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New system design for the cultivation of extractive species at exposed sites - Part 1: System design, deployment and first response to high-energy environments

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ABSTRACT

The purpose of this publication is to perform a system analysis of new cultivation technology for exposed bivalve farming. The technical feasibility of the new construction, called *Shellfish Tower*, was assessed. The device has gone through several very different phases of development on its way to the deployment of the prototype. These included multiple iterations during the designing stage, wave tank testing, fabrication, loading and unloading on trucks and vessels, deployment at sea, installation and assembly on the single mooring line, and bring it to its final position in a submerged mode 5m-10 m below the water surface. The final structure has a hexagonal body, with a centrally orientated variable buoyancy unit with culture sub-units on each of the six corners. These sub-units can be used for the culture of oysters (*Magallana gigas* – formally *Crassostrea gigas*) as well as for the collection of mussel spat (*Perna canaliculus*). Other possible candidates could be seaweed, lobsters, sponges or tunicates. The operational depth of the whole system can be at any depth but was tested at between 5 and 10 m below the water surface positioned on the mooring line between the screw anchor and surface floats for the prototype tests. The system was deployed in March 2019 six nautical miles off the Bay of Plenty, North Island (New Zealand), in exposed waters near a commercial mussel farm and has been in test mode since then. The modelled structure indicates a design tolerance of significant wave height of over 7 m and currents of over 0.8 m/s. Initial results show that the new design has survived waves at 4.6 m significant height and current velocities of up to 0.7 m•s^{-1}, while showing best growth conditions of the cultured oysters as well as for the spat settlement of juvenile greenshell™ mussels.

1. Introduction

New Zealand is well known for its aquaculture of greenshell™ mussels (*Perna canaliculus*), which started in the late 1960s and has grown since to a significant economic sector with approx. 100,000 tons of mussel production in 2017 (FAO 2020). Today, mussel farming predominantly takes place in nearshore or inshore sheltered environments. Only a few farm operations have started to consider or extend into more exposed and remote sites of up to 10 km from the coast, such as in the Bay of Plenty and Hawke's Bay (North Island) as well as at Pegasus Bay, D'Urville Island and in the Cook Strait (South Island) (Government, 2017).

Traditionally, the mussel industry produces mussels on a continuous mussel production rope referred to as a *longline* (Dawbar, 2004; Hickman, 1992; Buck, 2007; Cheney et al., 2010), (Fig. 1). This longline is suspended from two parallel surface ropes called *backbones* (or

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collectively a *double backbone*), which are held 1.3 m apart by multiple 300 L floats that are intermittently spaced along the backbone length. The continuous longline is suspended from the double backbone using short ties called strops to form *dropper lines* upon which mussel crop grows. These strops are usually spaced 50 to 70 cm apart. This design has since been modified for more exposed sites to a single submerged backbone with smaller intermittently spaced subsurface floats (90 L) and larger 300 L surface floats which are tied to the backbone using longer strops (Fig. 1) (Buck and Langan, 2017). This modified design keeps the crop portion of the structure submerged, away from high-energy surface waters.

Mussel spat is either caught wild on longlines, harvested from seaweed that has been washed up on the beach at Ninety Mile Beach, (Alfaro et al., 2004)) or, increasingly, is hatchery-produced (SPATNZ LTD (SpatNZ 2013)). At present, seaweed-based spat is by far the most prevalent. Washed-up seaweed is placed on spat longlines and covered with a cotton stocking. After 4 to 8 weeks, a percentage of the spat moves onto the spat longline, the stocking rots away and releases the seaweed leaving the mussels to continue grow on the dropper lines.

One issue with this method of spat harvest is that the arrival of spat on beaches is sporadic and unpredictable. Hatchery-produced spat can offset this uncertainty as well as allow for selective breeding. However, there are too few hatcheries in New Zealand to produce sufficient spat for industry requirements. Until more hatcheries are constructed, an alternative to hatchery-produced and seaweed-based methods is the increased collection of spat at sea. Catching wild spat on longlines at sea could help meet the demand for mussel spat in New Zealand. However, it is believed that the spat catching technology and methods currently in use can be improved, particularly for exposed sites.

The New Zealand Government believe there is potential for a five-fold increase in annual aquaculture sales by 2035 (New Zealand Government Aquaculture strategy 2019 (Ministry of Primary Industry NZG 2019)). Species showing the greatest potential for increased production are greenshell™ mussels and pacific oysters (Heasman pers obs) which had a production of 97,462t and 14,180t respectively in 2018 (AQNZ 2020). Expanding aquaculture of these species into fjords, bays and other near-shore areas is becoming increasingly difficult due to the increasing pressure of multiple stakeholder overlap (Buck et al., 2008), (Cheney et al., 2010), (Heasman et al., 2020). Heasman et al. (Heasman et al., 2020) believe the best way to expand the New Zealand aquaculture sector is by extending current aquaculture activities into the exposed offshore waters of the New Zealand EEZ. This area presents demanding physical, oceanographic and biological conditions. The well-known farming technology that has been developed for protected areas cannot simply be copied and extended into these sites. Innovative, robust systems and mooring designs that can be submerged during high-energy storm events must be developed. For this reason, New Zealand Ministry of Business, Innovation and Employment (MBIE) has financed a project led by the Cawthron Institute, to develop new technologies that meet these conditions (Heasman et al., 2020). The main objective, amongst several other targets, is to develop a farm design that can cope with up to 7 m 11 s waves and 0.8 m/s current velocities while allowing easy deployment, operations and management (O&M), and harvesting.

With such demanding requirements, it was questioned how designing a new system of offshore aquaculture technology could be tackled. Current literature on how to effectively stream-line such design process is scarce, with little guidance as to how the design should be led and which requirements to prioritize during the respective technology readiness levels. At present, example technology design processes and guidance are insufficiently illustrated in literature to facilitate future developments. Buck and Lagan (Buck and Langan, 2017) described the development process of an offshore mussel longline connection that can be attached to existing monopiles and a sample tripod. These authors used a combination of numerical modelling, field testing in a highly-energetic environment (North Sea), and analytical modelling to achieve their development goals. In a recent review of feasibility studies focusing on ocean multi-use concepts, Dalton et al. (Dalton et al., 2019) describe the development of a submersible fish-cage electrically supported by a novel wave energy converter device, and summarize financial and technological benefits of multi-use concepts. The early design phases of a combined aquaculture fin-fish farm sustained by wave energy are described by Lagasco et al. (Lagasco et al., 2019) who have targeted (i) expected nominal fish production, (ii) pollution minimization, and (iii) maximization of electric energy of their device as design goals for open ocean conditions. Goseberg et al. (Goseberg et al., 2017) have also used case studies to elucidate on requirements for designing aquaculture technology in severe offshore conditions, advocating multi-use concepts, yet without clearly outlining the required procedural design steps to approach the demands prescribed by high-energy environments.

The literature reviewed above contained valuable aspects of the procedural design chain and technological development of sub-components, and examples of site-selection (Benetti et al., 2010), control engineering technology development (Kim et al., 2014), offshore potential analysis (Cheney et al., 2010), experimental investigation on aquaculture technology elements, such as netting drag forces (Lader et al., 2007) or monitoring telemetry devices for operations and maintenance applications (Irish et al., 2004) can be found. It is however still difficult to provide a clear pathway and recommendations to practitioners, technology developers and academics that facilitates the design process from the first idea to a prototypical device out in the sea.

In this work, we hence present a new system design and its design process. This system has been designed for specific offshore conditions and is suitable for the collection of greenshell™ mussel spat and oyster cultivation at offshore sites. The system has easily tolerated exposed

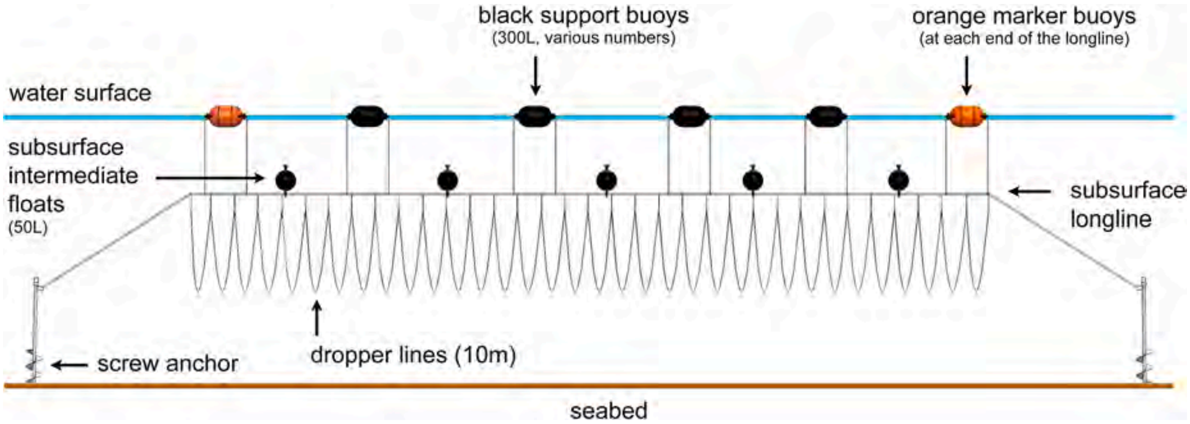


Fig. 1. A diagram of submerged mussel ropes currently used in open ocean aquaculture in New Zealand.

conditions and has shown to support good growth rates and production of the tested candidate species. This system is commonly referred to as the “*Shellfish Tower*”. This novel work is the first part of a two-part publication intended to provide a holistic picture of the design process and technological development, stimulated and enriched by various disciplines.

2. Materials & methods

The considerations and subsequent construction of a first prototype were preceded by an iteration process that started with a workshop involving engineering scientists, marine biologists, aquaculture researchers, modelers and representatives from the mussel farming industry. At this workshop, several new designs were discussed of which the *Shellfish Tower* was one. The construction process, in which we translate design into physical reality, requires important steps of planning, engineering, management, and verification. The following outlines these steps.

2.1. Conditions at the test site

The site where the new structure was moored (S 37° 53.410 - E 177°16.299) is in the licensed area of an existing offshore mussel farm (Whakatōhea Mussels [Ōpōtiki] Ltd.) approximately six nautical miles seaward of Ōpōtiki, Bay of Plenty (Draughting 2018) (Fig. 2A-B). This mussel farm is 3700 ha in extent and consists of 12 individual farming blocks of similar size, which are (or will be) equipped with 82 mussel longlines of up to 150 m in length running perpendicular to the coast (Fig. 2C). Blocks populated with mussel lines have backbones spaced approximately 50 to 100 m apart. The prototype structure was deployed in the centre of this mussel farm (point 1, Fig. 2C) and the monitoring buoy was installed nearby (point 2, Fig. 2C). Deploying the structure within an existing operational mussel farm made the deployment, surveillance and servicing of the new device much easier. Furthermore, since the farm is operating in exposed waters, the mussel farm equipment (seaworthiness of the service vessel, crane, etc.) and its operations and management is already adapted to the exposed conditions.

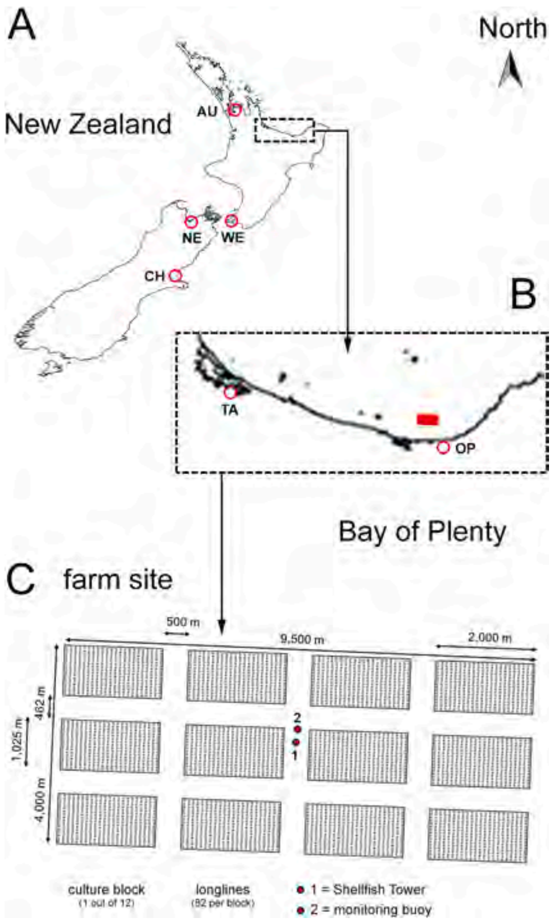


Fig. 2. Location of the experimental site. (A) Map of New Zealand with an inset (B) showing the Bay of Plenty including the offshore mussel farm (red square, not to scale); (C) shows the layout of the mussel farm as well as the location of the *Shellfish Tower* and the measuring buoy. AU = Auckland, CH = Christchurch, *N* = Nelson, Op = Ōpōtiki, *T* = Tauranga, *W* = Wellington. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In July 2018, a monitoring buoy was deployed at the identified test site (depth of 45 m, 6 nm from the coast in the middle of the farm area Fig. 2C) and has been continuously recording data, which are transmitted to the Cawthron Institute via telemetry. The data recorded includes: Current velocity, wind velocity, wave height, wave direction and wave period, surface temperature, weather conditions (air pressure, air temperature); buoy motion (pitch and roll).

Water currents in the Bay of Plenty are a consequence of eddies borne from the interaction of the East Auckland Current with East Cape (Stevens et al., 2019). They are largely non-tidal, highly variable and sensitive to wind conditions (Longdill et al., 2008; Chiswell et al., 2015). Current velocities were measured at the test-site using a downwards-facing acoustic Doppler current profiler (ADCP) mounted to the monitoring buoy; (point 2, Fig. 2C). Based on data recorded from July 2018 to April 2019, the net flow over the entire water column is along the NE-SW axis (54 °T) with slight bias in the NE direction (53% of the time). Current velocities at the site vary with depth (Fig. 3a). At the depth range of the deployed prototype (described subsequently, −5 to −20 m), current speeds were slightly lower and 25° further anti-clockwise (29 °T or NNE-SSW) relative to the entire water column (Fig. 3b). Speeds at this depth remained below 20 cm/s for 93% of the time and below 30 cm/s for 99% of the time. The mean speed at this depth was 9.5 cm/s and the mean of the fastest 1% of recorded current speeds was 34 cm/s.

Wave data measured over the same time period and at the same location (point 2, Fig 2C) are presented in Fig 3C. Measured waves were predominantly of NW-origin with significant wave height lower than 2 m during 94% of the time and lower than 3 m during 99% of the time. The highest recorded significant wave height during the year-long period was 4.6 m. Approximately 20% of the waves recorded by the monitoring buoy were of SE-origin although these waves all have small significant wave height (mean $H_s = 0.21$ m).

2.2. Planning conditions and prerequisites

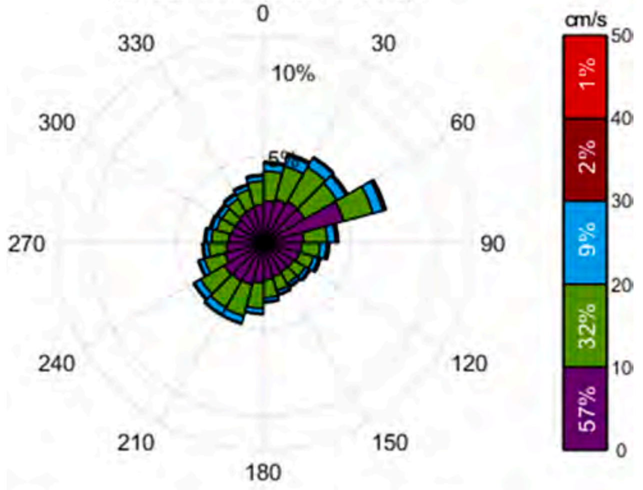
The planning of new innovative designs is not about modifying existing systems to make them suitable for use in exposed sites by using thicker ropes and larger screw anchors. Open ocean aquaculture requires a revolution of farm designs, not an evolution of existing concepts (Landmann et al., 2020). The following were considered essential or high priority aspects that should be incorporated into the new design, we call these the primary design attributes:

P1 Robustness: The system and its mooring(s) must be able to withstand worst-case storm conditions. If the system is not sufficiently robust, the system is useless.

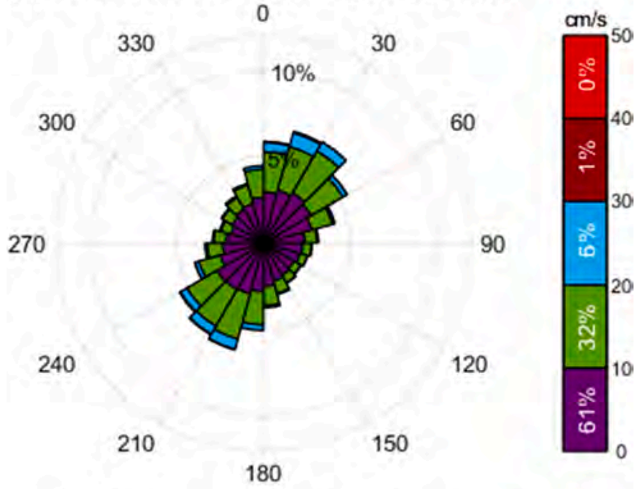
P2 Simplicity and ease of use: The system should be made as simple to operate as possible during all stages of its life-span: mooring, normal operation, inspection, maintenance and harvest. This will necessitate less additional specialist equipment (e.g. special vessels) and reduce operational expenditure (e.g. fewer divers).

P3 Economics: The new system must be economic. The size of the structure must be balanced against the cost to manufacture and ease of handling (P2). Space should be carefully used to maximise return of

(a) Current rose (all depths)



(b) Current rose over depth-range of prototype



(c) Wave rose (significant wave height)

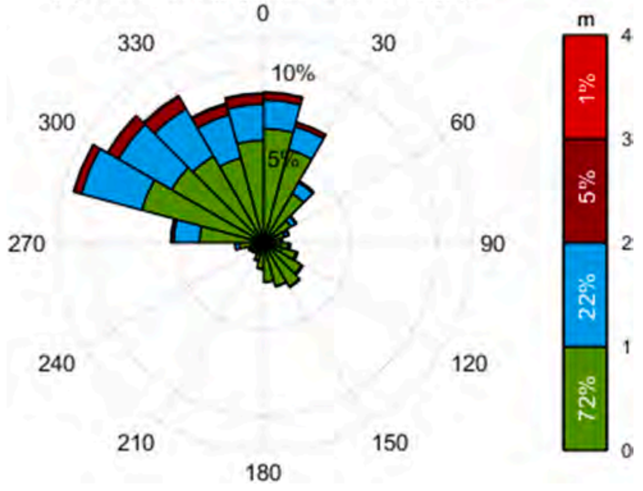


Fig. 3. (A) Current conditions (velocity in cm/s), throughout water column (B) current conditions (velocity in cm/s) over deployment depth of prototype and (C) Significant wave height (H_s in m) and wave direction at test site. Note that directionality of currents is in the ‘going to’ sense while wave direction is given in the ‘coming from’ sense.

investment.

P4 Diversity: The system should be able to be deployed in a diverse range of environments and be capable of farming a diverse range of species (e.g. shellfish, crustaceans, seaweed). This will make the system widely applicable as well as resilient to environmental change.

The following were considered desirable but non-essential to the design of the device. We term these secondary design attributes.

S1 Smart: the system should incorporate new materials and technology where possible.

S2 Optimised husbandry: The system should provide husbandry conditions that optimise the cultured species’ health and growth.

2.3. *Iterative design process*

The iteration process this design went through is described in detail in Tab 1 below. When relevant, the design attributes listed above are referred to in brackets. We believe the individual development steps and reasoning behind them can inform the reader on how the final design was reached and assist future developments, be they adaptations of this system or completely novel. Table 1 and Fig. 4 detail the eight sequential design iterations of the device. Versions 6 to 8 were subsequently investigated using lab-scale wave and current tests at the Leichtweiß-Institute for Hydraulic Engineering and Water Resources, Braunschweig, Germany as well as the Ludwig-Franzius-Institute for Hydraulic, Estuarine and Coastal Engineering, Hannover, Germany where it underwent current-alone, wave-alone and wave-current testing at scale. More information regarding this process and subsequent results are provided in (Landmann et al., 2020) (*this issue*).

2.4. *Design and use of sub-units of the final shellfish tower version*

For the *Shellfish Tower*, different sub-units were planned to address the requirement of Multiple species production from the same main structure. Each sub-unit can rotate about its own central axis using water-lubricated synthetic bushes. This allows for a greater amount of each sub-unit’s surface area to be exposed to incoming currents as well as allowing for easier O&M, seeding and harvesting. Each of the species candidates have different biological and culture requirements. The sub-units are designed in a modular way to give the farmer freedom of diversity over which species they cultivate depending on site conditions, market preferences, season and risk.

Fig. 5 shows the design of the two primary sub-unit types. The cylindrical unit (Fig. 5) is targeted at the collection of mussel spat on coil/rope but could also be used for the growth of macro-algae on pre-sown linen. Lines can be wrapped around the sub-unit and harvested when and as required. Mussel spat could also be collected on the square units (Fig. 5). For this purpose, cultivation frames, which are wrapped vertically with collection rope, are inserted into two boxes designed to hold the frames. Each frame box can be inserted into the sub-unit and stacked one above the other. The frame boxes are designed to easily slide into and out of the sub-unit. Once spat catching is complete, the *Shellfish Tower* can be brought to the surface and the frame boxes can then be removed and placed into onboard aerated tanks to keep the spat in good health. Oyster baskets can also be inserted into the square sub-units (Fig. 5 left) and held in place with vertical rods. When the *Shellfish Tower* is brought to the surface and lifted into a horizontal position, the oyster baskets (which have their openings at outward-facing end) can be easily harvested by rotating the sub-units causing oysters to fall out into receptacle tray placed underneath. Methods to facilitate the vertical or horizontal harvest of the *Shellfish Tower* on or next to a vessel are being developed.

To complete the selection of possible candidates, a curtain of young sporophytes could be wrapped around the cylinders instead of the spat line. In this way, at least the young algae could better develop their holdfasts in the current, develop a streamlined structure and thus not be detached so easily due to adaptation (Buck and Buchholz, 2005).

Table 1
Structure analysis on the iteration process of the development of the *Shellfish Tower*.

Table 1 (*continued*)

Current Fig. 3	Conceptual and technical considerations
V. 1	This first device (V1) was rectangular with a vertical long axis. It was connected to a single mooring that ran through its centre (P2). Like a spar buoy, all the device's floatation was at the top end, which kept it floatation stable (P1). The top float could house a combination of water and air which could be adjusted to increase/decrease buoyancy when required (S2). The device could be submerged to any depth (P1, P4, S1, S2). It was designed to be pushed over and deeper during storm events thus reducing its exposure to high energy near-surface conditions (P1). The internal section was left open to house oyster cages or, alternatively spat line could be wrapped around the outer edges (P4). Issue 1.1: The unit appeared weak and required reinforcing Issue 1.2: Having the floatation closer to the waves at the top made the upper part of the structure more responsive compared to the rest of the structure Issue 1.3: The base, where the rope meets the structure, was identified as a wear point Issue 1.4: The top float would act like a drogue in high currents, compounding the issue of high wave energy with high current energy Issue 1.5: All the floatation is contained in a single sector – there is no redundancy
V. 2	Design V2 retained the rectangular shape of V1 but shifted the floats to the entire length of the vertical corner pillars to address Issues 1.2, 1.4 and 1.5 (P1) of design V1. Issue 1.1 was addressed by adding reinforcing bars to the bottom half of the system. There were considerations to reduce the buoyancy bodies by half and increase their diameter, but our basic analysis suggested no increase in floatation stability. Even if the full-length floats on each corner pillar were reducing stability, resulting in a very high amount of movement of the structure. It however caused the unit to flip onto its side at the surface, which had O&M benefits (P2). Design V2 was meant to house oyster cages internally between the four corner floats while also allowing for the spat line to be wrapped around the outside of the whole structure (P4). This would have to be done such that enough water could still flow through the spat lines to feed the interior oyster crop (S2 Issue 2.1: Wrapping and un-wrapping the spat line would be difficult which presents problems when trying to service the oyster crop i.e. the spat rope would need to be unwrapped and rewrapped every time. Issue 2.2: The added reinforcing took up a considerable portion of the internal section used for oyster cages resulting in lower productivity as well as creating O&M difficulties. Unresolved Issue 1.3: Wear-point for mooring still present
V. 3	The next device's floats were elongated to extend the full height of the device and extensions were added to all four corners. The lower reinforcing of V2 was removed (resolving Issue 2.2) and circular discs on the inside were added which can hold oyster trays (P3) and add additional strengthening components to the device (P1). The extensions of the corners increased the length of spat line that could be wrapped around the outside (P3) while simultaneously providing protection for the oyster trays within (S2). Iteration V3 was designed to allow for easy harvest of the oysters (P2): the whole unit can be lifted from the water and turned 90-degrees (such that the buoyancy units are horizontal). The inner-circular section can then be rotated on-deck causing oysters to fall out of their trays into a receptacle tray. Issue 3.1: Design is less stable than V2 Issue 3.2: Large amount of unused space Unresolved Issue 2.1: Accessing oyster cages through spat line is difficult. Unresolved Issue 1.3: Wear-point for mooring still present.
V. 4	Design V4 shifted to a single conical float running longitudinally along the central axis. The conical shape was chosen to address Issue 3.1 – it provides more buoyancy at the top than the bottom end which gives it more stability (P1). Four (4) rotating rectangular sub-units were added to the corners of the system. Each sub-unit rotates about a central longitudinal axis and can accommodate spat line and/or be used to store oyster trays (P4). The sub-units were made to rotate to both expose all sides of the sub-unit to water currents (S2) as well as permit easy access (resolving Issue 2.1) for inspection, maintenance, and harvest (P2). These sub-units could potentially be accessed (i.e. for cleaning) without having to remove the entire structure from the sea. The addition of these sub-units increased the productivity of the structure as a whole (P3) by utilising more of the unused space present in V3 (Issue 3.2). Moving floatation to the centre of the structure and production to the outside greatly improved usability while also protecting the float from piercing (P1). In addition, this design also allowed for a modular build, meaning a flat pack structure when dissembled, requiring less area to store, and allowing for easier transport (P2). Issue 4.1: No redundant buoyancy Issue 4.2: The conical float would likely be difficult and expensive to manufacture. Unresolved Issue 1.3: Wear-point for mooring still present.
V. 5	To address Issue 4.2, the float was returned to a constant diameter cylindrical design (P3). This cylindrical float could provide some strength to the device (P1) thus removing the need for some of the additional reinforcements present in V4 (P3) that interfered with the rotating sub-units (P3). This addition also meant the structure would float horizontally when brought to the surface which would make it easier to work on the device for maintenance or harvest (P2). To increase productivity, the sub-unit axes of rotation were moved outwards to each corner allowing for large sub-units (P3). Issue 5.1: Reduced stability due to increased size of sub-units Issue 5.2: Sub-units cannot fully rotate? Unresolved Issue 4.1: No redundant buoyancy Unresolved Issue 1.3: Wear-point for mooring still present.
V. 6	To resolve Issue 5.2, the width of the sub-units was reduced to prevent clashing with the main structure. Issue 5.3 was resolved by proportionally increasing structural support and decreasing sub-unit size. A middle ground was found by moving the sub-units' central axes halfway between the edge of the main structure and the central float. This added protection for the sub-units within the main frame without compromising the total volume for production (P1, P3). To reduce weight (P2, P3), the central axis of the sub-units were removed and replaced with small pins on the top and bottom to hold the sub-units in place. This weakened the structure at the sub-unit locations. To compensate for this, the sub-units were fixed in place. Issue 6.1: The sub-units cannot rotate at all – increased difficulty with O&M and harvest plus loss of modularity. Unresolved Issue 4.1: No redundant buoyancy Unresolved Issue 1.3: Wear-point for mooring still present.
V. 7	V7 adopted a hexagonal frame which added strength to the structure (P1) as well as supporting two additional sub-units (P3). Vertical support beams were introduced at the mid points of each of the sides (P1). Overall, the device became stronger but the amount of reinforcing per sub-unit decreased (P3). The underwater excursion of the shellfish tower was investigated by the scaled laboratory tests (Landmann et al. 2020, companion paper, part 2, this issue) to prevent collision of adjacent moored towers (P1) and to maximise space utilization (P3). For all tests the structure's response due to superimposed waves and currents were tested to improve the robustness (P1) by avoiding slack in the mooring line in terms of the ratio of remaining positive buoyancy linked to the total mass of the system and the hydrodynamic load excitation. Two stacked tower sections with one mooring line were tested as well to evaluate the changed excursion (P1), a simple and modular way for an extended system (P2), and higher space utilization (P3). The fluid-structure-interaction for various shapes of the cages for diverse species (P4) was tested to evaluate the impact on the system excursion (P1, P3). Issue 6.1 was addressed by adding a water lubricating synthetic bush to the top and bottom of each sub-unit shaft at the point of attachment. This permitted the sub-units to rotate again. Further, sub-units mounting points were changed from a shaft insertion to slots at each end so that the subunits could be inserted and extracted with greater ease. The central pole that ran through the cylindrical float was elongated and squared at each end to allow mounting onto a frame for harvesting (P2). The cylindrical float was split into 10 discrete sub-floats, each of 140 l volume. These floats were self-locking in position. The floats can be filled with water or air allowing the operator/farmer to elect if they want the unit to be horizontal or vertical during maintenance and servicing. Unresolved Issue 1.3: Wear-point for mooring still present.
V. 8	

(*continued on next page*)

Table 1 (*continued*)

Current Fig. 3	Conceptual and technical considerations
	A manual clamp unit was introduced for the final design V8 to the centre top of the structure which the mooring rope came through to allow for the structure to be set at any depth required. Issue 1.3 was addressed by having the mooring rope entered the bottom of the structure through a “trumpet cone” which significantly reduces the wear and tear of the rope at this potential wear point)

However, after a certain length growth of approx. 50 cm, the algae substrate would have to be transferred to another technology in order to grow to market size, as otherwise they could be pressed against the frame structure and thus be damaged. Thus, the shellfish tower provides an intermediate stage between hatchery and growout.

2.5. *Construction and deployment at sea*

The first prototype *Shellfish Tower* was built at a construction site in Nelson (South Island) and was load tested by hanging 1.5 t of water from different parts of the frame (Fig 8B). No distortion was detected. At a

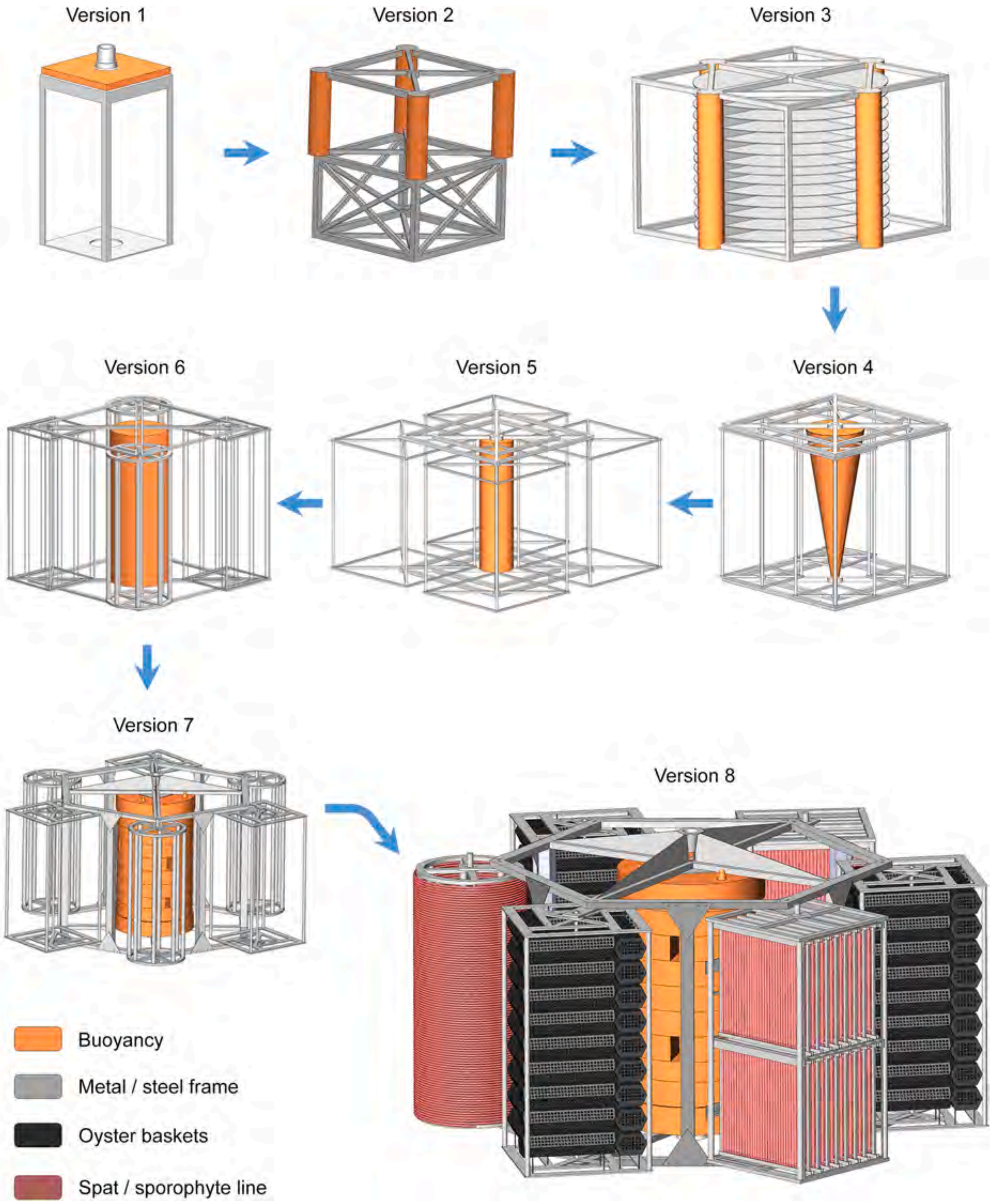


Fig. 4. Iteration process of the *Shellfish Tower* starting with a box-like structure at an early stage until it reaches its final design.

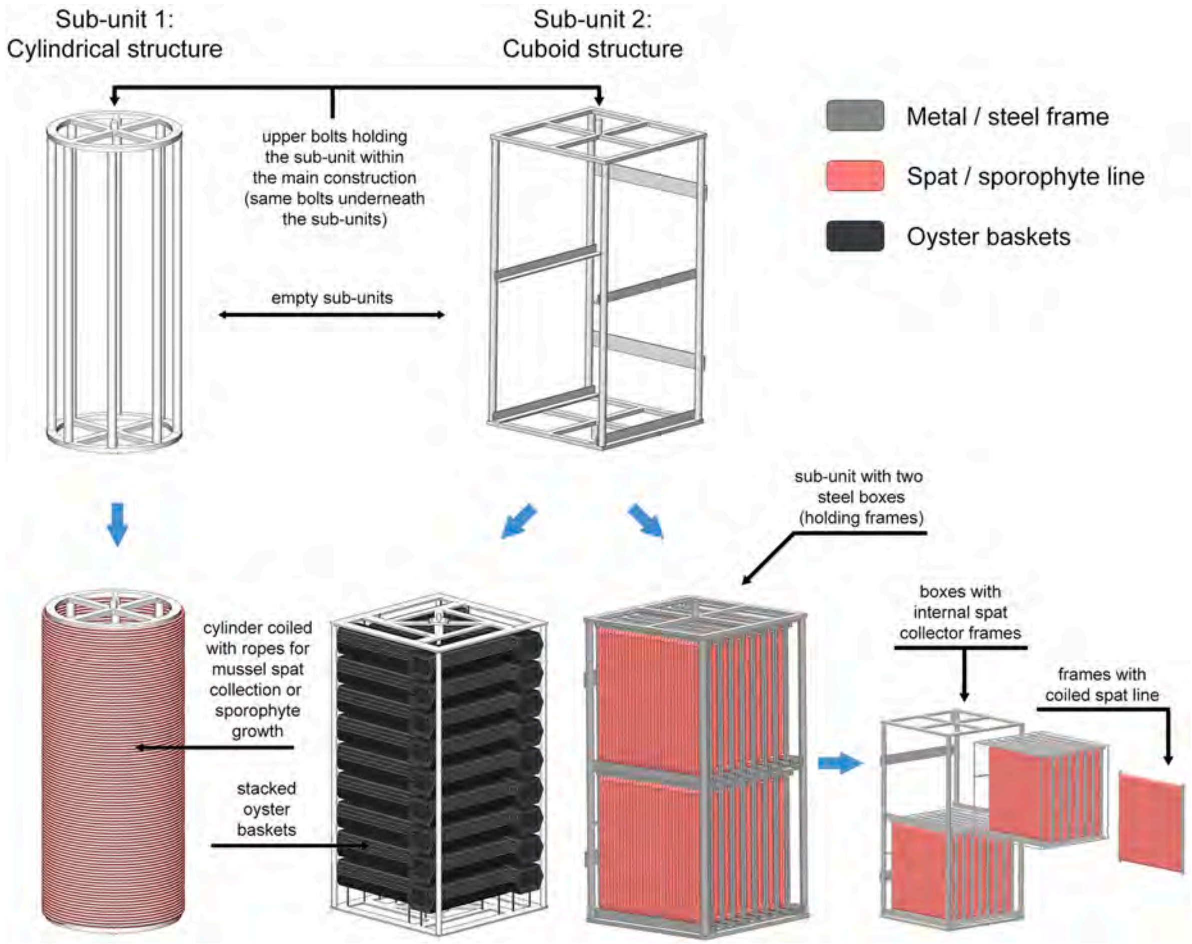


Fig. 5. Sub-units of the *Shellfish Tower*. On the left (cylindrical) spat collecting / sporophyte coil devices are shown while on the right (cuboid) sub-units can either host oyster baskets piled up on top of each other or units for holding frames with coiled spat lines.

latter design stage, detailed finite-element modelling of the steel structure may highlight areas where metal-use (and thus cost) can be reduced. After construction, it was then disassembled and transferred to the Bay of Plenty (North Island), where it was re-assembled on the deployment vessel.

The mooring arrangement of the prototype *Shellfish Tower* (Fig. 6) was designed to gather information on mooring tension and allow O&M procedures to continue unhindered. To secure the unit to the seabed, a screw anchor was installed in the seabed. A swivel was added 30 m upward from the seabed to remove twisting forces from the line which can reduce the rope's strength - this depth was selected to allow for easy access by divers during safety inspections. Seven meters above the swivel, a load cell was added to measure forces experienced by the mooring line. The mooring line then extended upward from the load cell, through the middle of the *shellfish tower* to a second swivel and then to two floats, one of which is a standard 300 L surface float and the other a surface buoy with a solar light attached. At the point where the mooring rope enters the bottom of the *shellfish tower* a trumpet-shaped central guide is found which reduces wear on the rope at this point. The entire length of the mooring rope was 60 m which gave some slack rope on the surface to allow for O&M. A GPS tracker was mounted on the light float to provide warning and location data should the unit break free. The *Shellfish Tower* itself was fixed in place with a clamp (Heasman 2019 – patent pending) at the desired depth. This clamp can be operated from the surface. In March 2019, the *Shellfish Tower* was deployed by a mussel farm service vessel (Northern Quest) at the test site at a depth of 9 m (Fig. 8A, 8C, 8D and 8E).

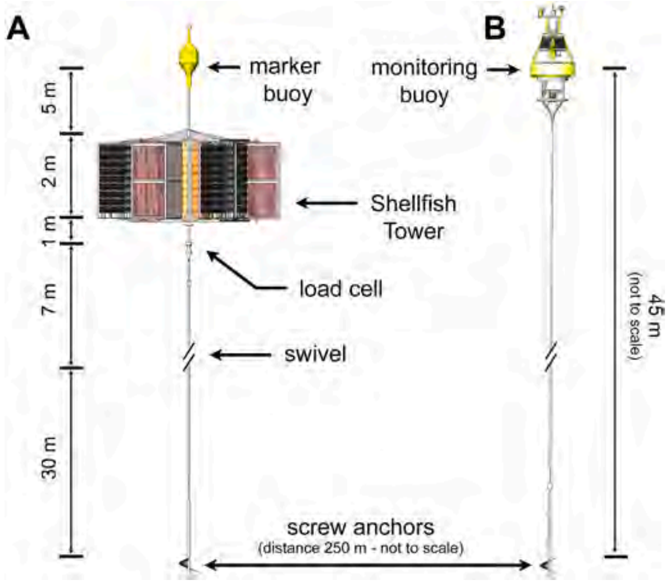


Fig. 6. Design and depth information of the moorings of the *Shellfish Tower* and the measuring buoy.

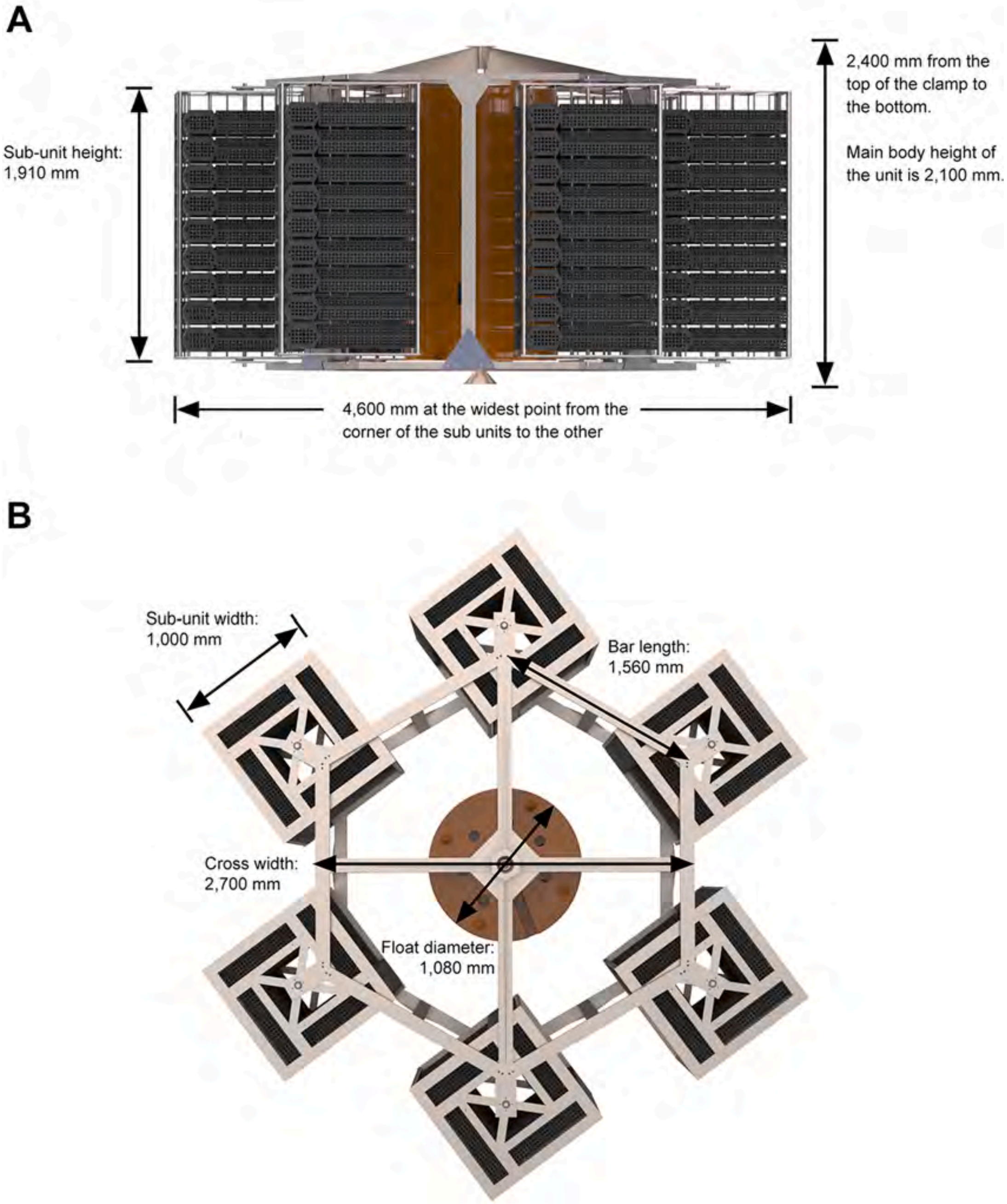


Fig. 7. The dimensions of the unit. (A) shows the side view. (B) shows a top down view.

2.6. *Current structure dimensions*

The dimensions of the current structure are shown in Fig. 7. One of the benefits of this system however is the ability for the structure to adapt further depending on farm situation, farmers requirements and aspirations. For example, the structure may be extended vertically improving the cost to production ratio however, the structural integrity may suffer and should be considered.

2.7. *Deployment of culture species*

Biological data such as the growth of the oysters and the verification of the settlement success of the mussel spat were only considered of secondary importance, after the O&M, structural integrity and mooring tension, at the time of deployment. In November 2019, however, the oyster baskets were loaded with Pacific Oysters (*Magallana gigas*), which were then measured monthly. Initial settlement success of mussel spat is encouraging but since it is seasonal more defined data and results will be forthcoming in August 2020. At this time, the main focus for the spat collection ropes was on performance, i.e. the technical prevention of lines stretching, unwinding, laying on top of each other or tangling with each other.

Seeded lines with macroalgal sporophytes have not yet been integrated into the Shellfish Tower at this point. This important step will be made up for at a later date but is no longer part of the current study at this stage.

2.8. *O&M of the shellfish tower*

Monthly inspections were carried out by divers equipped with

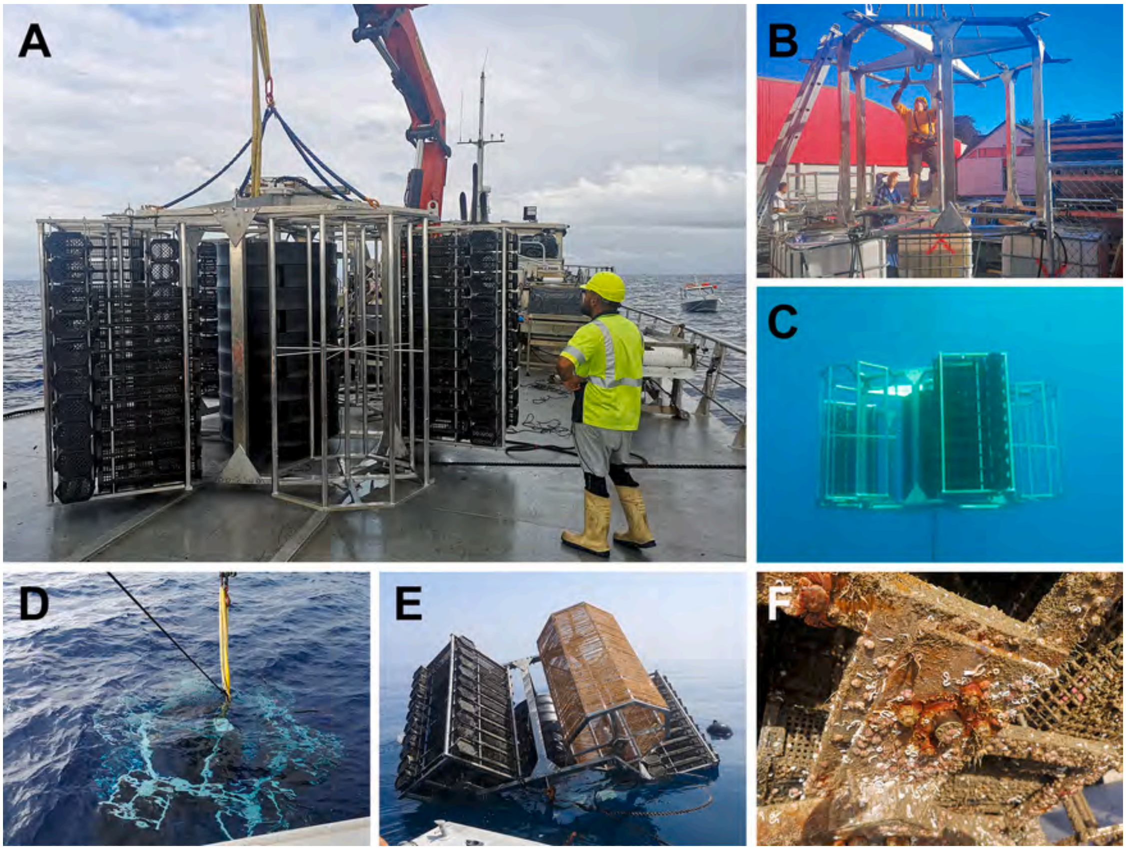


Fig. 8. Images from the set-up, deployment and operation of the *Shellfish Tower* at the Ōpōtiki site. (A) *Shellfish Tower* loaded on the service vessel just prior to deployment, (B) construction of the *Shellfish Tower* and conducting a weight test, (C) underwater image after deployment, (D) response test during deployment, (E) inspection after 4 months and horizontal test mode including a fouling inspection (F). .

underwater cameras. The inspection started at the lower swivel and followed the line past the different connection points (shackles, swivels, rings) to the marker buoy. Special attention was paid to the *Shellfish Tower* itself, its fixing clamp, as well as all sensors that were attached thereto. The batteries of the data loggers (load cells, accelerometer) were replaced, and their data downloaded. In addition, a ROV (BlueRov 2) was deployed to support the visual inspection completed by the divers. The data acquisition of the monitoring buoy proceeded continuously.

3. Results

As with many prototypes, the first deployment was challenging. Issues arose due to unfamiliarity with the new system and mooring attachment procedures – only made more difficult by less than ideal weather conditions. However, these challenges were overcome, and the system was deployed with some minor damage. The floatation units and their inflation valves were custom-made, and this was their first test. Some leakage occurred in the valves over the first weeks of the deployment which resulted in the unit losing buoyancy and sinking to a point where only the surface floats were supporting the system. At the next fair-weather window, the unit was recovered and taken ashore. The valves were redesigned, and the unit was redeployed. This caused some delays in data collection however the new valves have subsequently been proven to be reliable.

3.1. Conditions at sea and data from underwater loggers

Here, we show the deployed-system's response (mooring tension in kN) to a storm-event during the period 5th June 2019 to 7th June 2019. Time-series of significant wave height and current speeds measured during this period are contrasted with recorded mooring tensions in Fig 9. The maximum significant wave height during this event was 2.9 m with wave periods between 5 – 12 s and the maximum current speed was 0.24 m/s. The load cell attached to the mooring line (Fig. 6) measured line tension for an hour, every four hours, at a rate of 2 Hz. Tensions shown in Fig. 9, are the maximum tensions recorded during the hour-long periods that the load-cell was measuring.

Prior to the storm event, the load cell recorded a background tension of c. 500 kg (400 kg of positive buoyancy on the structure plus some drag forces). As the storm progressed and wave height increased, there was a marked increase in measured tension (peak snap forces of 2800 kg). Poor correlation between tension and current speeds (Fig 9B) suggests waves were by far the most significant factor affecting device dynamics during this event. Bardestani and Faltinsen (Bardestani and Faltinsen, 2013) conducted experimental and numerical analysis of snap loading concluding that snap loading is often found for structures that are loaded close to the heave resonant mode, indicating that wave events are far more likely to induce snap loading than currents. The prototype was deployed only 5 m from the sea-surface which is evidently still within the high energy wave zone of the water column. Should we examine data during a calmer period, we may find the effects of currents to be more pertinent to the tension measured by the load cell. Note that tensions recorded during this event are well within the safety levels (3 times the engineering predicted stresses) of the equipment and unit. Furthermore, on the 13th of May 2019 (a few weeks prior to the set of data shown in Fig. 9) the unit survived a storm event, with a significant wave height of 4.68 m. A more detailed analysis of the influence of waves and currents on the unit is provided in (Landmann et al., 2020) (*this issue*).

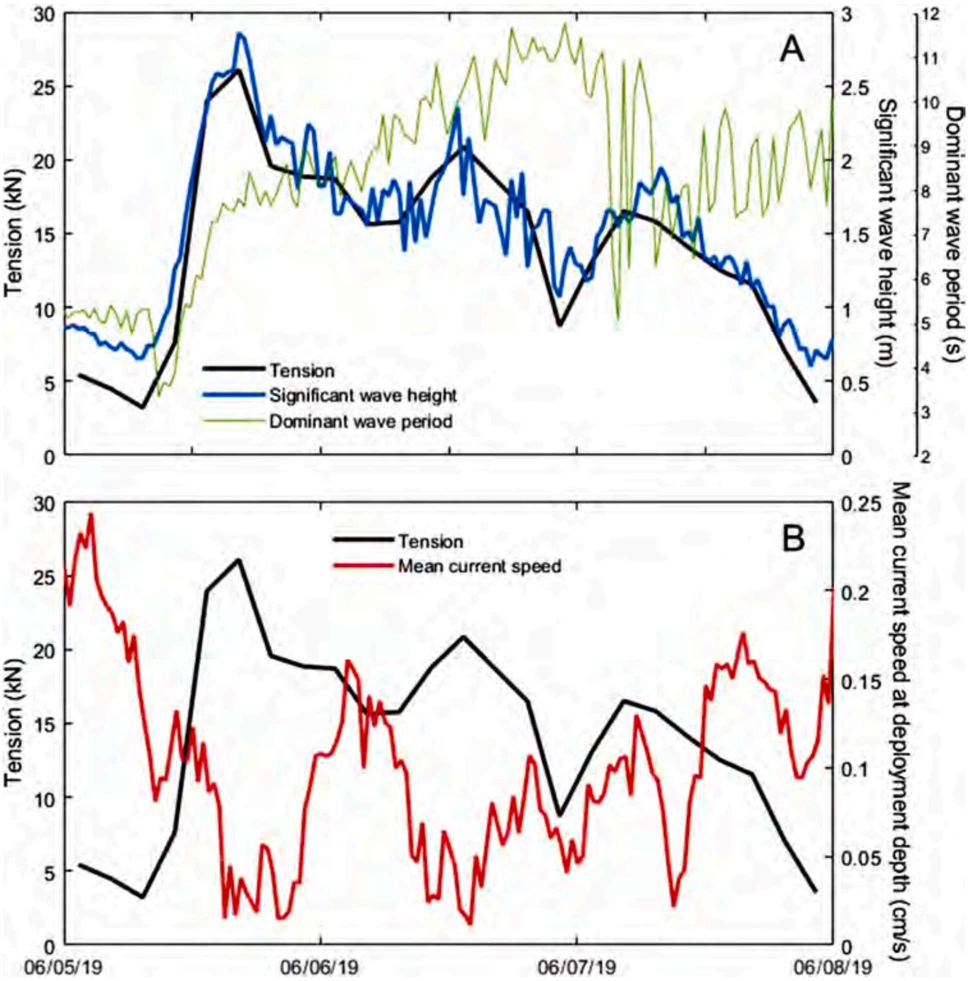


Fig. 9. (A) the significant wave height and dominant wave period at the site and maximum tensions developed in the mooring lines of the *shellfish tower* showing a strong correlation. (B) the mean current speeds at the site and the maximum hourly tensions developed in the *Shellfish tower* moorings showing low correlation.

3.2. Oyster growth and mussel spat

Oyster growth trials and mussel spat trials were started in late 2019. However, the trials were interrupted by COVID-19, which resulted in poor access and management of the trails. This resulted in a statistically untestable result. However, the results obtained did provide a good indicator of the potential as some of the oysters reached 99 mm (from an initial size of 1.5 mm) in the 10 months. This provides confidence for the future trials of oysters in the system. Trials are ongoing.

The mussels spat settled well (visually) however management issues resulting from COVID-19 interference resulted in unquantified results. Again, indications provide us with confidence for the future in spat collection.

3.3. Future candidates

Demand for products from marine plants is growing worldwide and marine areas are being sought to make such cultivation possible. In a future extension study, the tower will be equipped with seeded seaweed sporophyte lines and tested for its operational capability. Other candidates may also play a role in the future e.g. other bivalves, lobsters, sponges.

3.4. Other observations

The floatation units described here are specially designed floats that have had limited testing. Due to some failures during deployment and sea testing we are in the process of re-engineering the floats to make them more robust. This process includes incorporating a polyethylene foam into the manufacturing process to strengthen the floats from compression, reducing overall maintenance and increasing durability of the unit.

Every system has its benefits and drawback depending on species and environment. In this instance there are limited structures suited to fully exposed sites with similar species and habitat diversity as the shellfish tower in use, or in the literature, with which to make comparisons. No literature could be found on single seed structures (e.g. oysters and scallops) suitable for fully exposed sites. In terms of spat catching it is suggested that there are only longline themed systems and the Smart Farm (Lien and Fredheim, 2002) which are currently in use. In terms of algae sporophyte establishment (the shellfish tower is better suited to sporophyte establishment than a full grow-out system) longline systems can be used but the tower may provide a means for intermediate establishment and development of the sporophytes. Longlines provide a means to establish and grow algae however it is suggested that the shellfish tower provides better depth control and more stable substrate reducing exposure of the vulnerable developing sporophyte. Other systems e.g. Spanish large rings considered for algae has a single mooring however it is too big to be cost efficient and durable. There are some additional advantages with the shellfish tower for both algae and single seed shellfish: the shellfish tower, and associated vessels, can be used for Multiple species without major modification (sub-unit changes) providing the farmer with diversity of production; the tower can be set at any depth suitable for the species, developmental phase and conditions targeted; it provides surety of management in that in its submerged state it is out of the reach of any storm; having a single mooring it is easier to deploy and retrieve completely however daily operation and vessel requirements are more complex compare to a longline and perhaps the smart farm, however it is suggested that increased use will generate efficiencies as farmers adapt it to their environment;

4. Discussion

Through an iterative design process, the *Shellfish Tower* has been developed as an aquaculture structure useful for production and research alike. This manuscript while describing the design process for a specific aquaculture technology, showcases the entire procedural design process, from its inception of an idea to a first prototype structure that survived a severe storm event with no noticeable damage. This was done to provide valuable and novel information, guiding innovators in the offshore aquaculture business through a commented design case.

At the start of the program, several aims were set out (Section 3.2) which have been largely achieved. A simple mooring has been achieved and has proven to be reliable to date; the *shellfish tower* can produce a large number of oysters or length of spat catching rope for its footprint; the ability to set the *shellfish tower* at any depth has been attained and more than one species can be produced from it i.e. oysters, mussel spat and scallops.

The current *Shellfish Tower* is made from stainless steel (MT-316 L GRIT 180 stainless steel according to ASTM A554–16 standard) which has an intended lifespan of 15 to 20 years after which it can be recycled as scrap. The cost of the unit is expensive although preliminary projections indicate it is still a viable economic option for oysters and mussels over the 20-year period. Follow-up product design cycles using FEM analysis and optimisation are expected to bring down the amount of stainless steel used to build the *Shellfish Tower* which will decrease upfront investment.

A mild steel galvanised option and a mild steel polyurethane coated option are currently being produced and will be tested in the next year (2020/2021). If successful, this could reduce the unit-cost by 40% although will come at the expense of the unit having a shorter lifespan (8 to 15 years) as well as needing more frequent servicing and/or coating. This reduction in durability may prove to be more expensive in a 20-year economic forecast. A synthetic option has also been considered (e.g. High-Density Polyethylene – HDPE) but there are several issues with using these materials – in particular, they are difficult to join perpendicularly. Using a bolt-join causes the material to deform around the bolts which causes movement that intensifies with fatigue and inevitably results in structural failure. There is also the issue of controlling the torque that the unit is subjected to if synthetic materials are used. While metal has sufficient rigidity to offset this, using synthetic materials could necessitate a complete redesign of the structure (i.e. cross members could be added to reduce torque in this structure). Some polymer materials have been investigated that could potentially be manipulated into the desired structural shape, but at present they could not be recycled at the time of decommissioning. Additionally, they were expensive.

The *Shellfish Tower* can be positioned at any depth to avoid wave energy and maximise production. By avoiding the highest energy, structural damage is reduced and it becomes less necessary to check each unit after a storm. This provides more production surety, reduces operational costs as well as vessel carbon footprint. Although it is preferable to keep the unit away from the high wave energy zone from an engineering perspective, there are some operational advantages of holding the unit within this part of the water column. For one, there is generally greater productivity closer to the surface, and additionally, the wave induced water movement breaks down the boundary layer at the surface of the production units (spat rope or oyster bags) which increases the delivery of nutrients to culture species.

The *Shellfish Tower* has been designed so that as water currents or horizontal wave velocities increase, the structure's profile and drag is reduced. The *Shellfish Tower* has large spaces between the sub-units and the central floatation and as previously pointed out is on a single point mooring. This facilitates an energy release function when high water currents are dominant. High water currents will not only force the unit to greater depths away from waves but also force it become more horizontal. This will allow water to flow through the gap between the sub-units and the central floats and subsequently reduce the drag forces on the unit. Tilting angles between 30° and up to 75° were observed for single modules in the flume and wave basin experiments. As expected, the angle was sensitive to the buoyancy. However, the angle was also sensitive to the shape and orientation of the sub-units, e.g. of not rotationally symmetric sub-units like cubic units. The two tower sections on a single point mooring line showed slightly reduced angles for cubic sub-units and rather increased tilting angles for cylindrical sub-units (Landmann et al., 2020) (This issue).

The clamping system incorporated into this design lends itself to automation. It is intended to automate structure positioning in the future and have reporting technology which will indicate each unit's status to a management land-based office twice a day. The requirements which include, telemetry, power sources and control mechanisms for this are being developed.

The floats developed for this system are self-locking and therefore do not require additional equipment to lock or hold them in place. There are ten discrete floats on the prototype which collectively provide a total of 1400 kg of buoyancy. The reason of this is twofold: the first is that it adds redundancy (i.e. a single float failure is not catastrophic). The second reason is that the operator can select the amount of buoyancy they require for the operation in hand. If the operation is in an area which is not subject to long-duration large waves, they can reduce flotation to reduce stress on the mooring.

The production of mussels to full size on this system is not viable, there is insufficient value (in New Zealand) in mussels to cover the costs. The capture of spat, however, has a fast turnover. Spat is valuable and multiple "crops" can be captured each season making it viable in the right market. Single seed shellfish such as oysters and scallops have sufficient value (in New Zealand) at the time of writing to justify this type of unit. A 2 m tall unit can hold 240 oyster bags and therefore the *Shellfish Tower* can hold between 12,000 and 24,000 oysters depending on production density. Previous small experiments at the current trial site, oysters (hatchery produced single seed tested in small experimental baskets hung from mussel lines) have been harvestable at a mean of ~ 90 mm length in 10 to 12 months after being seeded out at 6 mm to 10 mm in size.

It is anticipated that there will be variations to this structure in the future as industry members manipulate it for their purposes and situation. The *Shellfish Tower* can be adapted, possibly through lengthening or widening of the main structure and sub-units or increasing from a hexagonal to octagonal unit.

Efficient harvesting systems which will either harvest the product horizontally or vertically, in or out of the water, are being considered and designs are in process. Testing is anticipated in 2021.

Declaration of Competing Interest

None.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.apor.2021.102603.

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