Novel Concepts for Offshore Ocean Farming

Authors names: Alexandria Austin[1](SM), **Alessandra Chieff**[1](V), **Julianne Depardieu**[1](V), **Max Gratton**[2](V), **Thomas Holdaway**[2](V), **Wei Tian Lee**[2](V), **Mary Libera**[1](V), **Ahmad Naqiuddin**[2](V), **Faris Yusof**[2](V), **Nicholas Townsend**[2](V), **Mirjam Fürth**[1*](AM)

1. Stevens Institute of Technology, Hoboken, New Jersey, USA
2. University of Southampton, Southampton, Hampshire, UK

Sustainably feeding the growing world population is a major challenge. With 70% of the Earth's surface covered by oceans, the potential of ocean farming is huge. However, the development of offshore aquaculture systems is in its infancy. This paper discusses and presents concept designs for offshore ocean farming, based on collaborative group projects between students at the Stevens Institute of Technology, US, and the University of Southampton, UK. Through the presented concepts and preliminary results, the work highlights the engineering challenges as well as the huge impact sustainable offshore ocean farming can make.

KEYWORDS: Kelp; Ocean Farm; Sustainability

1. INTRODUCTION

1.1 Motivation

Food shortage is one of the biggest challenges facing humanity in the 21st century. Currently, 1 in 9 people (821 million) are malnourished (FAO, 2018a). By 2050 the world's population is expected to reach 9.8 billion (UN, 2017). To lift people out of poverty and into the middle class, the availability of affordable, healthy and sustainable food is paramount (Lester et al., 2018b). Thus, the pressure to increase farmland or crop yields are enormous. The UN is calling for an increase in food production by 70% by 2050 (FAO, 2009; Hunter et al., 2017). However, with many regions such as Japan, South-East Asia and North Africa, having no additional agricultural land available (Bruinsma, 2003) and/or inadequate infrastructure (Iimi et al., 2015). In addition to projections of decreases in yield (Ray, 2013), increases in prices (Agrivi, 2019) and climate change concerns (United States Environmental Protection Agency, 2018), and the UN's forecast that aquaculture will need to supply an additional 40 million tonnes by 2030 to feed the rising world population (Manning and Hubley, 2015), the potential impact of sustainable ocean farming is significant.

Ocean aquaculture offers a space-efficient way to produce nutritionally valuable food (Lester et al., 2018b), at high yields/production (FAO, 2016) with ample space for scaling production (Li et al., 2019; Edwards, 2015). For example, seaweed, high in minerals, has 2 to 4 times the amount of fiber compared to various whole foods (MacArtain et al., 2007) and fish are a rich source of protein, essential amino-acids and minerals (Steffens, 2016; FAO, 2009; Rice and Garcia, 2011; Merino et al., 2012). Ocean aquaculture obviates the spatial requirements of more traditional land based or near shore aquaculture systems (Lester et al., 2018a; Welch et al., 2019) and should reduce conflicts with other ocean-user groups (Li et al., 2019; Manning and Hubley, 2015). Furthermore, ocean aquaculture may provide healthier harvests with lower environmental impact (Welch et al., 2019) with ocean currents continuously replenishing oxygen levels, feed and dispersing waste (Manning and Hubley, 2015), reducing the issues of infections, contamination and algae growth, widely experienced in lagoons and coastal water systems (Bruinsma, 2003).

1.2 Background

Current aquaculture practices include aquatic plants (e.g. seaweed), shellfish (e.g. abalone, oysters, prawns, mussels) and finfish (e.g. salmon).

1.2.1 Seaweed

In 2016 Aquatic plants were estimated to comprise of about 27.3% of the total world aquaculture production, totaling roughly 30 million tonnes (FAO, 2018b). Currently, China, Indonesia, Japan, North Korea, South Korea, and the Philippines account for 99% of worldwide farmed seaweed production (Roesijadi et al., 2008) with, for example both China and Indonesia producing over 10 million tonnes of seaweed each in 2014 (Buschmann et al., 2017). Although, historically South Asian countries have been the leaders in harvesting and consuming seaweed, the state of Hawaii has over 100 facilities and numerous technology companies specializing in seaweed production (Hawaii Department of Agriculture's Division of Animal Industry, 2019). Commercial practices in the US include Salt Point Seaweed (Salt Point Seaweed, 2019), and GreenWave who have developed a $30,000 open source model for seaweed and shellfish farming (GreenWave, 2019). Typically, seaweed is grown vertically from rope hung close to the surface between buoys just off the coast (NASA, 2015 and GreenWave, 2019), as illustrated in Fig. 1.

* Corresponding author

1.2.2 Shellfish

Marine and coastal aquaculture (i.e. aquaculture practiced in the sea) is dominated by the production of shelled mollusks, with a production of 16.9 million tonnes, compared to 6.6 million tonnes of finfish and 4.8 million tonnes of Crustaceans (FAO, 2018b). Typically, shellfish are farmed on either ropes or in meshed cages, as illustrated in figure 1.

1.2.3 Finfish

Although the global aquaculture production of fish food is estimated at 80.0 million tonnes, of which 54.1 million tonnes is finfish (FAO, 2018b), the production of finfish from marine and coastal aquaculture is estimated to be 6.6 million tonnes (FAO, 2018b). That is, inland finfish aquaculture accounts for 89.1% of total production, which may suggest that offshore finfish aquaculture has great potential if it can be safely and sustainably realized. While ponds, raceways and recirculating systems can be used for inland practices, open net pens and cages are used for coastal and offshore aquaculture, as illustrated in Fig. 1.

1.3 Challenge

Despite the potential impact of ocean aquaculture, most aquaculture systems are nearshore, and unsuitable for open seas (Li et al., 2019). Previous attempts of offshore ocean aquaculture, have been unsuccessful with loss of equipment and cultivation problems, attributed to the challenges of containing and protecting the system and harvest from the wave loads and current forces, including overcoming the difficulties in anchoring systems in deeper water (Troell et al., 2009; Manning and Hubley, 2015). Coupled with often lacking or underdeveloped institutional and regulatory frameworks for offshore aquaculture and public concerns over the environmental impacts (Troell et al., 2009; Manning and Hubley, 2015), there is currently uncertainty surrounding the proper and safe development of offshore aquaculture systems.

1.4 Paper Contribution

This paper presents two concept designs for offshore ocean farming, based on two collaborative group projects at the Stevens Institute of Technology (US) and the University of Southampton (UK). The first concept design focuses on externally farming seaweed and extending horizontally to maximize the waterplane area and the growing space (production). The second concept design focuses on internal hydroponic vertical farming, protecting the produce from the harsh marine environment, minimizing the waterplane area and the wave motions and loads, to exploit the available ocean volume.

The paper is structured as follows; a description of the projects and project briefs is given in section 2. The project results are presented in Section 3 which includes a review of the produce suitable for offshore ocean farming, a description of the proposed concepts and operation, and prototype testing results.

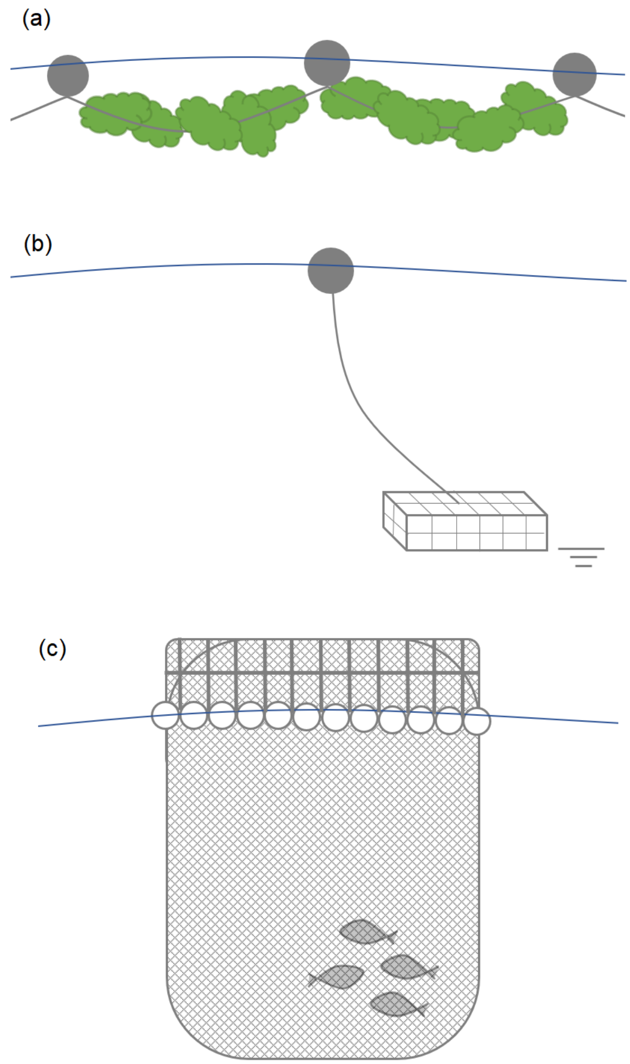

Fig. 1: Overview of current marine and coastal aquaculture practices ((a) Seaweed, (b) Shellfish, (c) Finfish)

2. THE PROJECTS

To explore offshore ocean farming two group projects were run simultaneously at the Stevens Institute of Technology (US) and the University of Southampton (UK).

The project at the Stevens Institute of Technology was run as a Senior Design project. A team project, consisting of five final year students from a mixture of engineering disciplines, run over 2 semesters with the requirement to design an engineering system, develop a business plan and build and evaluate a prototype.

Similarly, the project at the University of Southampton, was run as a Group Design project. A design project undertaken by 6 (in this case) final (4th) year Master of Engineering (MEng) students, and similarly consisting of students from different disciplines (and nationalities) including naval architecture and mechanical engineering.

The projects, investigating the engineering feasibility of offshore ocean aquaculture were given the brief "*By 2050 the world's population is expected to be 9 billion. So how do we feed an extra two billion people by 2050? Land is 2-dimensional and limited. The total amount of agricultural land is unlikely to change. However, the oceans cover ~70% of the earth's surface and have a depth (~4km on average). That is, there is plenty of space to 'farm'. This project aims to research and develop sustainable, engineering offshore ocean farming practice – designing, building and demonstrating an engineering solution to this global issue. The project will need to consider range of aspects and is open to new/novel/adventurous solutions. While the project is open, a clearly defined scope will be needed with the primary focus on the responsible/sustainable engineering challenges.*"

3. RESULTS

An overview of the design approach taken by both groups is summarized in Fig. 1. Initially, a review of the produce suitable for offshore ocean farming is presented in section 3.1, followed by the two proposed concept designs in section 3.1. Results from model scale prototype tests are given in section 3.3.

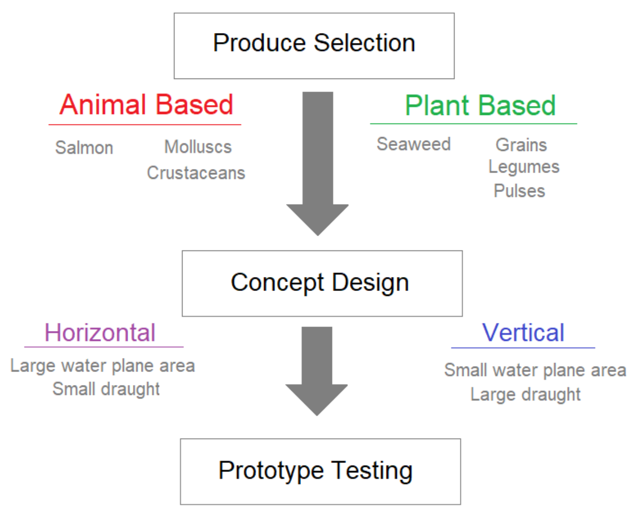

Fig. 2: Overview of the design approach

3.1 Produce Suitable for Aquaculture

The produce suitable for ocean farming can be broadly categorized as animals and plants, as shown in Fig 3. Traditional aquaculture practices include animal (e.g. shellfish and finfish and) aquatic plants (e.g. seaweed, kelp). However, theoretically the oceans could also be used to farm typical land crops such as lettuce and cereals, to alleviate the demand on arable land.

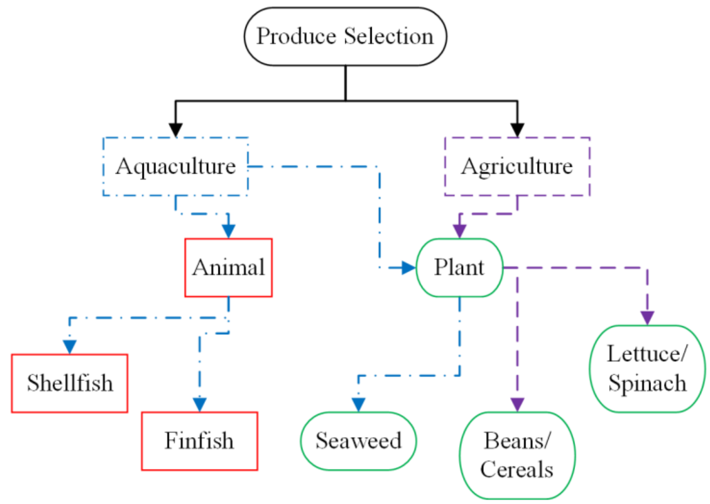

Fig. 3: Produce selection procedure

3.1.1 Finfish and Shellfish

Seafood contains high-quality protein and is low in saturated and unsaturated fat. For example, a 3-ounce cooked serving of fish or shellfish contains one-third of the RDI of protein (Seafood Health Facts, 2019). However, with varying food tastes across the globe, there is no universal fish or shellfish common through all cuisines. Furthermore, there are ecological concerns with finfish aquaculture practice, such as the risk of inadvertently introducing foreign species to the local ecosystem (e.g., by fish escape).

3.1.2 Aquatic plants

Aquatic plants, such as seaweeds are a rich source of minerals, dietary fiber, protein and antioxidants. For example, in terms of fiber, seaweeds have from 2 to 4 times the amount of fiber compared to various whole foods, such as brown rice, whole milk, green and brown lentils and bananas (MacArtain et al., 2007). Or in terms of nutrition, a single 8-gram portion of seaweed provides 10% of the recommended daily fiber intake (MacArtain et al., 2007). Seaweed has also been shown to lower cholesterol and with antimicrobial properties has a potentially long shelf life (MacArtain et al., 2007). While seaweed is traditionally part of Asian cuisine, it has seen recent success in the United States (Future of Fish, 2019; Salt Point Seaweed, 2019). However, seaweeds contain on average a ⅓ of the carbohydrates (energy) compared to whole foods (MacArtain et al., 2007) and there are concerns over metal absorption and the potential health implications if consumed (Pomin, 2012).

3.1.3 Conventional produce

The ocean space could also be used to farm conventional crops (e.g. grains, legumes, herbs, root and leaf vegetables) to alleviate demand on arable land. To avoid the necessity for soil, these crops could be grown hydroponically, which, based on a study comparing conventional and hydroponic lettuce production, could provide a 92% reduction in water requirements and 11-fold increase in yield (Barbosa et al., 2015). Albeit, requiring approximately 90 times the energy compared to the conventional farming (Barbosa et al., 2015). However, with the majority of the power demand required for temperature control (up to 82%

(Barbosa et al., 2015)) the insulation or temperature stabilizing effect of the oceans could reduce the power requirements significantly. That is, although initially appearing outlandish, an offshore hydroponic system to grow conventional crops may be viable.

3.1.4 Produce Selection

Comparing the produce and typical nutritional value, Table 1, the most valuable crop depends on the definition of value. For example, seaweed is not especially high in calories but is high in nutrients such as Calcium and Vitamin A. So for regions with micronutrient deficiencies this crop could be very valuable. Whereas, production of high protein produce in other regions may be more valuable e.g., offshore salmon farming in Scotland and Norway.

Table 1: Comparison of the aquaculture produce and nutritional value (per 100g serving). (USDA, 2019)

	Shellfish (Mussels, raw)	Finfish (Salmon, raw)	Seaweed (Seaweed, raw)	Beans/Cereals (Beans, lima, raw)	Lettuce/ Spinach (Lettuce, raw)
Energy (kcal)	86	127	38	113	14
Protein (g)	11.9	20.5	2.38	6.84	0.9
Total Fat (g)	2.24	4.4	0.26	0.86	0.14
Saturated Fat (g)	0.425	0.81	0.087	0.198	0.018
Fiber (g)	0	0	0.8	4.9	1.2
Sugars (g)	0	0	0.5	1.48	1.97
Calcium (mg)	26	7	91	34	18
Iron (mg)	3.95	0.38	3.85	3.14	0.41
Sodium (mg)	286	75	89	8	10
Vitamin C (mg)	8	0	11.2	23.4	2.8
Vitamin A (mcg)	48	35	68	10	25
Cholesterol (mg)	28	46	0	0	0

3.2 Concept Designs

To maximize the crop production, an offshore ocean farm can either be extended vertically (using the water column, exploiting the 3-dimensional space available) or horizontally (exploiting the available space) as illustrated in Fig. 4. Based on these opposing design philosophies, the group design projects developed and proposed two design concepts:

1. Externally farming seaweed and extending horizontally to maximize the waterplane area.
2. Internally hydroponically farming, protecting the produce from the harsh marine environment, extending vertically, minimizing the waterplane area.

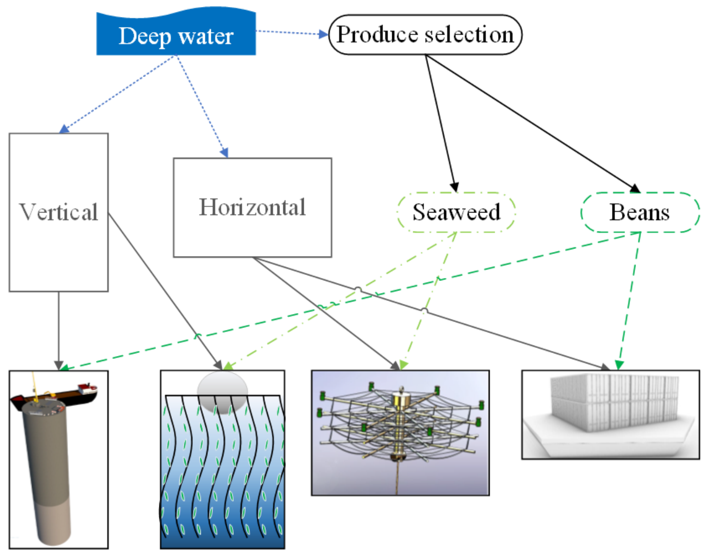

Fig. 4: Concept design selection

3.2.1 Concept 1: A Seaweed Farm concept

To grow seaweed in the deep ocean, a scaffolding system threaded with pre-seeded nets was proposed. This system must be sustainable and self-sufficient, an overarching design scheme was established with this purpose in mind. The farm consists of multiple growing units, each unit will have eight arms with a diameter of 10.7 m in five different layers. The top layer will be fitted with wave energy generators, the system electronics will be housed in the central cylindrical hub at the free surface, as seen in Fig. 5.

The system will collect data regarding the current growing conditions such as water pressure and temperature. The pressure is used to determine accurate depth, as the farm may need to temporarily submerge to avoid rough weather or to maintain optimum water temperature for seaweed growth. The growing cycle for seaweed depends on the species and may vary slightly depending on the weather and local growing conditions. Camera monitoring will take place from the central vertical shaft, see Fig. 5, to more accurately determine when the harvest should take place and to monitor the structural health of the system. The data collector is capable of collecting information about the water conditions, is low powered such that a wave energy harvester can power it and can transmit data to a remote server.

The system must be self-sufficient, and the required power is generated by eight wave energy generators fitted at the end of each growing arm (green cylinders in Fig. 5). The power generators must be able to operate in very rough weather with minimum downtime.

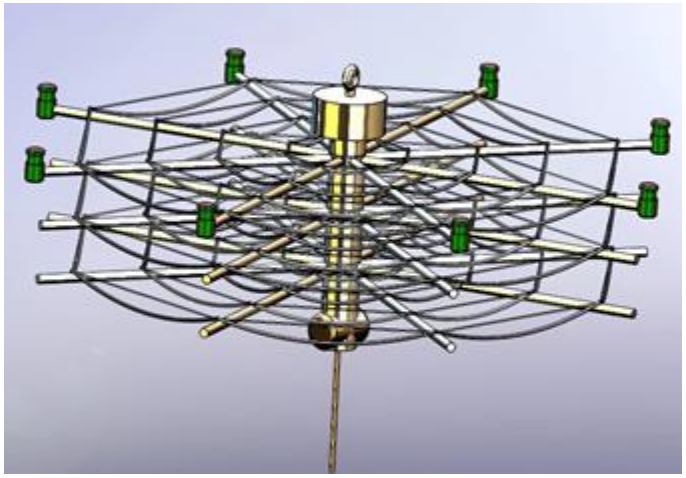

Fig. 5: Proposed Concept Seaweed Farm

3.2.2 Concept 2: A hydroponic farm concept

To grow conventional crops offshore (e.g., common beans, spinach, herbs depending on the market), a hydroponic ocean spar farm structure was proposed. The proposed steel spar structure, illustrated in Fig. 6 and 7, has a diameter of 24 m, a height of 98.4 m and a total mass of 44408 tonne and displacement of 43325 m^3. The spar structure contains 20 harvest levels (equivalent to 290 containers) of area 423 m^2, with a harvest area of 288 m^2 (or 68% area utilization) per level (after accounting for walkways, pumps and piping).

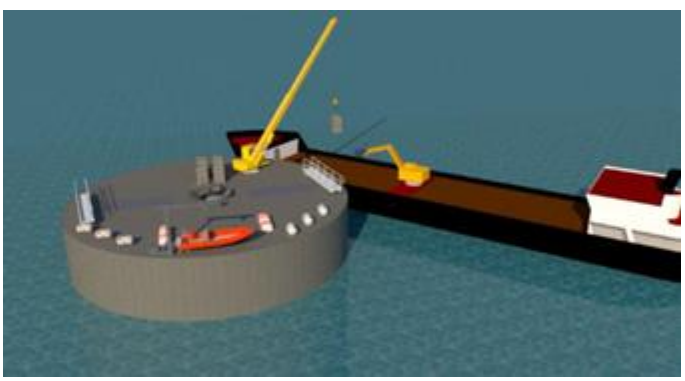

Fig. 6: Top deck of the proposed deep hydroponic farm

The hydroponic fluid created by mixing plant nutrient and freshwater is pumped around the farm. To take advantage of the relative height, the freshwater tanks (and diesel tanks) are located above the harvest levels on the tank deck, see Fig.7. The nutrient depleted fluid is then desalinated and recycled back into the freshwater tank.

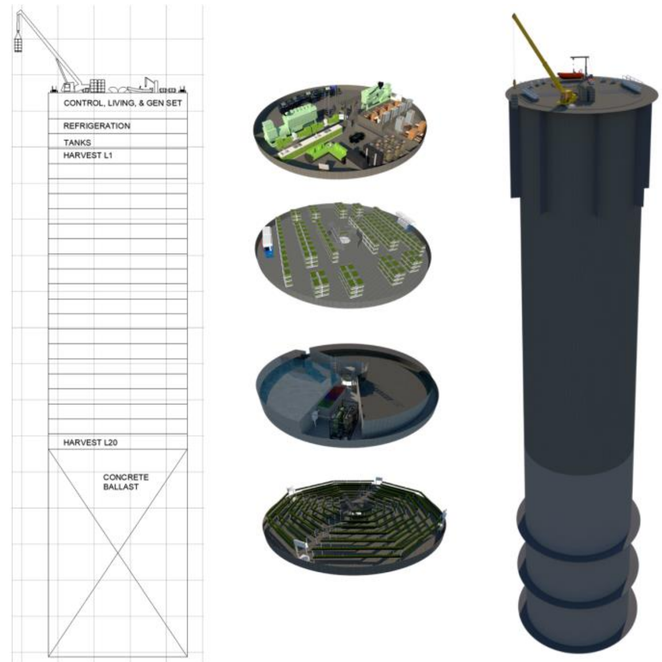

Fig. 7: Proposed hydroponic spar ocean farm (Left: general arrangement. Middle (from bottom): harvest deck, tank deck, refrigeration deck, accommodation. Right: spar rendering showing the weather deck).

A refrigeration deck is used to store the harvested crops prior to transportation whereby a 15 m 3 tonne crane would be used to load boxes of crops onto pallets through one central hatch (alongside two maintenances hatches). Although the operation could become autonomous, initially a manned system is considered, with an accommodation level including a control center, galley, mess and laundry spaces located on the top deck. The crew would use an extendable gangway to access the spar and two HVAC systems would service the refrigeration deck and accommodation deck.

3.3 Prototype Testing

To assess the two concepts, scaled prototypes were manufactured and their seakeeping properties were evaluated at the University of Southampton Towing Tank and the Davidson Laboratory Towing Tank at Stevens Institute of Technology.

3.3.1 Seaweed farm

A 1/7 scale prototype was constructed to be tested in the Davidson Laboratory Towing Tank. The prototype has a pressure sensor, temperature sensor, and rotating camera on a physical structure with four arms, as seen in Fig. 6.

The shaft and arm design was constructed out of PVC piping and connected using a two-part epoxy to ensure a watertight seal. The aluminum hub was custom designed, machined, and sealed using a silicone adhesive. Initial testing showed that the system was too buoyant, and a ballast weight of nine kg was added around the central shaft, below the lower level arms.

The electrical components of the sensor suite were coded using a 1010 MKR Arduino and powered with a rechargeable battery pack. A temperature and pressure sensor were utilized to collect data on the conditions to ensure ideal water conditions to grow and harvest seaweed. A motor was added to power a 360-degree rotating camera to document and monitor the growth of seaweed underwater.

Fig. 6: Prototype shaft, arm, and hub assembly

The motions of the system can be captured both by mounting a wire spool to the towing carriage and recording the Response Amplitude Operator (RAO) and by utilizing an Inertial Measurement Unit (IMU) fitted inside the aluminum hub. Further testing of the prototype will be undertaken during the summer of 2019, focusing on obtaining the prototype RAO.

3.3.2 Hydroponic farm

To evaluate the seakeeping performance of the hydroponic ocean farm concept, a series of 1:120 model scale experiments were conducted at the University of Southampton Towing Tank (dimensions L=138m, W=6m, D=3.5m) in regular waves, over a range of frequencies (0.6Hz to 1.0Hz in 0.1Hz increments) and wave heights (0.04m to 0.08m). The 1:120 model spar (height 0.8m, diameter 0.2m, displacement 25.7kg), illustrated in Fig. 7, was made of discs of foam around an internal aluminum box-section structure (for housing ballast weights). The (6DOF) motions of the spar were measured at 100Hz using a video motion capture system (Qualisys). In total 5 sea states were tested, as summarized in Table 2.

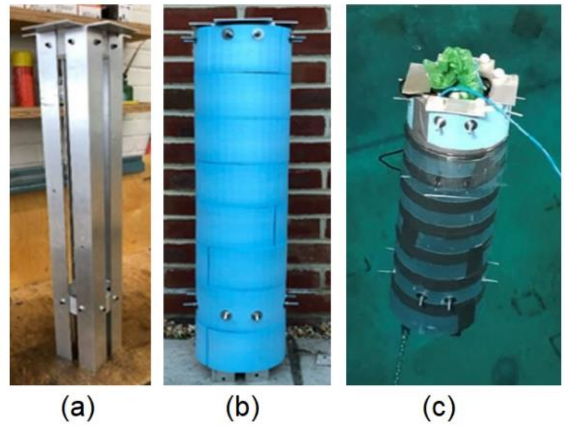

Fig. 7: Experimental model spar (a) Aluminium core (b) Assembled 1:120 model spar (c) Model spar in the tank

Table 2 Model and equivalent full-scale regular wave frequencies and heights investigated

Model Scale		**Equivalent Full Scale**	
Wave Frequency [Hz]	Wave Height [m]	Wave Frequency [Hz]	Wave Height [m]
0.6	0.04	0.055	4.8
0.7	0.05	0.064	6
0.8	0.06	0.073	7.2
0.9	0.07	0.082	8.4
1	0.08	0.091	9.6

The heave and pitch responses of the moored spar were found to be regular and oscillate at the wave frequency. The heave and pitch RAOs presented in Fig. 8 are relatively low compared to RAOs for similar structures (United States, 2013) with the greatest response occurring at the lowest investigated wave frequency. Estimating the spar's natural heave frequency (ω_{*3}) as:

$$\omega_{*3} = \sqrt{\frac{c_{33}}{m + a_{33}}}$$

and assuming $a_{33} \approx m$ and $c_{33} = \rho g\, S_{wl}$, where m, a_{33}, c_{33} and S_{wl} represent the mass, added mass, hydrostatic restoring coefficient in heave and the waterplane area, respectively. The ω_{*3} is estimated to be 0.036Hz. This equates to a 27 second period, sufficiently outside the range of expected sea states.

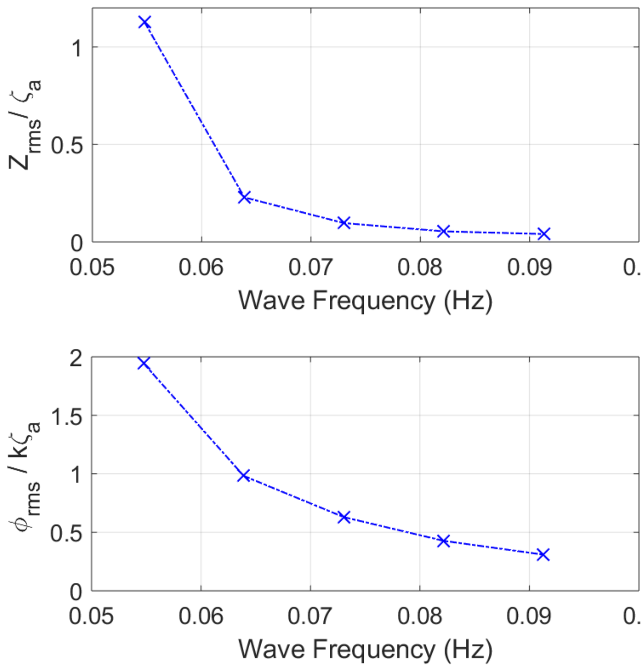

Fig. 8: Heave and pitch response of a single, moored spar in regular waves (full scale)

As shown in Fig. 9(a) the spar surge motion was found to exhibit a slow time-varying motion in addition to an oscillatory motion at the wave frequency. Applying a high pass filter the magnitude of the oscillation at the wave frequency was found to decrease with increasing wave frequency (Fig. 9(b)). While the slow time-varying motion could be attributable to mooring line interactions, as no discernable trends were identified this remains an area for future research. Similarly, as shown in Fig. 9(c), a slow time-varying sway motion was also observed. This suggests that, in addition to mooring line interactions, the spar may also experience VIM.

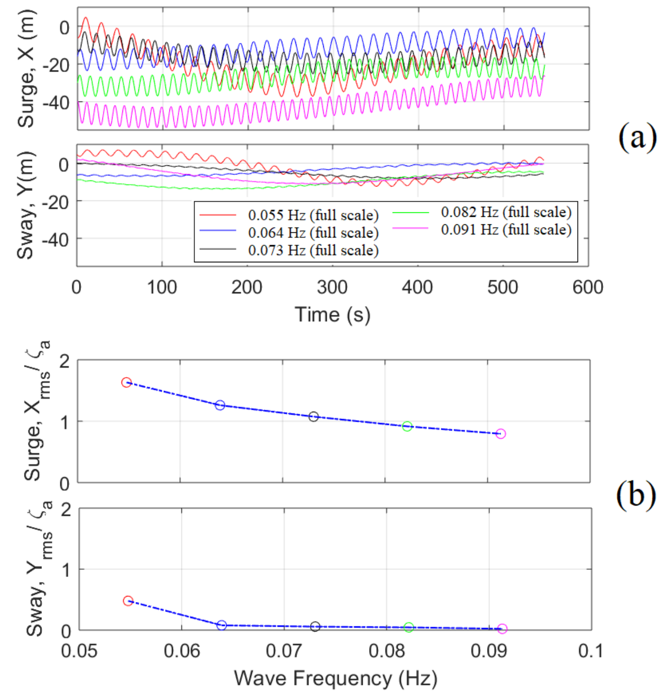

Fig. 9: Surge and sway response of a single, moored spar in regular waves ((a) Time histories (unfiltered) (b) High pass filtered non-dimensional response ($f_{cut} = 0.0456Hz$)) (Full scale)

To quantify the power required to heave the spar, an instantaneous power ($P_z(t)$) based on the kinetic energy (E_k) of spar's heave motion ($\dot{z}$) was calculated as;

$$P_z(t) = \frac{E_k(t)}{dt} = \frac{1}{2}\frac{m\,\dot{z}^2(t)}{dt}$$

As shown in Fig 10, the rms power associated with the heave motion is significant. Although not representing the available or harvestable power, this finding suggests that the application of wave energy recovery could be used to recovery energy and power installed systems, reducing energy costs, improving the operational capability and potentially enabling self-sufficient or autonomous operations. However, further research is needed.

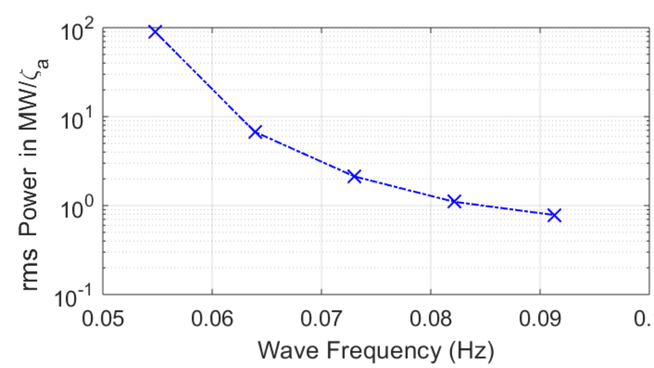

Fig. 10: Power associated with the heave motion of the spar (Full scale)

4 DISCUSSION & FUTURE WORK

The potential impact of sustainable ocean farming is significant; the High Seas cover 50% of the earth's surface and thus represent a giant potential for food production (Ocean Unite, 2019). Ocean aquaculture offers a space-efficient, high yield production with ample space for scaling, and can thus help to address the global challenge of feeding the world's growing population. However, the development of offshore aquaculture systems is in its infancy.

To address this, this paper presented two concept designs for offshore ocean farming, based on two collaborative student group projects at the Stevens Institute of Technology (US) and the University of Southampton (UK). While the success of offshore ocean farming will depend on multiple factors e.g., produce demand, nutritional value, local infrastructure, regulations, local economies and finance. Given the wide variety of produce (ranging from finfish, shellfish, seaweed and potentially hydroponic grown crops) that can be produced offshore, it is unlikely that there is an optimal, single design. It is anticipated that a mixture of solutions/designs will be needed to cater for varying markets and acceptance of technology and produce.

While this study has explored two concepts, the engineering challenges associated with offshore operations are vast and to realize offshore farming much remains to be investigated. For example, to scale production, arrays of moored farms are envisioned which will require the effect of wave loads (seakeeping) on unconventional floating structures and the mooring and array interactions to be identified. In addition, further research will be needed to assess the feasibility of autonomous operations and energy harvesting for improving safety and reducing costs of offshore ocean farming.

5. CONCLUSIONS

This paper discussed and presented concept designs for offshore ocean farming, based on collaborative group projects between students at the Stevens Institute of Technology, US and the University of Southampton, UK.

The work highlights the huge impact sustainable offshore ocean farming will have and the engineering challenges that remain to achieve this ambition.

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