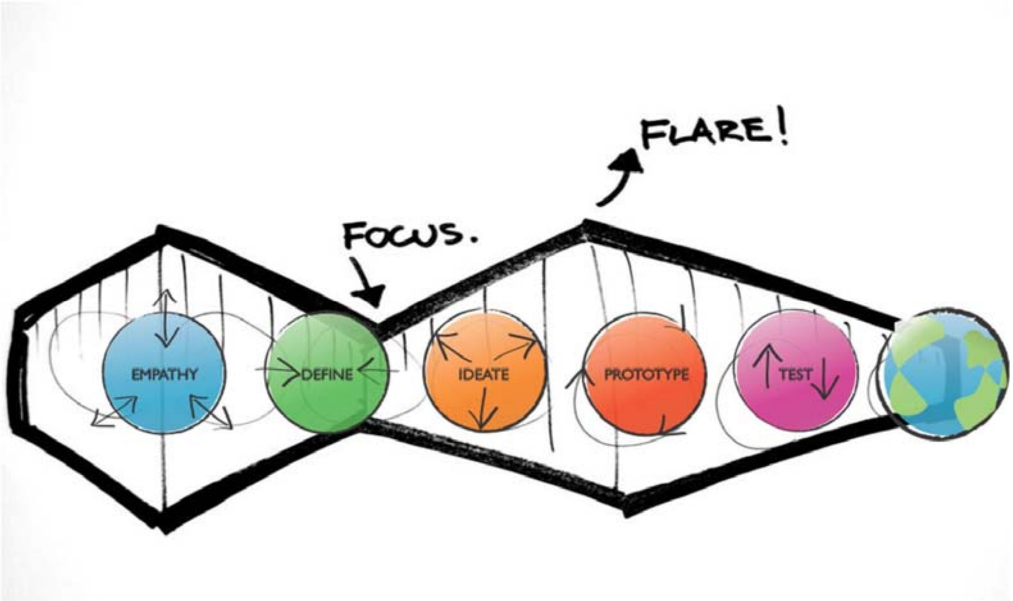

Figure 1: Visualization of Stanford's Design Thinking Model (Photo: http://listenlearnleadaterics.blogspot.no/)

Design Thinking is heavily used in this process. Prototypes consist of sketches and descriptions. During the empathy phase I talked to all of the industrial partners of MACROSEA. They also participated in a survey that formed the basis for "State of the art". I also went on a trip to Hitra to see the cultivation testing facility to experience the environment and talk to fellow co-workers, including Terje Bremvåg, who is employed by AquaCulture Engineering and holds 30 years of experience from shipping companies and shipbuilding yards. I also read research papers on kelp cultivation, which included requirements for cultivation period, environment and other considerations, and media articles about the project, seaweed cultivation and other relevant industries such as fish farming. Learned as much as possible and identified the needs. Then followed the POV ("A new, emerging and rapidly growing industry needs a substrate infrastructure that promotes seeding, deployment and harvesting because (or and) worker satisfaction is essential for a sustainable production.") and from that, ideation. The result of this, including the feedback from industry partners, is the following. The concepts aim to give a holistic and thorough introduction to solutions and related challenges, and give inspiration. They consist of a descriptions, discussions and feedback with additional discussion and related questions. It is aimed at a larger industrial scale, as it most likely will be in 5 – 10 years.

Concepts

Extensive illustrations listed in appendix.

1 Pieces

Description

Concept consists of a framework with a square pattern. The framework consists of extruded[2] plastic (imagine the framework as a long profile, much like a beam with a rail in it); it should be both ductile and strong. The cross section has a certain shape, and the pieces have the inverted shape of this so they can glide in and out of a rail. The framework can be deployed into the water beforehand and be a stationary rig. A robot can distribute the pieces down into the framework, like an elevator. The pieces can be made of a pre-seeded material or they can be seeded after placement. I could be interesting to try and make the material of alginate or some other biodegradable material (maybe a piece of a fabric woven from kelp threads), so that it is unnecessary to remove the material before processing.

A robot will harvest the pieces, either top-down (potential loss of biomass because it is scraped of when the piece passes internal framework on its way up) or from the side. From the side could be done by one or two robots who pumps/sucks/pushes/punches the pieces out followed by transportation in a pipe to a container (collapsible pieces could simplify this process), followed by processing or directly transportation to processing. Need to have a fastening mechanism on the top of the framework to prevent the pieces from floating up and away. If the pieces are manufactured in a way that makes them easy to remove from the side, they still need to withstand the forces from current and waves. Not sure how big of a problem this would be, as the framework would be free to swing from side to side depending on the current and tides. Both sides of the substrate would get enough light and seaweed would grow on both sides.[3] An alternative is to have the robots (this might be a subsea drone of some sort) equipped with a net and a passage. The kelp could be pumped from its place in the framework, through the robot and into the net. The robot should tie the net and then leave it (with a buoy if necessary) for collection.

Mechanism for deployment: Picture a box with a container filled with pre-seeded pieces, three pistons and track between them. The track starts at the container; one piece is shoved from the container and into position for deployment, which is directly above an opening. A telescopic piston pushes the pieces into the first position before it retracts and a new piece is placed into position for deployment. The piston pushes this piece into first position and the other piece is pushed into second position. So it continues. A spring mechanism keeps the pieces in the container in tension in a way that positions the pieces for transport from container to deployment position (reducing the need of one piston). The deployment region would need a seal assembly or a gasket. It could also be interesting to have a snap connection between pieces, where the tension from the push is enough to fasten the connection. That way the same telescoping piston/arm could be used for harvesting (thereby reducing the need of an arm with the same length as the framework.)

[2] This was the main takeaway from a Bachelor Thesis done at HIST in cooperation with SES. They produced pins using different manufacturing processes, including moulding and extruding and found extruding to be the most cost efficient.
[3] From Hortimare's experience. Growth occurs on both sides, with the most growth on the side with the most sun exposure. SES says this is the initial idea of their seaweed carrier, but in practice it has not shown to be more practical or more space-efficient than horizontal substrates. However, it is still sensible to believe that several vertical substrates would be more space-efficient than one horizontal.

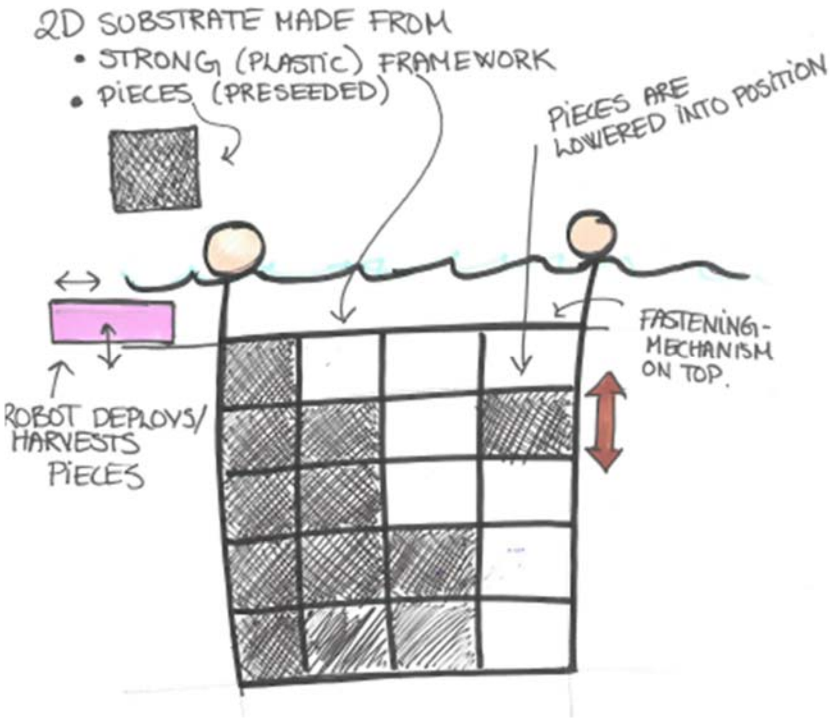

Figure 2: Sketch of the pieces during deployment

Discussion

If the framework is too strong it might make us loose biomass if it is harvested from the top, because the kelp is scraped off. If the pieces are harvested from the side, or if you have some other robot or mechanism that catches the biomass, for instance a vacuum tube or pipe, this might not be a problem.

The waves or currents in the sea will probably make the kelp flow naturally on one side, and push the kelp into the substrate on the other side. This might stop the kelps natural tendency to adapt to the currents. We do not know if this is a good or a bad thing. Also that might impose large forces and drag on the framework and/or the substrate and the kelp (or maybe smaller forces and drag on the substrate and the kelp). This might restrict or inhibit the natural growth of the kelp, or it might make a positive impact. This if you consider deformation hardening and training, e.g. the larger forces the kelp is exposed to during growth, up to a certain point, the stronger the kelp becomes. Might lead to an increased amount of fibre, alginate, celluloses, amyl, nutrients and cell walls. Would it be beneficial with larger currents or a frequent change in tides?

Further questions includes; the size of the framework and the pieces, how many they should be, and it needs to be assessed if one row should consist of one framework or several parts of framework.

Feedback

The choice of the biodegradable material might be difficult. Hortimare have experienced that natural materials do not tend to work very well for sporophyte attachment and growth. Lignin based material is unsuitable, as is PVA or PLA based material.

Collecting the kelp and keeping it in a net before processing seems like a realistic idea. Still it is important to not leave it for extensive periods of time as the kelp will degrade as a result from the lack of oxygen supply.

SES believes the positioning and removal of large semi-rigid beams or other structural pieces that have to be fit into rather exact openings sounds to complicated and hard to carry out in the conditions at sea. The structure would probably have to be quite rigid for the pieces to be able to easily slide into a fixed position, which is hard to combine with a movable and flexible structure. They find it difficult to imagine this being a practical, cost-efficient, weather-robust and easily up-scalable process. It will only convince if we avoid this extra step of inserting pieces. Either by gluing seedlings on the existing surface, or by shooting small threads with seedlings onto the structure. Threads could be biodegradable within 6-12 months. The problems stated above might be solved with a very rigid framework, however free to pivot about its suspension. This provided the deployment mechanism could handle the variations in angle, for instance by being attached to the framework or hold dynamic positioning. SES states; cultivation of kelp will be on suspended structures that allow for some movement. Further questions could include to which degree the framework is allowed to move.

Larger currents and tides will increase nutrient refreshment and this will have a bigger impact on the growth than the forces itself as a result of these currents on the growth of seaweed. Hortimare have not experienced any difference in growth pattern between kelp grown on ropes, ribbons, nets or sheets of fabric. In addition, cultivated kelp shows to be more subjected to unwanted fouling than natural kelp, and this might be related to it being more flexible and free to move and not fixed to a substrate. This have also been experienced at Faroe Islands, who have larger currents and waives, implying high nutrient refreshment, which have resulted in good growth with minimal or no biofouling. Therefore, I think it is safe to conclude that larger currents are beneficial for growth and reducing fouling, however it is inconvenient for deployment and it requires a stronger substrate. The focus on the differences in the strength of the kelp due to forces can be neglected, as the strength of the substrate and the vessels ability to handle rough weather will be the deciding factor for how large the currents and waives can be.

SES believe the idea of a vacuum hose operated from a ROV is attractive, however the description above is vague. A suggestion is to use ROVs at least in an initial phase. Drones/AUVs might be very practical and efficient for deployment, but they do not add value for harvest, unless they are quite big and have lots of autonomy, or can work in ”squads” and with ocean-based energy-recharging units. It is possible to look at this in two phases. Phase I is done with ROVs and support vessels with personnel, quite advanced. Phase II will be fully autonomous without personnel at sea, quite futuristic. To use AUV for deployment and ROV for harvest does not seem so smart; it is a double investment for a similar task. Both phases are separate, so it makes sense to have one device that covers both tasks. Technically a solution involving an ROV does not seem so far away from current possibilities, and SES would like to focus on this.

2 Knitting a net

A 1D substrate, a rope, seems to be easier to seed, deploy and harvest. However, in order to fully utilize the area given for cultivation, the density of kelp needs to be larger, which is the main argument for 2D substrate.[4] To maximize the density we should make a 2D substrate that can be disintegrated to 1D and harvested in that fashion.

Description

One way to do this is to knit a net, which can be deployed in a 2D form and then later harvested as a 1D rope. A net could be knitted or woven by a seeded rope, or the net can be seeded after it is knitted. A loosely knitted net (standard knitting) can easily be disintegrated and harvested as a rope. The challenge is to disintegrate this in a larger scale, when the seaweed is fully grown and interlaced into each other. This should not be a problem if the machine that pulls the rope is strong enough and there is a mechanism that makes sure no knots got into the machine. The main issue is the potential loss of biomass due to tearing the kelp off at the same time. Could be solved by doing this in a closed container or have something that catches the biomass that is torn off before it reaches the harvesting-machine. The thickness of the rope needs to be evaluated, the rope can not be too thin because of the weight of the kelp once it is fully grown. The rope cannot be too thin or thick as it would be hard to knit and (as I understand) the kelp grows best, and the strength of the kelp is best, at some optimal thickness of the rope.

Harvesting can be done in two ways:

1. A machine/ROV/robot/drone is submerged in the same way as when it is deployed. The net is disintegrated, harvested and pulled in. Everything happens subsea. This might require something like a pump, to catch the falling biomass and the harvested biomass and transport it into a container. It could also be transported into a net (different one) where it can be connected to a float and be left in the sea for a vessel to come and pick it up right before processing.[5]
2. The net is pulled on board and then harvested, either from the side in a 2D fashion or in a 1D disintegrated form. The disadvantage here is that it should be possible with a higher degree of automation, with no hands on rope and no heavy lifts. In addition, there is the problem of proper storage. It is also possible to put the net in a closed container under the waterline, which is filled with seawater, and then remove the kelp from the net. Net/rope can be pulled out of an opening in the container leaving the kelp for storage there.

Removing the kelp from the a rope could be done using a conical shaped box or container with a sharp edge or blade on the narrow side.[6] This needs a mechanism that pulls the rope, for example two or more pulley with tracks. This is very similar to a tree cutting machine and a significant amount of technology can be transferred from that machine. What needs to be done is to make the machine work under water and implement a pump or another mechanism that transfers the kelp away from the machine. Another possibility is to cut the kelp using a water jet or a laser. However, the forces required to remove the kelp from a rope substrate are small[7] and therefore a cutting or scarping process should be enough.

Discussion

There are existing knitting machines which are automated and it should be looked into whether or not these can be used or if an entirely new or partly new machine should be developed. This because they are manufactured to product mainly tight pieces of fabric, and we want a net or a very loose piece of fabric.

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[4] SES argues the real reason to do 2D-out-of-1D substrate is to avoid entanglements. This is an important argument, however the initial statement stands.

[5] SES: Sounds feasible. Of high importance here is also to make this all in a way that the seaweed is ”handled with care”, i.e. not squeezed or ripped of too brutally.

[6] Se figure in appendix F.

[7] The forces have been found to be less than or equal to 5N, by WP6 in MACROSEA.

Once the machine is automated, it can be scaled up using more machines and/or larger ones in a production line. It might be interesting to look at knitting over water versus under water. Say you have an ROV/AUV that is connected to a pre-submerged mooring. It could seed the net top-down or bottom-up, or seed and knitt at the same time. Can also look at knitting pre-seeded rope, or spraying/vector seeding on the knitted nett. Can also look at different knitting patterns and see if one of them serves the purpose in a better way than the others. Also it would be interesting to look at automation of knitting versus automation of crocheting, as crocheting might requires less moveable parts. Crocheting is supposed to be as easily disintegrated.

Considerations:

- The impact of the tightness of the knitting on the yield of the seaweed. Will a tighter net give a higher yield or a lower yield? Reasonable to assume there is an optimal density and tightness and size of knitting. What about rope density?[8]
- Which way should the net be knitted, if it is knitted in the sea by an ROV? Vertical or horizontal? Top-down, down-up, right-left, left-right? This might be a secondary consideration, but will have a significant impact on the movement, i.e. the route the ROV takes, which again might impact the way the ROV is developed and designed.
- Is there an optimal pattern for cultivation of seaweed? (There are numerous knitting patterns)
- Which fabric should be used?

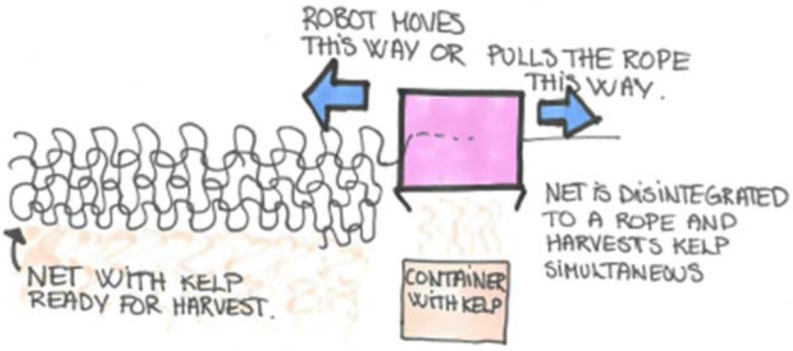


Figure 3: A knitted net is disintegrated into a rope using a robot that either travels along the main mooring or pulls the rope towards to itself.

Feedback

Hortimare say the handling method required for net making will remove a lot of seeds/sporophytes from the material due to the inherent method of knitting. SES say one difficulty might be the requirement to handle already seeded substrate, it needs to be handled with care. It is possible to combine this method with the shooting of small seeded threads into the substrate (knitted beforehand, left unseeded), or spraying seedlings on the already knitted net. The argument for using a pre-seeded material it that is might be more efficient than seeding after knitting, it takes less time. Therefore, this should be tested to find out which sequence would be more profitable. There is also the possibility that a net knitted of pre-seeded material would give a sufficient yield, despite some seeds being removed during knitting.

Regarding the thickness of the rope; kelp can grow on threads with a diameter of 2 mm and still have enough attachment force to stay in place in calm seas. The rope currently used for cultivation at Hortimare is 12 mm, and can be knitted into a net if need be. Another method would be to use ribbons which can also be knitted

[8] A lot of work has been done on this subject. Higher rope density does not necessarily lead to higher yield, due to competition. Higher seaweed density will likewise not always lead to higher yield due to increased competition for space and nutrients. Reasonable to assume there is an optimal density.

into a net structure. SES thinks the best trade-off for substrate thickness is 5 – 8 mm, they use 6 mm at the moment. Surface and internal microstructure is also of importance.

There must be an ideal size of the loops in the net, there needs to be a flow of water around all of the plants, to close of a knitting will counteract this. A first guess from SES is 20 – 30 cm for Saccharina Latissima, the optimum will be somewhere in the range of 20 – 50 cm rectangles. This can be adapted to the species. Knitting pattern is probably not the biggest concern. Still, some knitting patterns could potentially be easier to automate and disintegrate, and make it easier to have the correct loop size and distance between the ropes.

SES believes in harvesting using ROV machinery, and I agree as I see this to be the most efficient and as the other option requires heavy lifts.

The harvesting mechanism described is what SES calls ”biomass removal”. They do not see this as a challenge, they normally pull the rope through a larger hole (3 – 5 cm, without sharp edges) and everything comes off easily. It tends to be in clumps, but should be manageable, maybe by the introduction of sharper edges?

Storage of the kelp in a container with water on or off deck is discarded because the seaweed will suffocate within 2 – 3 hours if water is not actively refreshed, making the biomass useless. Storage of kelp in water can not exceed 24 hours. This comes from Hortimare, who suggest drip-dry storage in which you can maintain it for over 48 hours. A large container filled with water usually causes instability and it is possibly more energy-intensive. The way the kelp is stored will most likely affect what it can be used for, however processing directly or very shortly after harvesting could solve this.

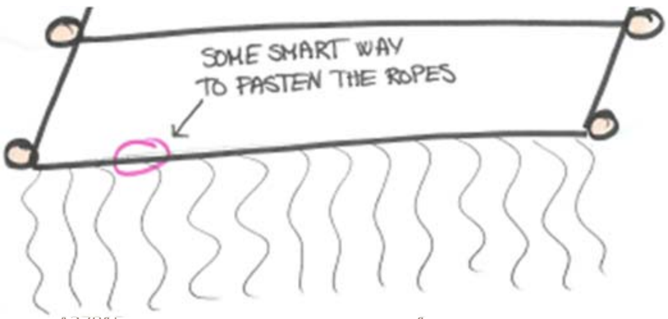
SES say possible fabrics includes; PE, PP, Danline, Polyester and Kuralon, which all work fine. Nylon was supposed to be less successful. It needs to be assessed if it is desirable to have a floating substrate (PE/PP) or sinking (Polyester, Kuralon, Nylon). The cheapest materials are Danline, PP and PE.
Hortimare say that PE is not suitable, because the holdfast of sporophytes produces a type of glue that only works with certain chemistries. The attachment is stronger with other materials. Current combination used by Hortimare and supplied by AT~SEA technologies consists of PES/PP. Internal microstructure is also important.

3 Other 2D substrate shapes

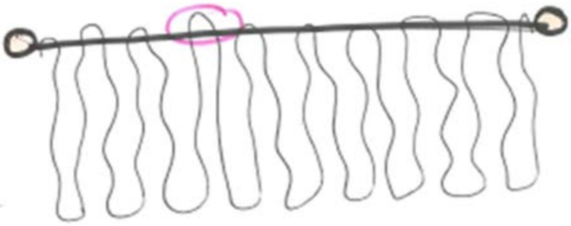
Other 2D substrate shapes would be interesting to look at.

Description
This includes more ways of spanning seeded rope transversely over mooring and then having some smart attachment mechanism (which makes automation possible) between the two. Different examples includes:

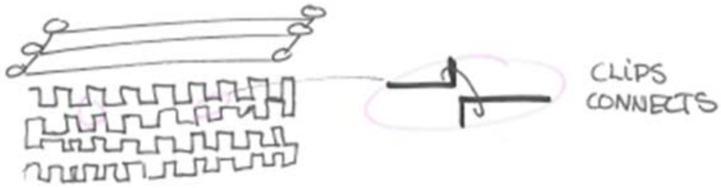
- Horizontal main mooring at approximately 1 m depth. 8 m seeded ropes is attached about every 20 cm along the rope. Done by some robot and an easy fastening mechanism. The opposite direction is done on Faro Islands. Might use a tree-cutting machine (or a similarity) to harvest this.



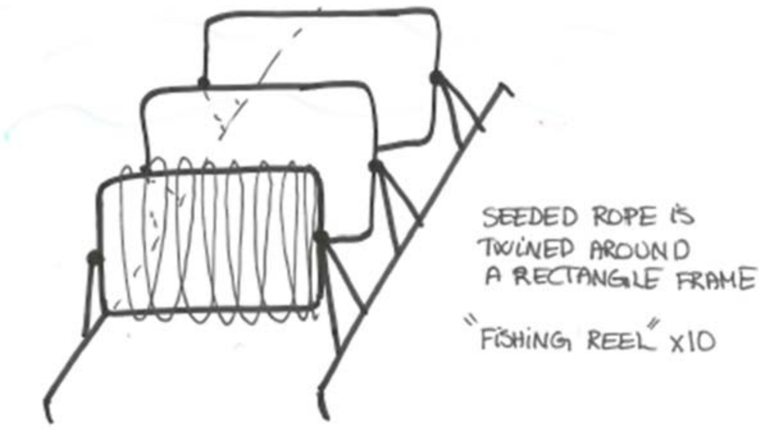
- Horizontal main mooring at approximately 1 m depth. One long and continuous seeded rope is attached every 40 cm along the rope and between the fastenings are approximately 16 m of rope submerged. The use of a sink rope might make anchors unnecessary.



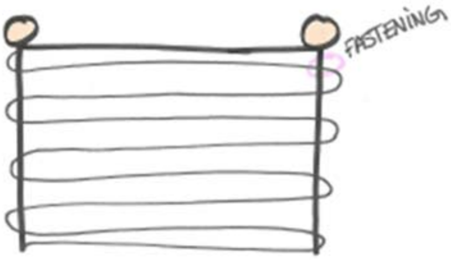
- Horizontal main mooring at approximately 1 m depth. Large square net (or other form) made of one long and continuous seeded rope. Clips will make the fastening mechanism, and some automated robot/process to do this would be required. Inspiration from crochet maybe? Harvest is possible under and over water. Disassemble the clips and harvest the rope.



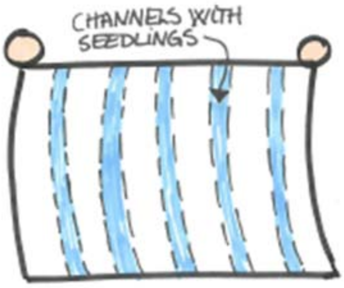
- Longitudinal main mooring set at say 12m. Seeded rope is draped/twined around a rectangle frame (approximately 8 m transversely) that is fastened to the main mooring allowing it to pivot about the centreline.



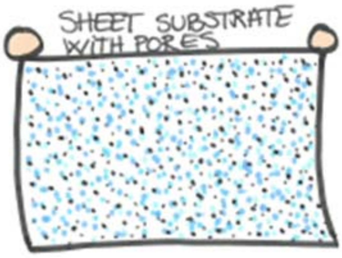
- Vertical main mooring. One long and continuous seeded rope is attached approximately every 40 cm along the line vertically and drawn back and forth between the vertical main mooring.



- A sheet substrate with channels sewn into it. These are injected with a gel containing seedlings. The channels might need holes or be permeable to allow for growth.



- A sheet substrate where a gel containing seedlings are sprayed, pressed or painted on. The substrate could have pores to make attachment easier.



Discussion

One variation of this is to combine ropes and pieces of fabric to produce different structures of the substrate. This could be flags, something along the lines of SES seaweed carrier, a box with a grid, some blob-shaped structure, pieces of fabric fluttering, layers of nets and lines either horizontal or vertical.

An extension of the argument of maximising the density of the substrate can be made to include 3D substrates. Possible 3D substrates include a collection of multiple 2D substrates in an ordered stack.[9] This can be done in various ways, for instance two sheets attached to the same horizontal main mooring with a fixed angle between them.[10] Then it would be interesting to investigate the relationship between the angle and the exposure of light. Is there an optimal angle and how much light is needed? Another possibility is a large net or a cage made of nets containing nets. Each corner could be equipped with an actuator and dynamic positioning could be used. That net can easily be repositioned and follow the best conditions, however this might be too expensive and unnecessary.

Feedback

The first alternative is similar to what will probably be SES's next step, called the ”violin”. Transverse long lines with 15 m spacing, and then every 1 m parallel 15 m long substrate lines, stretched in groups of 4 – 5 simultaneously over the long line system.

Hortimare say it is not a problem to sink a rope, but to keep it at the right cultivation depth. Perhaps this could be solved by using a material with the same density as water, so the buoyant force and weight neutralize each other.

A disadvantage of the net assembled by clips is that it would require a very large amount of clips.

[9] Figures in appendix B.
[10] Figures in appendix F.

The rope twined around a rectangle frame does not really have any advantages compared to others.

SES believes the substrate with channels sewn into it could gain importance, if the gel-technology is managed.

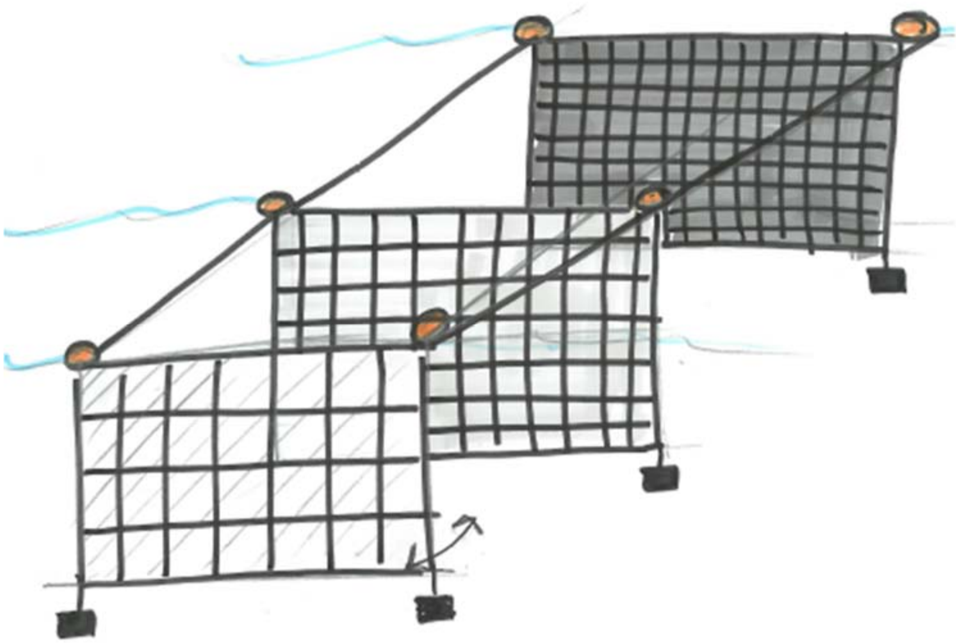


Figure 4: Possible setup of 2D substrates.

4 ROV, AUV or underwater drone

Description

Using an ROV, AUV, drone or something along these lines is possible. The substrate could be deployed beforehand, either manually using a fishing vessel or some other custom-made vessel (might be too low-tech) or some other more automated process. The substrate could also be deployed using the ROV. This implies the ROV needs a container (or a connection with a container) with substrate and some way of knowing where to place the substrate. For instance this could be a preprogramed pattern based on the anchor, or a combination of preprogramed pattern and autonomous behaviour. Then the ROV could perform the necessary operations, like cleaning the substrate before seeding (if the substrate has been out all year), seeding (various ways to do this, the substrate could also be seeded beforehand and only deployed by the ROV), and then later harvesting. Seeding would consist of application of the seedlings onto substrate and refilling the machine that does this with seedlings. Refilling could be done using a pipe and a pump from a container. The container could be placed on a monitoring vessel, it could be a separate container on or inside the ROV, it could be placed in a separate ROV, or in a small container-vessel. Harvesting could be done by cutting or scraping the seaweed off the substrate and transporting it (for instance using a flexible pipe and a pump) to processing. It could be transported directly to processing, to a container for storage, or into a net that is left in the ocean to be gathered later. If we want to use containers for storage, it might be possible to place them on a floating raft and/or a production line on-board. One idea is to have several ROVs (the ROV fleet) with an interconnection. One ROV removes the seaweed from the substrate, the seaweed is transported to the next ROV which executes the first step in processing, followed by transportation to the next ROV for the second step in processing and so on. An alternative would be a direct connection to the processing facility, it could be a vessel on site following the ROV or it could be a factory on land.

The ROVs should probably include alert-systems (implementing lean production), if anything is out of the ordinary or an error occurs, the process stops, production worker is alerted and fixes the problem before the process continues. If control systems for quality is needed this should also be implemented in the ROV. The use of ROV requires a Launch and Recovery System (LARS). Not sure to which degree a vessel following and monitoring the ROV is needed and how advanced it should be.

Discussion

The advantages of using an ROV is that it could be autonomous and it is or could be automated. It does not require a large amount of production workers. It is efficient (if it works and the process is fast enough). Could potentially handle rough sea and weather well (might include engine for stabilisation and dynamic positioning). Different sizes are possible. This could potentially give room for different substrate shapes. Any machinery for seeding and harvesting that can be mounted in the ROV infrastructure could be used. Harvesting could be performed under water, which helps seaweed quality. A couple of ROVs might be enough for several large production sites, if the ROV is fully utilized with high duty cycle and equipment.

The disadvantages include price, this is an expensive solution. Because this is a very technical solution, there is a need for technical staff and production workers need technical training. There is also the possibility for technical errors and problems. The ROV can potentially tear substrate and cause large damage to it and the rig in rough sea. This could be prevented by not using the ROV when the weather is terrible.

Considerations when assessing ROV versus AUV.

- An AUV does not require a cable or an operator.
- An AUV can operate at higher speeds, swims smoother and gives better data quality.
- Production cost for AUV versus operational cost on ROV.
- The difference in operational time because of a connected power supply or not. I addition the size and power of an AUV is often less than with an ROV due to battery supply.
- What detection systems should and is possible to use, for instance machine vision, sonar or others. The detection system could possibly include a tread of a special material that is sewn into the substrate to make the detection easier.

A combination with the best parts from either product would be better than choosing. Maybe a combination of marine robots and AUV. Related solution is an underwater seeding drone.

There are a lot of different possibilities regarding shape of this ROV/AUV/drone and the composition of them. This will of course depend on the choice of seeding process and shape of substrate. For instance, if the substrate is 2D the ROV could be quite large and flanked by two parts. These parts would contain the seeding machine, for instance a sewing or splicing machine that insert the substrate with little pieces of seeded fabric or a gel injection machine. If two ROVs are chosen to travel along each side of the substrate, should they both seed? Should they both harvest, should they do it together, should they have the same shape? One possibility is that they have the inverted shape of one another, which promotes their co-operation.

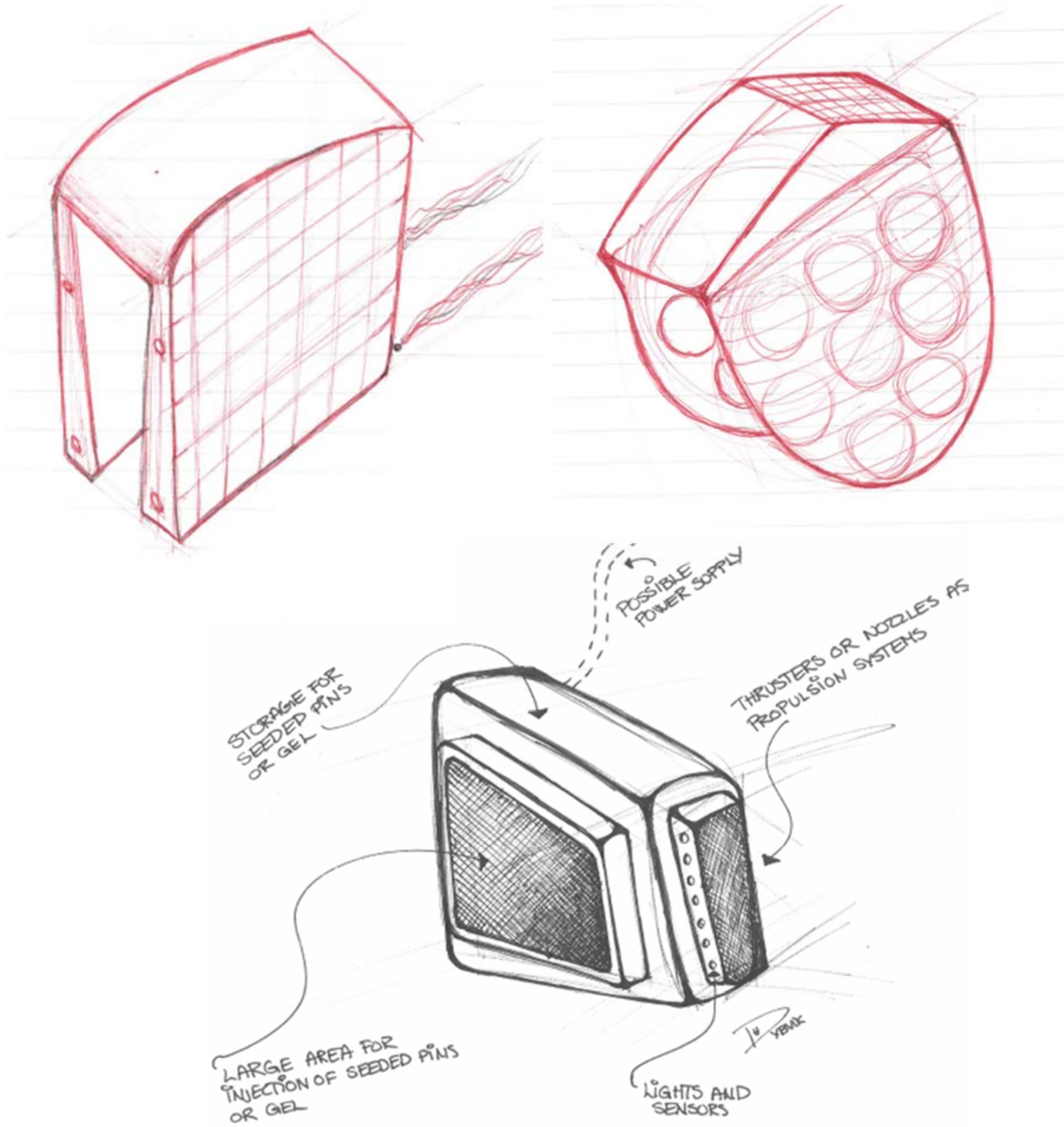


Figure 5: Two possibilities regarding shape. The first are ROVs with flanges to cover both sides of the substrate at once. The other is a concept design of an underwater seeding drone.

Feedback

There are a lot of existing technologies and looking into them could prevent high investments and R&D. It is likely that a first phase for the harvest will be realised with a ROV and not AUV, due to energy issues, autonomy and technical progress.

Implementing control systems in the ROV should not be a problem, as a large portion of current ROV and AUV technology is used for inspection and quality control.

ROVs always need a vessel, as they have a control and power umbilical, and it is interesting to combine this with a direct connection to a processing facility, a vessel on site following the ROV. SES strongly wish this to be reality soon. The dimensions that such ”swimming factories” would have to have in order to keep pace with the harvest is a potential issue. For instance if we want to dry a ton per hour or more per unit have to be managed. The shape, dimensions and number of such vessels is highly relevant for further work.

5 Integrated production and processing vessel

Description

A custom made vessel can be a mobile cultivation facility, with all of the required processes on board. This means there is no need for a factory on land and at most a small land facility. It could be constructed using a moon pool or catamaran shape as inspiration. Either it could be a housing for a processing line, packaging and storage of processed product, and deploy an AUV for seeding the substrate and harvesting. This requires a frame underneath the vessel which holds LARS for the AUV. Alternatively, the framework underneath could contain industrial robots and other equipment to perform deployment, seeding and harvesting. In this case, the vessel will follow the mooring and no AUV is required. Alternatively, the production vessel could have the shape of a train or eel, - meaning there would be several jointed units along a chain with one process per unit.

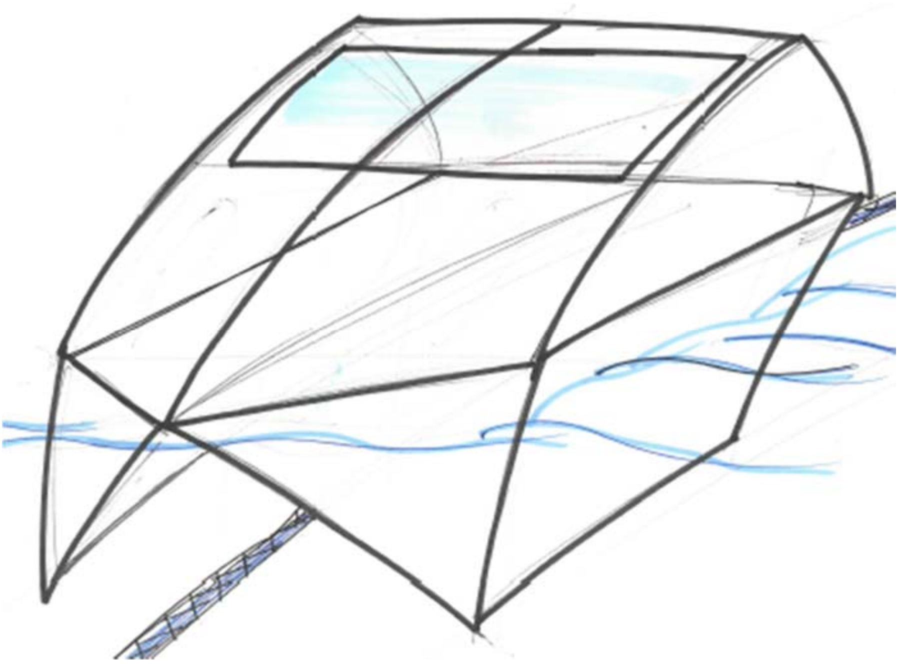


Figure 6: Possible start for a design of an integrated production and processing vessel. It is a blend between a catamaran and a moon pool. It follows the substrate while it seeds and harvests.

Discussion

Considerations and assessments:

- The order of operations and which component is to perform which operation.
- Should the equipment be stationary, or should it be interchangeable modules?
- Production on land versus on sea. This with regards to health, environment and safety for production workers and cost.
- Inspiration and technology transfer from 3d printing, those mechanisms, framework and setup could be significant.
- Inspiration and technology transfer could be drawn from Kongsberg Maritimes LARS, both for developing LARS[11] and developing framework/setup underneath the vessel.
- Production could be done just-in-time, meaning the kelp is harvested and directly processed, packed and sent out. Then then vessel does not need to be very large, which might be an advantage.

Possibilities includes different shapes of the vessel, for instance a catamaran or a trimaran with production equipment in-between the keels.

[11] Developing LARS is generally not seen as a major issue. (However, it still needs to be done.)

The advantage of this is that it can be assumed to be efficient because it is customized to the process and therefore all unnecessary activity is eliminated.
The disadvantage is that it requires more R&D and product development than other solutions.

Feedback
It is possible to combine submerged operations via a moon pool, directly under the deck (similar to sketched catamaran vessel) with the knitted net.

SES say they strongly believe in this concept, the "swimming factory”. The first steps could be a modular harvest vessel.[12] Later, such vessels can be bigger and carry container-based processing units. I agree with this, however I do not see a reason to postpone developing the larger and probably more advanced vessel. Early development might save time and money.

SES believes the equipment should be interchangeable modules. I agree, as this will utilize the vessel better.

6 "Normal" fishing vessel

Description
Today's fishing vessels are versatile and some of them can be customized with the correct equipment quite easily and could therefore be used. With machinery, industrial robots mounted on the die line or as a part of the vessel, underneath the waterline. That way seeding and harvesting could be done under water. It could be possible to have interchangeable modules, or stationary processing machines and production line on the vessel.

Discussion
The main advantage with this solution is that it is relatively easy to develop further compared to more specialized vessels and different machinery, industrial robots and processes. It is a quick fix.
The disadvantages to this is that it is a quick fix and one of the first solutions you would think of. It is not very new and innovative. Other, more specialized vessels or processes could potentially be quicker and more efficient. This is why this solution should be discarded from further development for now.

Feedback
SES say it is an interesting concept that deserves to be further developed, - it is good if there is an easy quick fix and it works. However, what we have to look at here is the seasonality of uses. For instance are pelagic trawlers available during the harvest season (mainly May-June in Sør-Trøndelag), but the availability during deployment season might be more complicated.

It is possible to use this concept in a transitional phase, while developing a smarter and more efficient solution. It should also be taken into consideration that a new solution will (probably and hopefully) be more environmentally friendly than the fishing vessels today.

7 Fleet of the boats (or similar) from Plastfabrikken AS

Description
The boats "Lamor Seahunter"[13] or something similar to them, for instance a floating stage solution, from Plastfabrikken AS can be interconnected and form a large vessel or fleet. In-between the boats the relevant

[12] Of the type they are hoping to start developing with partners.
[13] http://www.plastfabrikken.as/

machinery could be attached. Another possibility is that each boat holds a process and the fleet could be customized according to the processes needed. The boats could be constructed with interchangeable modules, which makes it possible to perform seeding, deployment, harvesting and possibly storage using the same vessels. Seeding and deployment could be executed over or under the waterline and the same with harvesting and storage.

Discussion
The main advantage with this solution is that it is easy to scale up and down.[14] More or less boats and with that more or less processes can be interconnected. However, I believe this would be limited to low-scale production. "Lamor Seahunter" is manufactured for a market in China and not fitted for Norwegian coastal environment. Suits current production and would therefore not be suited for the scale we want. Another disadvantage is cost. This solution might be cheaper than other alternatives in the beginning, however I believe the total cost for the correct scale would be higher than if automated processes were used. It would probably require more workers and be less efficient.
The solution is primarily for rope substrate although it could be used for other substrates shapes if the correct equipment is used. Based on this and the disadvantages versus the advantages this solution should be discarded from further development. Believe other solutions would be better.

Feedback
SES say the level of exposure is the main issue with this solution. Semi-exposed sites and especially future, more exposed sites, might be too demanding for these relatively low-freeboard vessels, designed for fjords and other protected areas. Still believe it is an interesting interim solution. These units could be the platforms needed for ROV operation, before AUVs become feasible. ROVs and modular work platforms can be combined with Seahunter units.

If this concept is developed further it could be done with the market in China and Asia in mind.

8 Sub-solutions and other

8.1 Different seeding (application of seedlings on substrate) methods

- Sewing or splicing machine that pulls the rope through it and inserts a pieces of seeded thread at a periodic distance, for instance every 10 cm. A related process is to use a nail-gun or a stapler that also inserts a staple or some other seeded bit into the substrate at a periodic distance. Snap mechanisms or screws might also be possible to use in a similar fashion. Snap mechanisms are easier to attach and detach than mechanical fastenings, which is an advantage, and it could also be a benefit when it comes to automation.
- Pressing or rolling the seedlings onto the substrate. One way to do this is narrowing a container with seedlings, where the substrate passes through and the seedlings is forced into or onto the substrate. It is most intuitive to use a rope, however it might be possible to do this with a 2D substrate if the machine that does this consisted of two separate pieces that co-operated across the substrate, or the machine is very large.
- Gluing and/or spraying seedlings on substrate, using gel and glue.
- Injection or filling a gel containing seedlings in pores, channels or openings in the substrate. These processes could be performed using a pump, a vacuum-space, compressor, water pressure, air

[14] Although the industry does not want to scale down, there has been a discussion on the size of the cultivation facilities and the possibility of having smaller producers, for instance in places with geographical restrictions or limitations, which would be forced to scale down from the equipment larger facilities use.

pressure, pistons etc., or a combination. The advantage of the processes that includes a gel is that it (probably) requires less laboratory facilities than a process including a seeded thread.

- Spinning process, where a seeded thread is spun on a larger mooring.[15] The disadvantage of this process is that it is too slow at the moment. It also requires a lot of seeded rope, and there are potentially large savings to be made. In addition, this threas is stuck in the harvesting machine as it is infiltrated in the pulleys and the blade. Other processes would be more efficient and suitable, and therefore I do not believe this is a solution worth pursuing.

Of course, the choice of seeding method would strongly depend on the shape of the substrate, if the seeding should be done on land before the substrate is deployed, during deployment or after the substrate is deployed, - and vice versa. All of the suggestions should be possible to automate using existing machinery, industrial robots and technology transfer from current related processes.

Further work could include a thorough identification of existing equipment and how using similarities could lead to a solution. What type and size of sewing machines and nail-guns exist? Could they be applied or modified to suit this type of application and how?

8.2 Requirement specification

Size of cultivation facilities and yield

Cultivation experiments with S. latissima in the North Atlantic coastal areas predict biomass production potentials of up to 340 tons wet weight per ha, however more conservative numbers range from 170-220 tons. (...) A single large scale cultivation farm (60-100 ha) for kelp is envisaged to produce in the order of 10 000 tons wet weight (1 500 tons dw) biomass annually.[12]

Depth of cultivation at sea

In the nature S. latissima grow down to 30 m depth and resist wave heights corresponding to storm conditions. Cultivation should, however, preferably be done only in the upper 10 m. Strong water current means higher nutrients supply per time and potential for higher biomass production.[16]

The research papers[17] also state that that kelp should not be cultivated in the top layer of the water. It is therefore reasonable to reach the conclusion that the kelp should be cultivated between approximately 1-2 m and 10 m depth.

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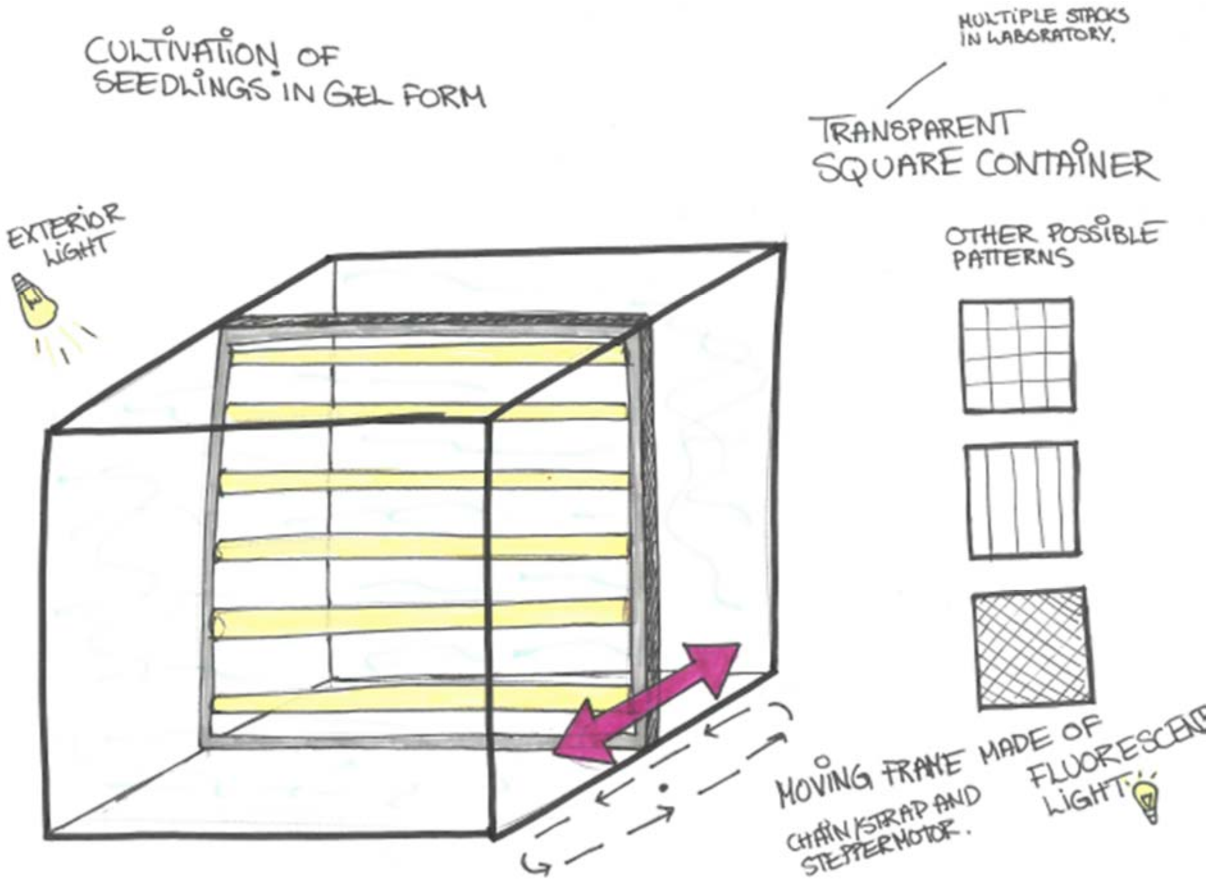
[15] Also, see SkyWrap https://www.aflglobal.com/Products/Fiber-Optic-Cable/Skywrap/SkyWrap.aspx.

[16] From "A new Norwegian bioeconomy based on cultivation and processing of seaweeds: Opportunities and R&D needs" REPORT NO: SINTEF A25981.

8.3 Cultivation of seeding gel (laboratory phase)

- If a seeding process involvs a gel with seedlings, this needs to be cultivated in a laboratory for approximately a month. There is the possibility of applying the seedlings within their first weeks, however I believe the yield is higher when the seedlings are a bit older. To cultivate the seedlings water, nutrients and light is needed. To maximise utilization of the laboratory it is possible to use a large container surrounded by fluorescent light. The container should have a square shape, as the room would probably have a square shape and the container could be placed in a corner. This as opposed to for instance a cylindrical container which would not utilize the area. The light would presumably be restricted by the density of the seedlings and some regions might be without access to light. To solve this the gel could be stirred by reinforced fluorescent light, for instance arranged in rows, columns or a square pattern. Other container shapes and geometry of stirring mechanism are possible, however I believe a square container would be the most reasonable.



- Cultivation of large amount of threads might be possible by using a large suspension of pulleys. There might be a problem with friction that scrapes the seedlings of and a large amount of pulleys enables the possibility of more errors.

It is normal to have a cycle with eight hours with light and eight hours without. Is it possible to speed up this phase using shorter day-night periods?

8.4 Other considerations

Deployment period is possible from August/September to January/February. This because the seaweed does not grow from November to January. This varies along the coast of Norway of course, due to different light, temperatures and other abiotic factors. It is possible to argue that the same equipment (for instance the same vessel or collection of ROVs) could be used for deployment in all of Norway, and therewithal reducing the investment cost and increasing the duty cycle.

Harvesting is possible from April to June. Later the seaweed degrades and is subjected to biofouling. The seaweed does not grow in the summer, due to the temperature and other conditions. If harvesting is efficient it could also be possible to use the same equipment along the entire coast (or with slight additions) because of this time span.[17]

If a unit/module change is possible the argument could be extended further, using the same equipment (vessel, ROVs) for deployment and harvesting. This would also release time in the laboratory for the laboratory cultivation period, and reducing the number of laboratory facilities needed. Cost effective. Time in laboratory, space needed and how difficult it is to perform the cultivation process should be considered when choosing or further developing the concepts.

It would also be interesting to investigate if it is possible to combine this with cultivation of a different species, a summer crop. If there is a species that grows well in the summer, the same infrastructure could be utilized.

8.5 Additional questions and further work

- What is the trade-off between harvesting under water and harvesting over water or in the water line and having a quick transportation to processing with regards to seaweed quality and degradation. I.e. comparing the option of processing on-board a vessel and transportation of fresh biomass to shore for processing there.
- It could be possible to perform FEM-analysis on different substrate infrastructures to further assess and decide between different solutions/possibilities. What are the effects from drag forces and forces from current, waves and tides on the infrastructure?

[17] See the research papers for detailed information on this. "Seasonal- and depth-dependent growth of cultivated kelp (Saccharina latissima) in close proximity to salmon (Salmo salar) aquaculture in Norway" by Handå, Forbord, Wang etc, 2013 and "Development of Saccharina latissima (Phaeophyceae) kelp hatcheries with year-round production of zoospores and juvenile sporophytes on culture ropes for kelp aquaculture" by Forbord, Skjermo, Ariff etc, 2012.)

- Does the infrastructure stay out during the summer? Will it need reinforcements or other maintenance? Presumably cleaning is needed if the infrastructure stays out during the summer.
- Transportation of processed product to customer/consumer. If the factory that processes seaweed is on board a vessel (processing vessel), the product could be loaded from this vessel to a cargo vessel and then to the customers nearest dock and eventually further transportation on land. This if it is desirable to have most of the transport on water. What is most economical and eco-friendly?
- What kind of motor/thrusters/nozzles on vessel/ROV should be used and what they should be fuelled on. As this is supposed to be eco-friendly and sustainable, it should be electric, hydrogen cell, biofuel, or driven by wind or wave generated current. SES states that this is a good point and suggests a performance matrix with focus on lifetime-costs. A life-cycle assessment should be made.
- How much time exposed to light does the substrate need? It is fundamental that the kelp is exposed to a sufficient amount of light and nutrients, and the substrates should not shadow each other. Can this be seen in relation with the currents and tides? If the least required amount of light and nutrients is identified (without reducing the kelp quality) the density of the substrates can maximised.
- What aspects from lean production can be implemented? For instance visualization, alert systems and worker involvement.
- An in depth mapping of all the processes needed, for instance seeding in laboratory, deployment of the substrate, application of seedlings onto substrate, harvesting, cleaning of the kelp, cutting, processing packing, transportation of product, cleaning the substrate and so on.
- Requirements for automation; hardware, software, control system electronics etc.
- Degradation of the kelp after harvesting.
- "Harvesting kelp gives relative large volumes, which causes some logistical challenges during harvesting and transportation if the kelp is not pressed and packed tightly together at the harvesting site. This will again influence what the kelp can be used for."[18]

Some of the questions imposed might already be answered in some research paper we are not aware of (especially biological questions).

9 Conclusion

As can be seen from the exclusion of concept 6 and 7, I believe the most reasonable would be to combine a 2D substrate with a custom-made vessel and ROV/drone. This will maximize the yield and be more efficient compared to semi-new/intermediate solutions, like customizing an ordinary fishing vessel. Therefore, this will suit industrial scale better.

The seeding method should involve a gel. This because it reduces required space in laboratory and because it can be applied to a 1D and 2D substrate. Imagine that it is easier to automate a spraying process than other application processes. Further research and experimentation is required here, as it is only Hortimare and AT~SEA who have made gel-technology work.

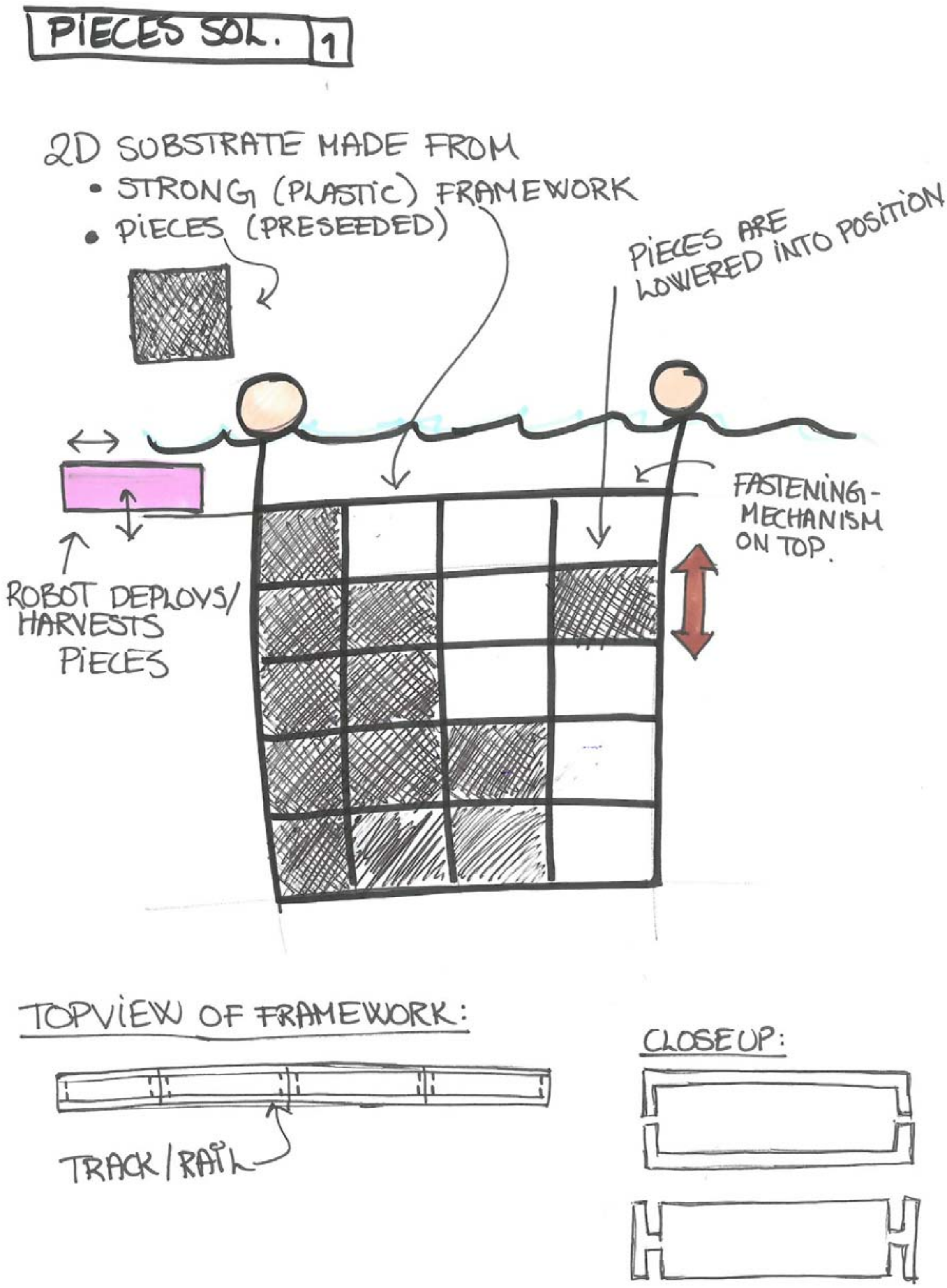
Harvest under water will minimize or eliminate the need for heavy lifts and reduce degradation of the kelp. The kelp should be processed directly after harvesting (possibly with an integrated production and processing vessel) or as soon as possible, because it is hard to store the kelp properly and it degrades quickly.

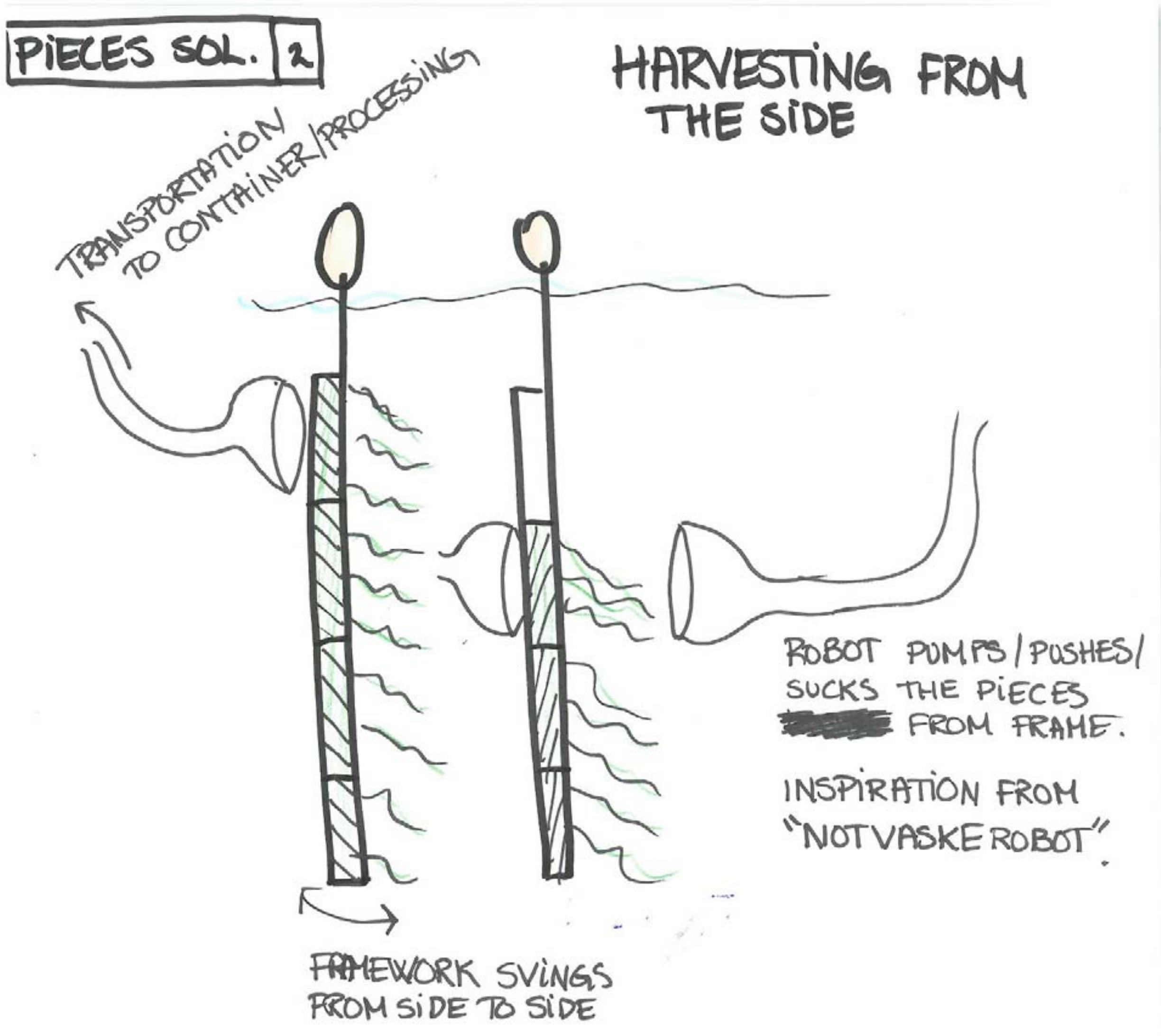
I believe the breakthrough will happen with the most feasible and profitable combinations of seeding, deployment, substrate shape and harvesting method.

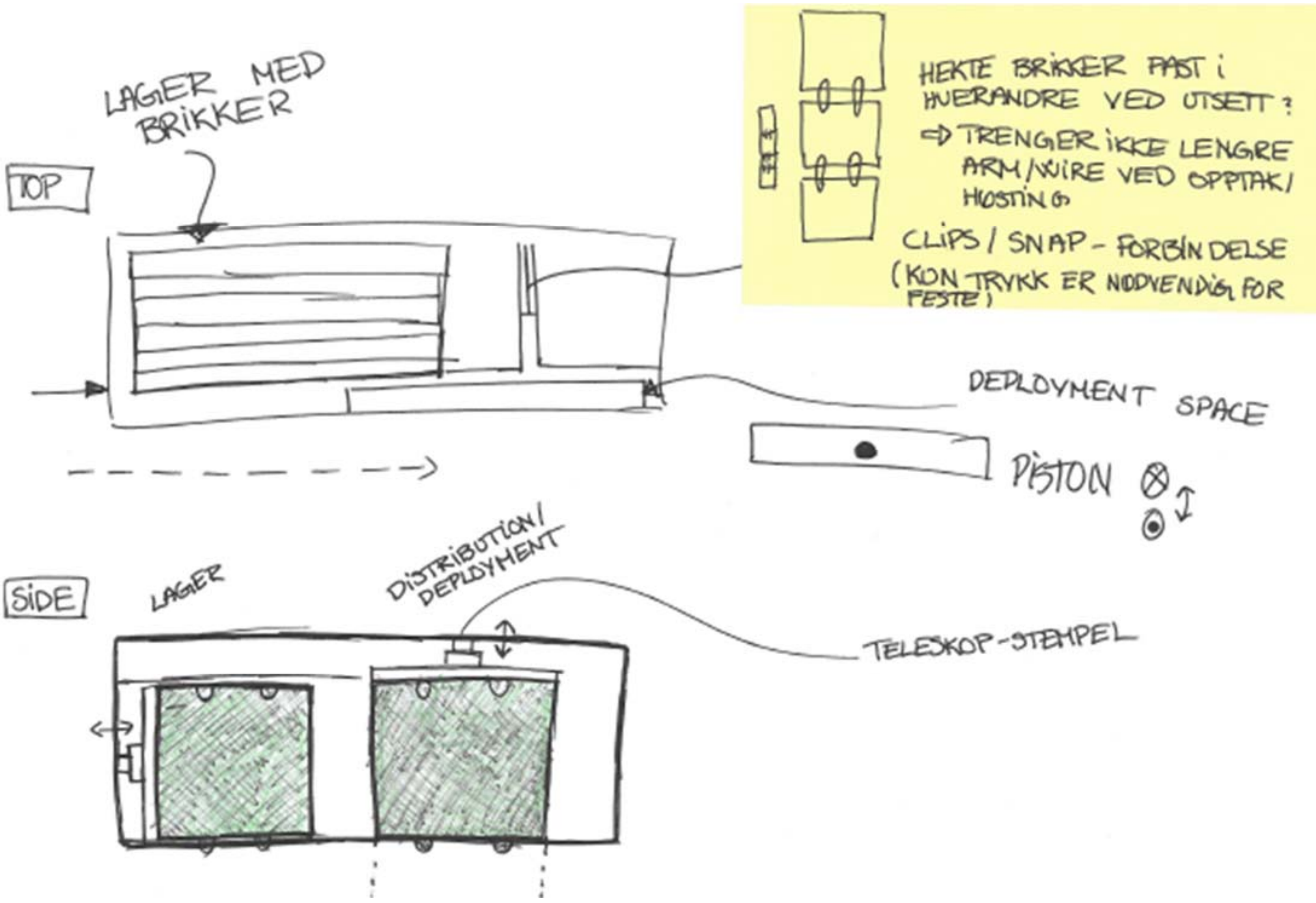
[18] Harald Sveier, Ocean Forest.

Appendix

A Sketches for concept: Pieces

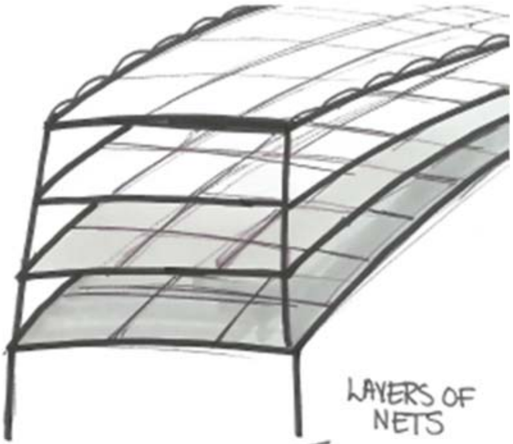


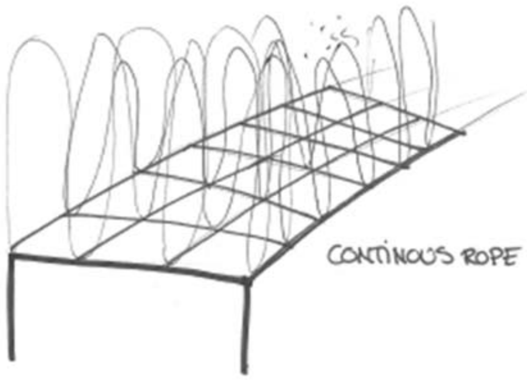

PIECES SOL. 2
HARVESTING FROM THE SIDE
TRANSPORTATION TO CONTAINER/PROCESSING
ROBOT PUMPS/PUSHES/ SUCKS THE PIECES [redacted] FROM FRAME.
INSPIRATION FROM "NOTVASKEROBOT".
FRAMEWORK SVINGS FROM SIDE TO SIDE

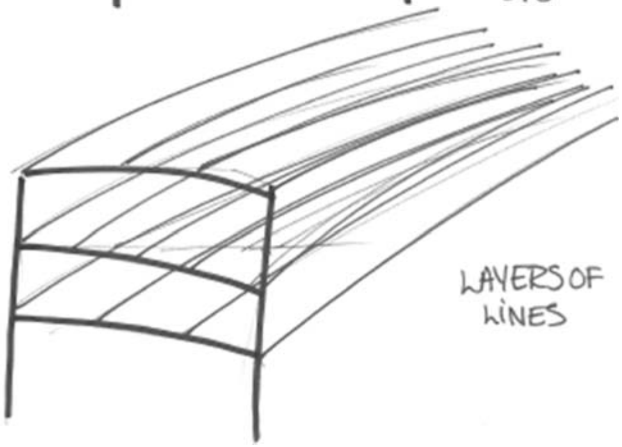


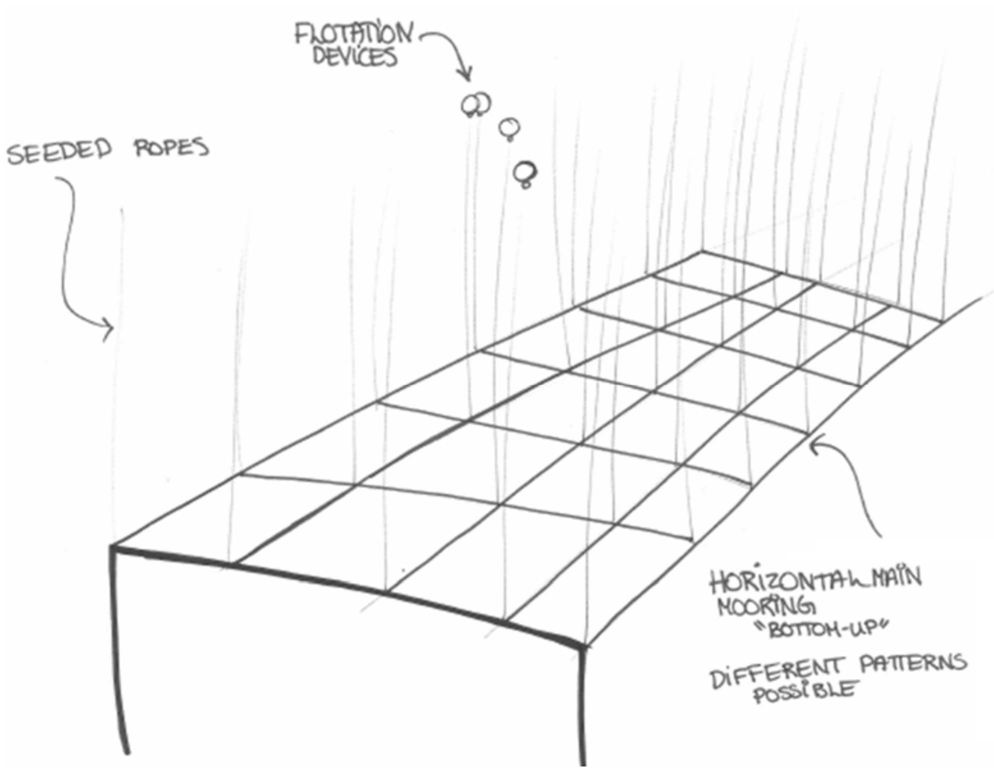
Mechanism for deployment of pieces: A container filled with pre-seeded pieces, pistons and a track between them. The track starts at the container; one piece is shoved from the container and into position for deployment, which is directly above an opening. A telescopic piston pushes the pieces into the framework and the process repeats. The same telescoping piston/arm could be used for harvesting.

B Sketches for concept: Other 2D (3D) substrate shapes

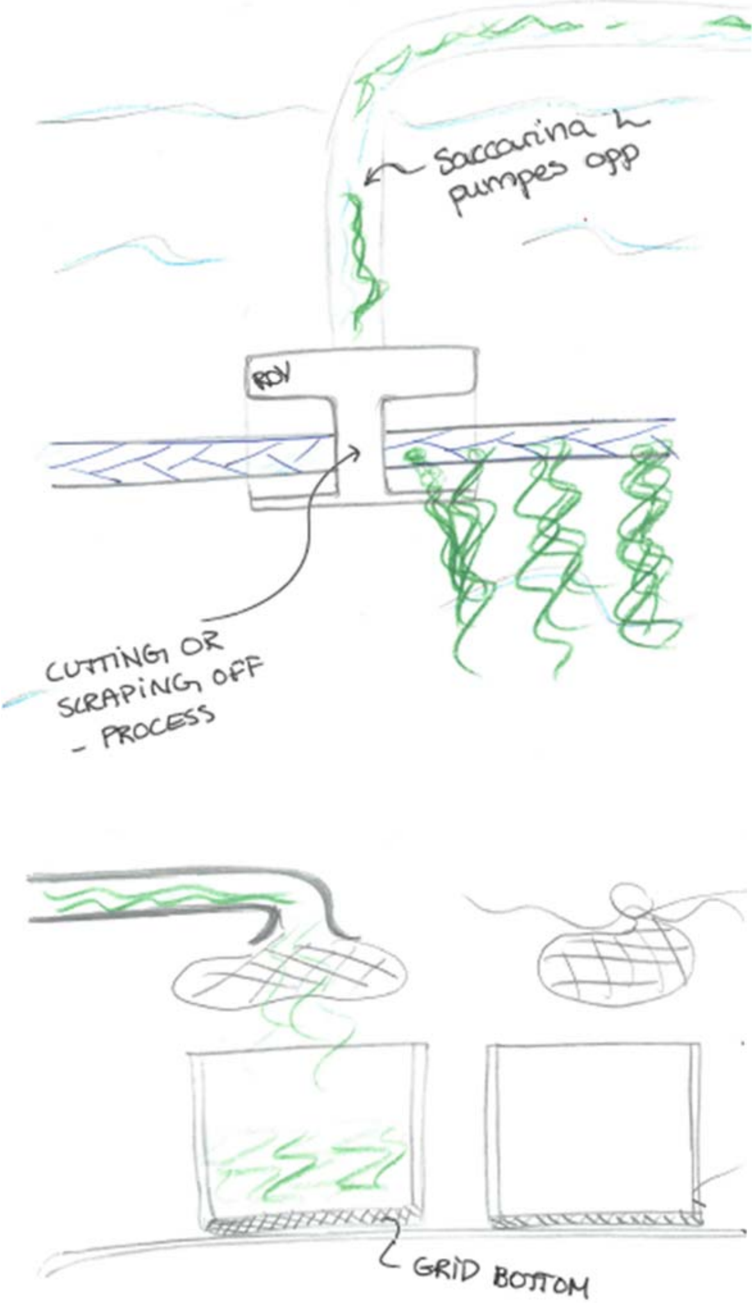




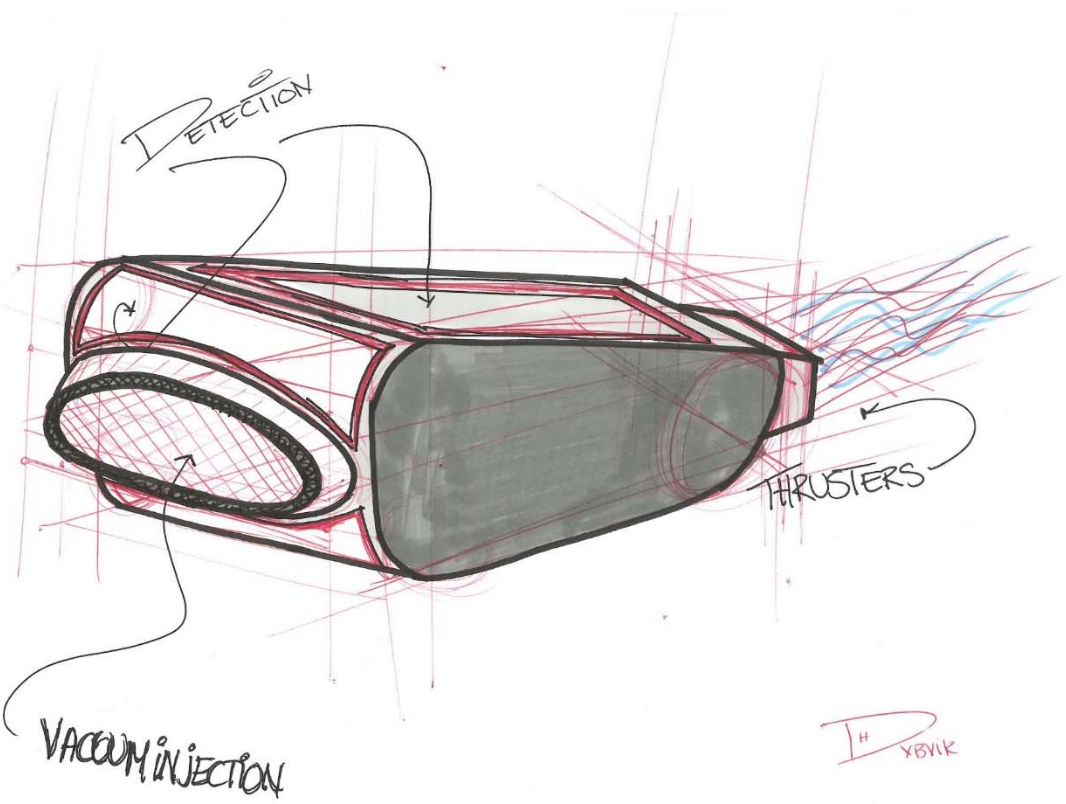


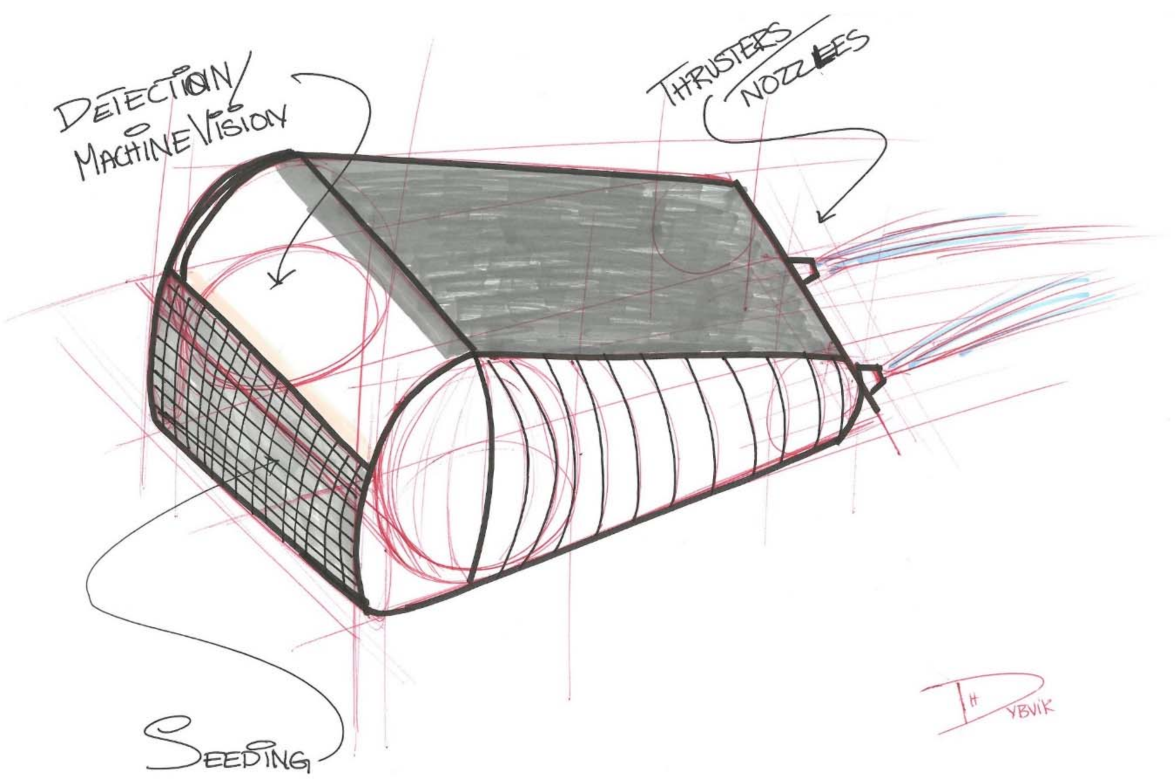


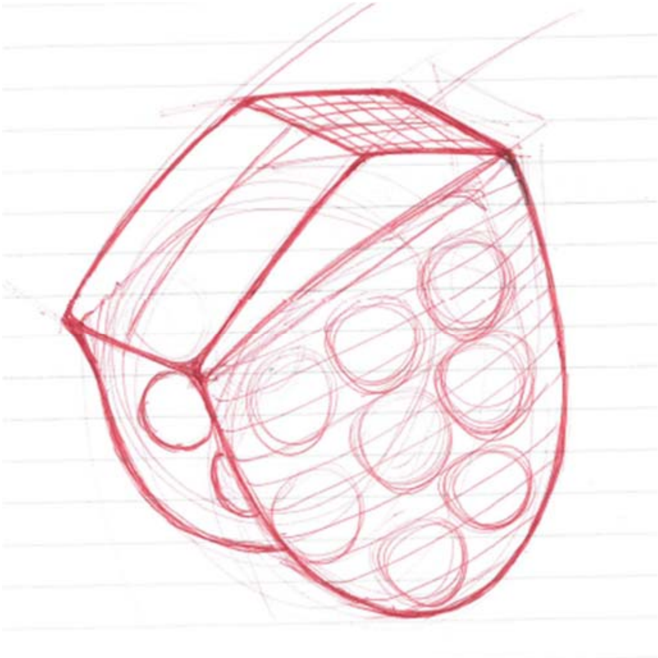
C Sketches for concept: ROV, AUV or underwater drone



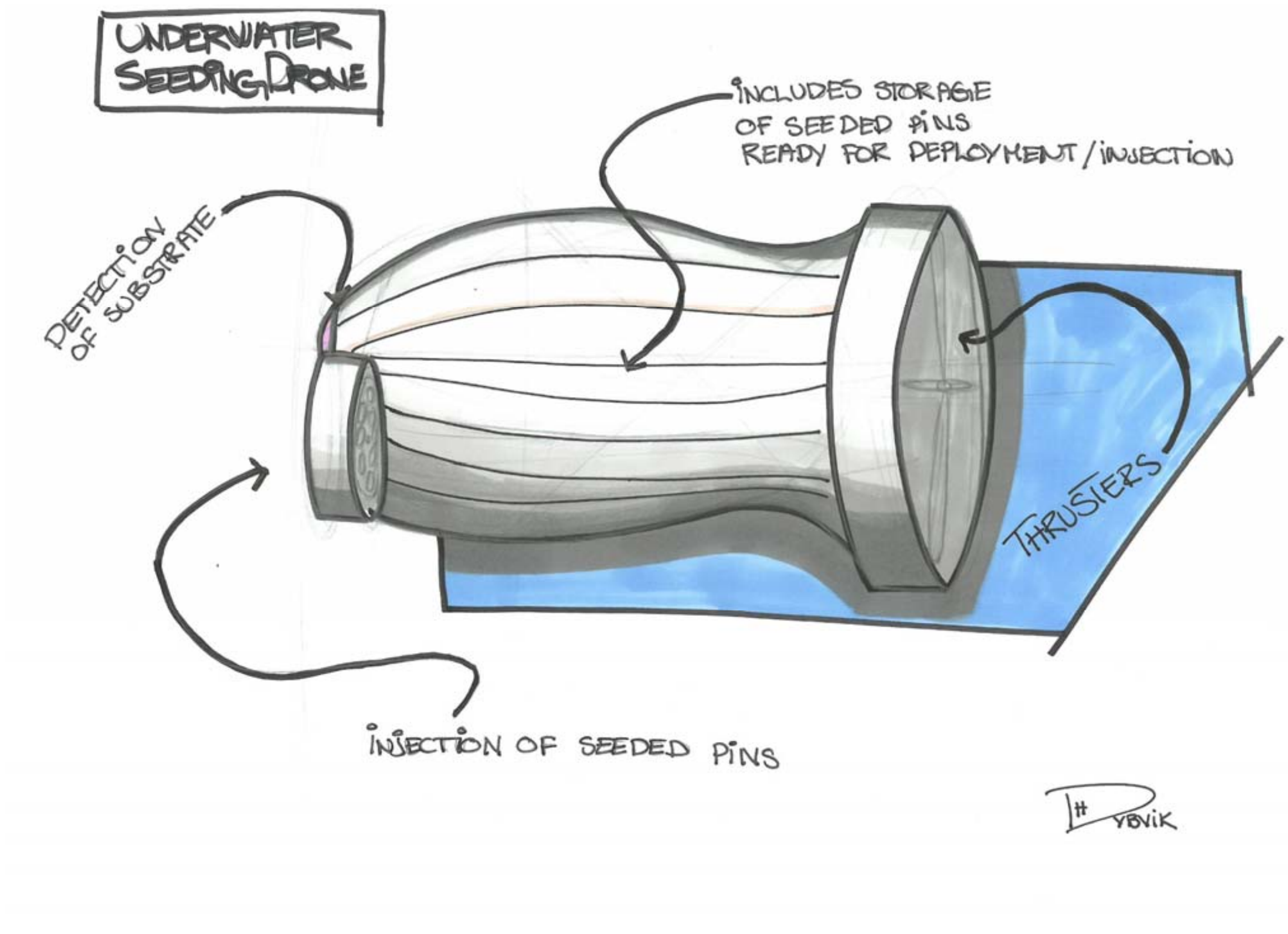
Harvesting kelp by cutting or scraping the seaweed off the substrate and transporting it, using a flexible pipe and a pump, to processing. Here it is transported to a container with a grid bottom, which easily removes the seawater and is part of a production line, which can lead to processing, - or directly into a net for collection later.


DETECTION
THRUSTERS
VACUUM INJECTION
DYBVIK

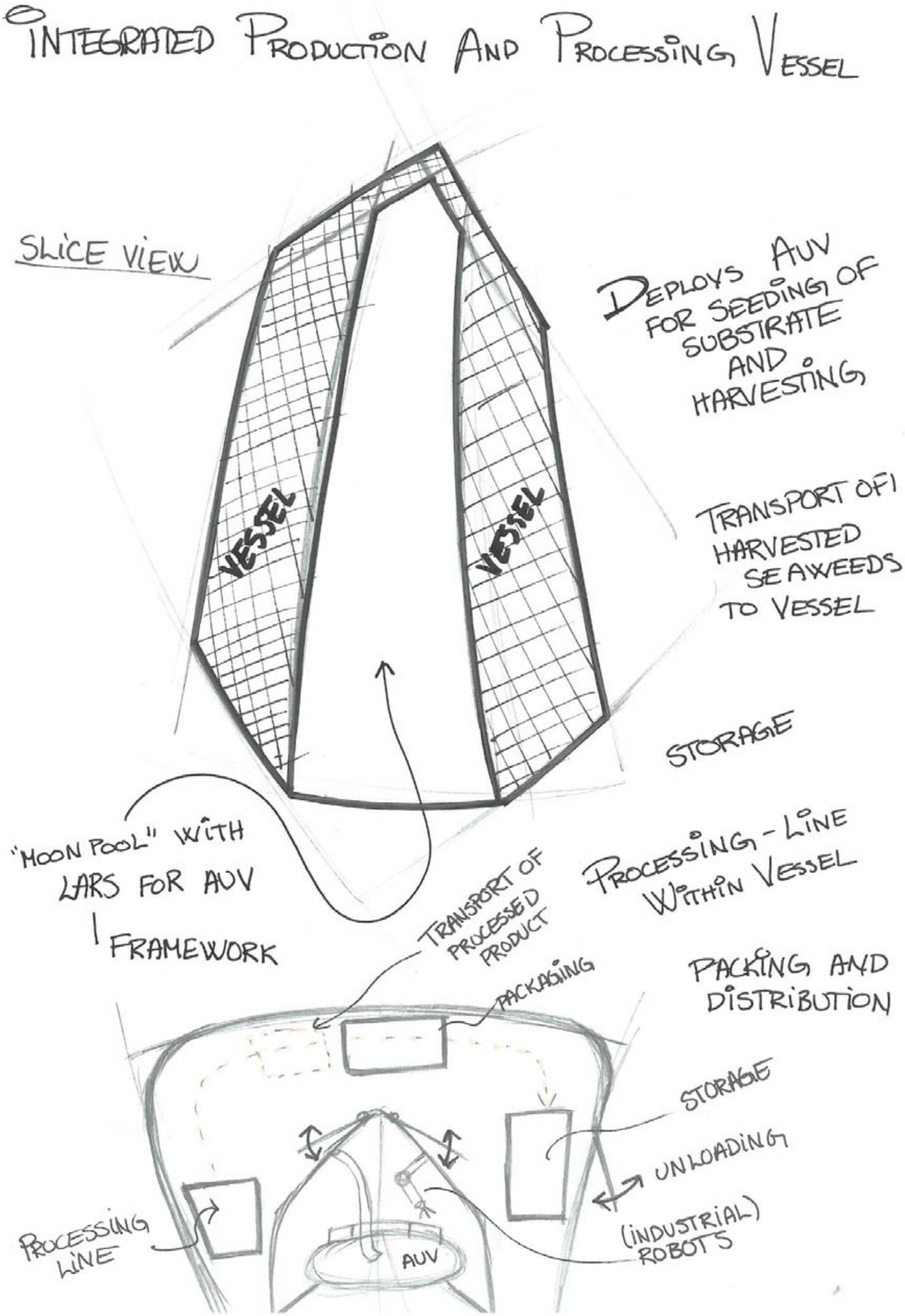

DETECTION/
MACHINE VISION
THRUSTERS/
NOZZLES
SEEDING
DYBVIK

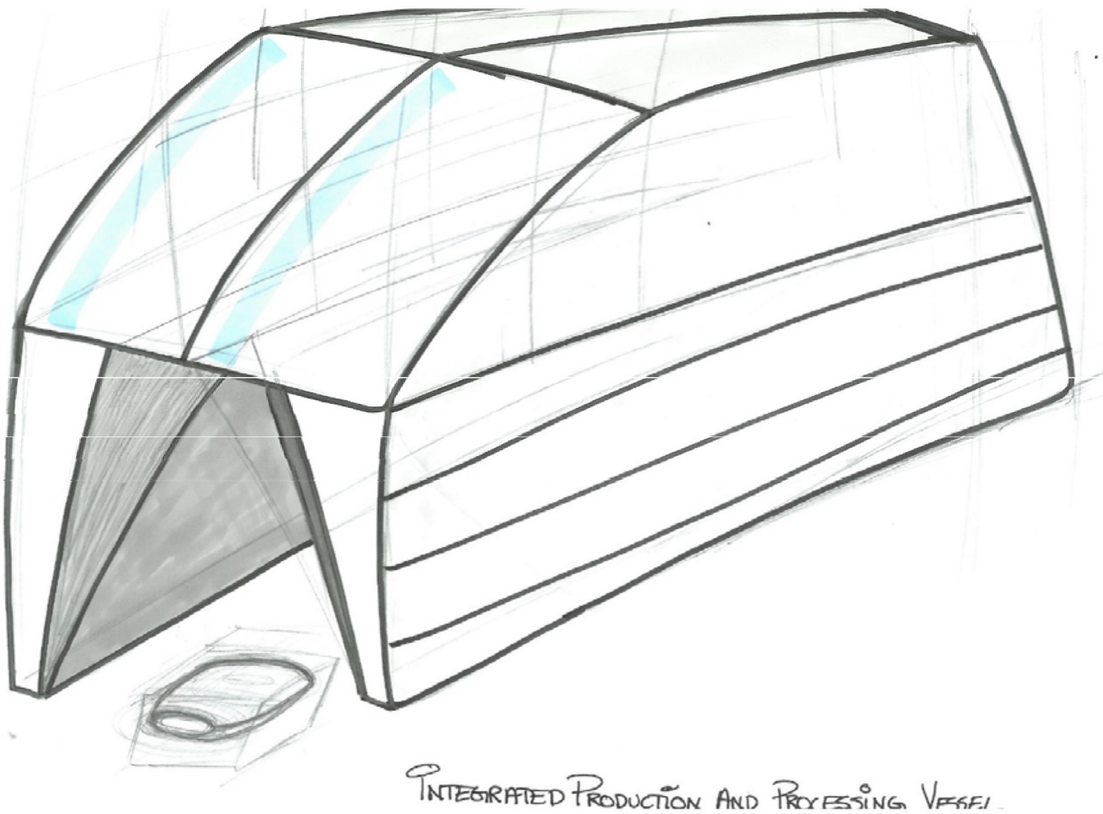


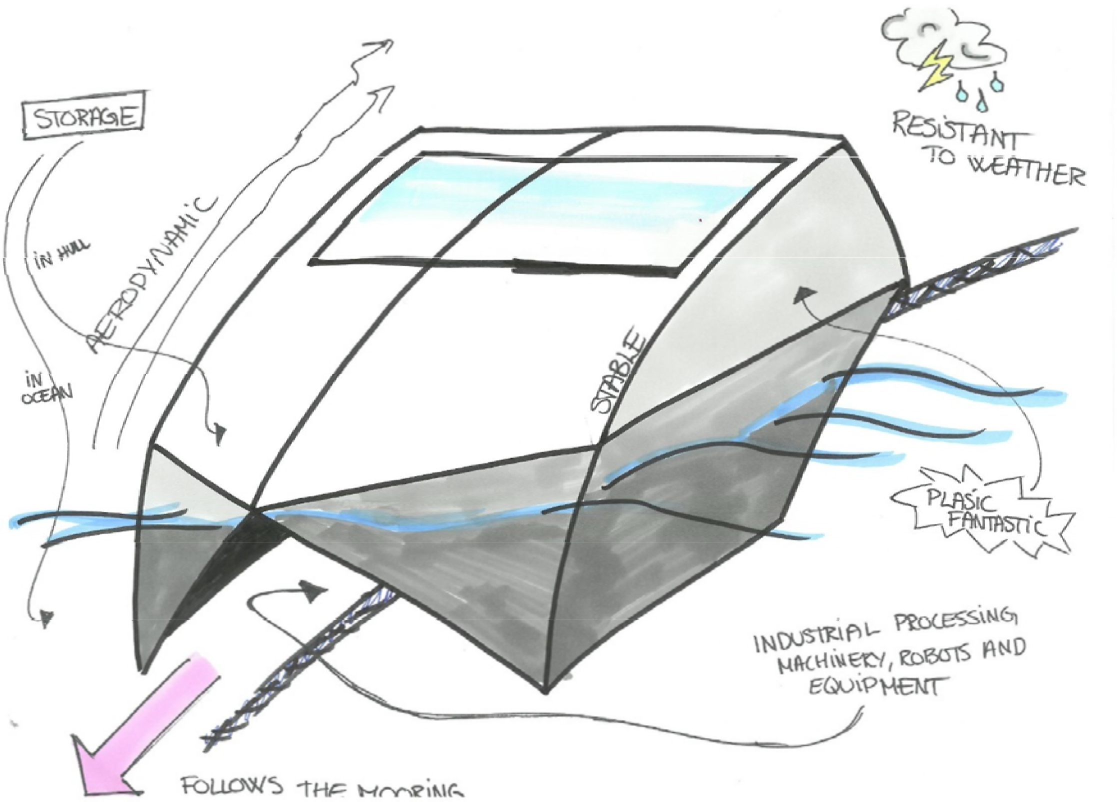
Possible shape of drone with flanges. Seeding process using a sewing machine or a nail-gun between the circles are two possibilities



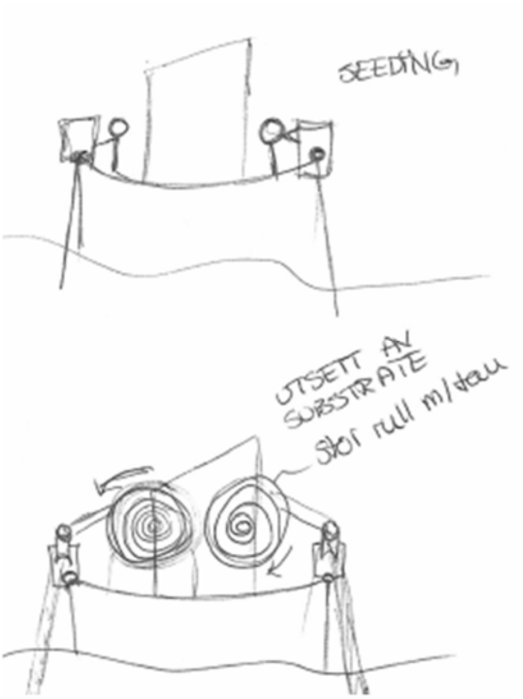
D Sketches for concept: integrated production and processing vessel

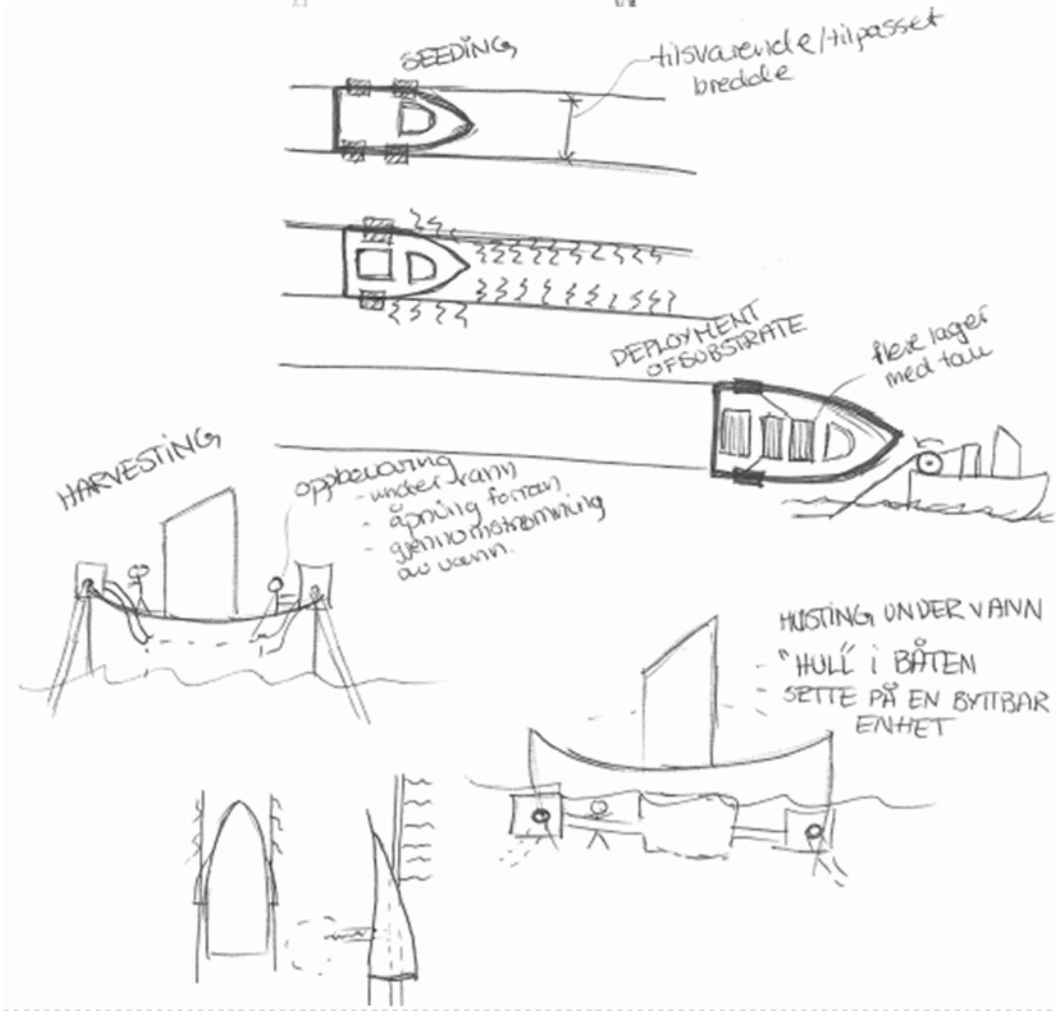


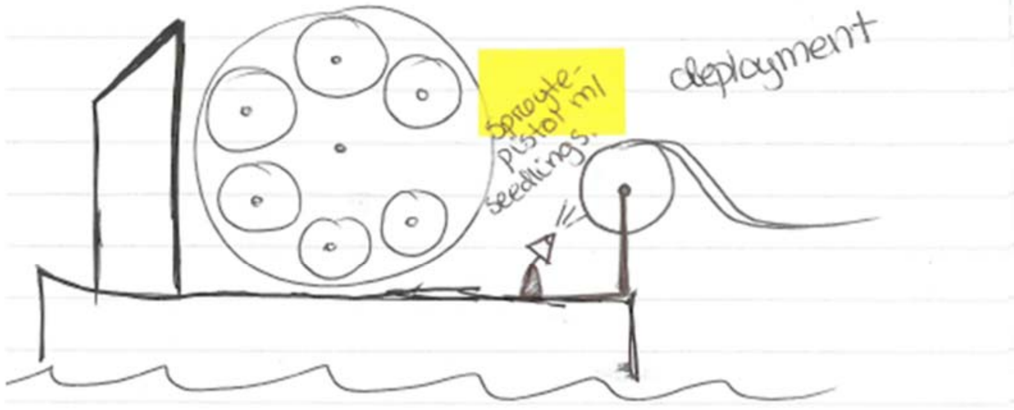

INTEGRATED PRODUCTION AND PROCESSING VESSEL

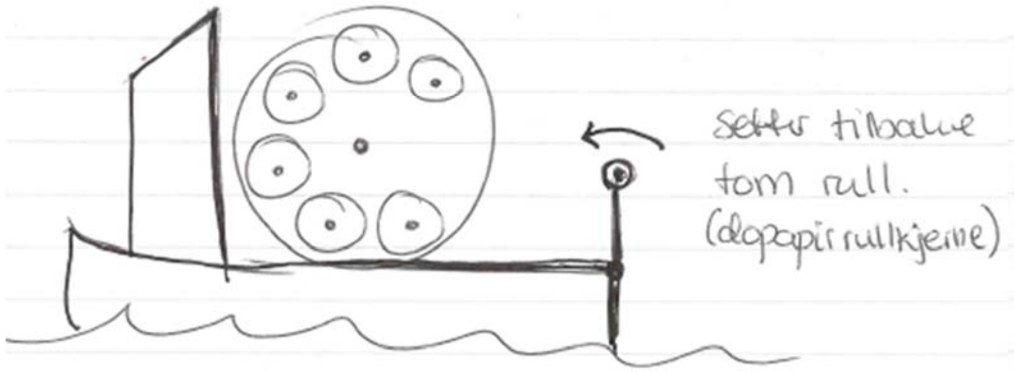

STORAGE
IN HULL
IN OCEAN
AERODYNAMIC
STABLE
RESISTANT TO WEATHER
PLASIC FANTASTIC
INDUSTRIAL PROCESSING MACHINERY, ROBOTS AND EQUIPMENT
FOLLOWS THE MOORING

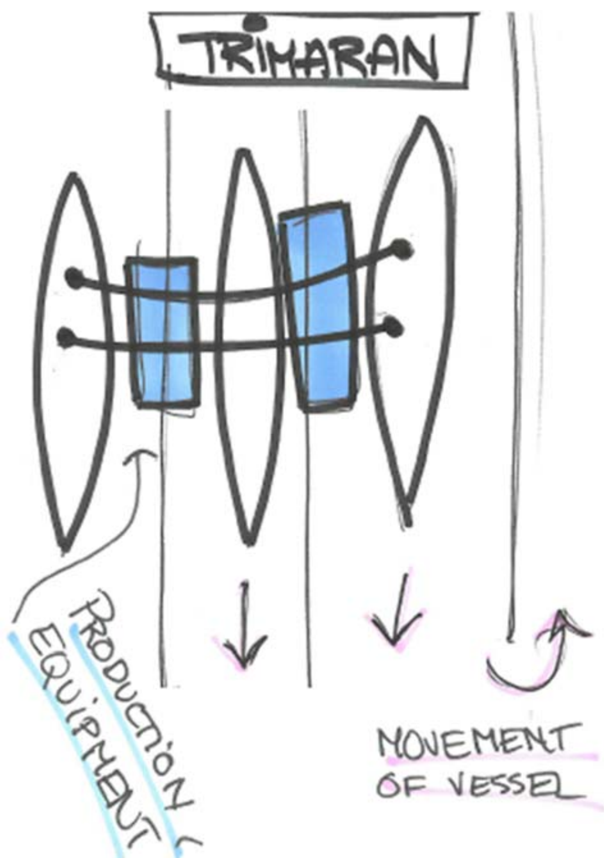
E Sketches for concept: "Normal" fishing vessel



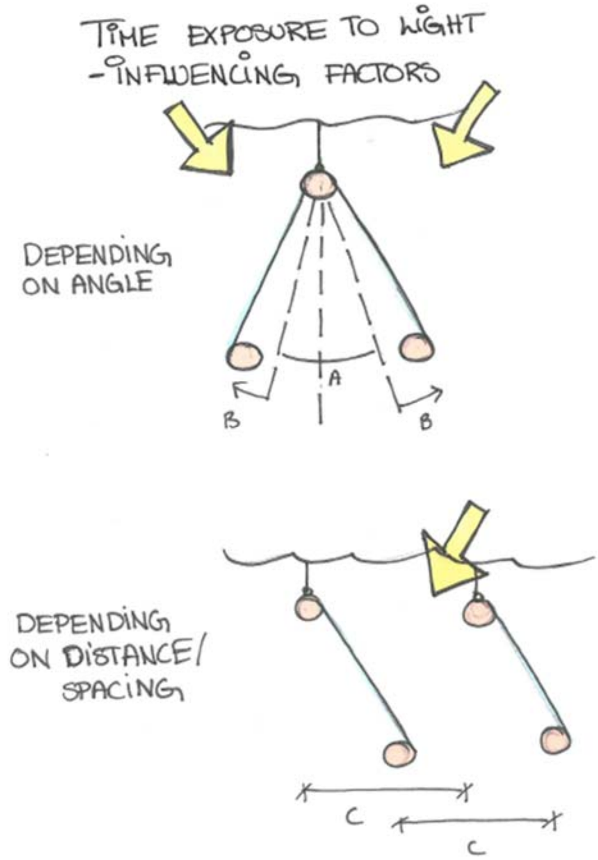


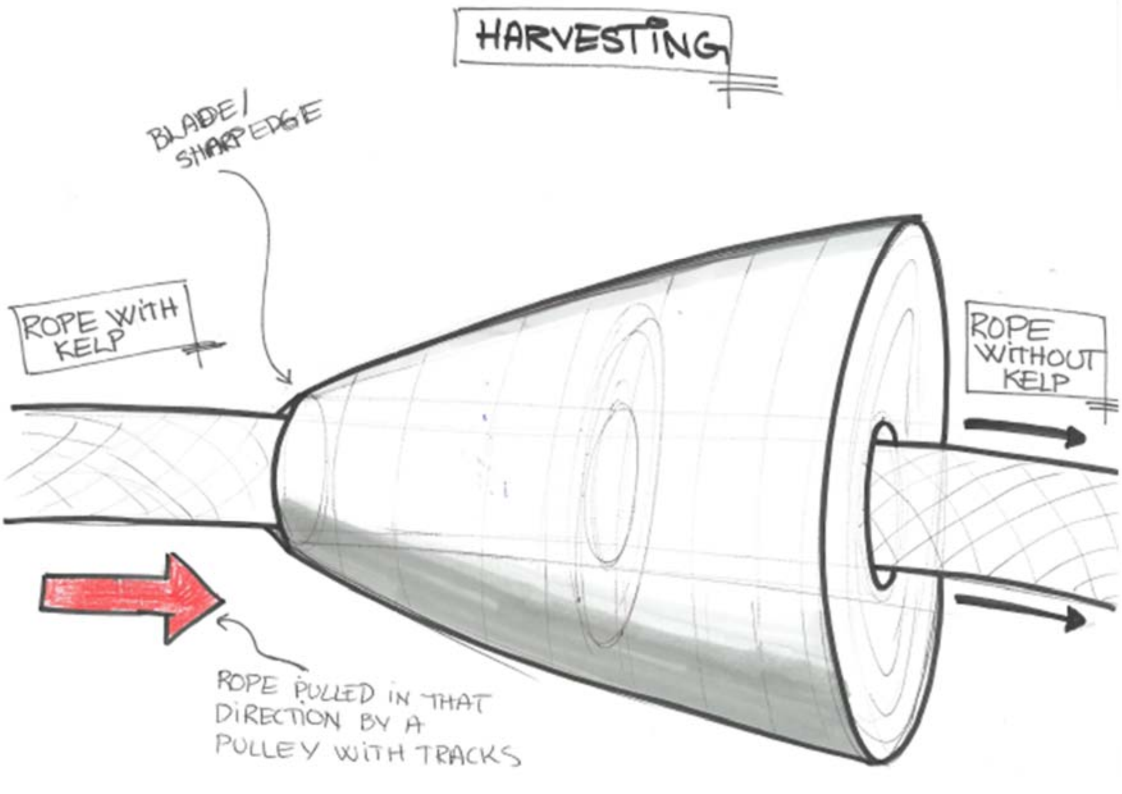

deployment
sprøyte-pistol m/ seedlings.


setter tilbake
tom rull.
(dopapirrullkjerne)


TRIMARAN
PRODUCTION EQUIPMENT
MOVEMENT OF VESSEL

F Sketches for other considerations





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