Floating Island Development and Deployment Roadmap

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SPACE@SEA

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Floating Island Development and Deployment Roadmap

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Contents

About the Roadmap

Dear floating island enthusiasts,

Rising sea levels, growing population in coastal areas, shortage of space and increasing activities at sea all call for safe and durable “land” at sea. Ground bound artificial islands are only feasible up to a water depth of 20 to 25 metres. Larger water depths call for floating solutions, which should be able to withstand environmental conditions.

Floating islands have been around since novelist Jules Verne described a floating city in the 1869 novel “*Une ville Flottante*”. Since then, floating cities have been investigated many times resulting in artist impressions of floating cities and multiple other applications of floating structures. Until date, it has not come to large scale deployment of floating islands. Small scale individual applications of offices, farms and houses in sheltered waters have been realised. Offshore and sheltered open water locations are still in the development phase, seeking a technical solution capable of withstanding environmental conditions. Applications on floating islands are as wide as one could imagine on shore.

Floating cities however, do not come out of nowhere, both onshore and offshore. It is the philosophy of the Space@Sea partnership that living follows work. Currently offshore workers live in simple quarters with limited functionalities. These workers have a working schedule of several weeks offshore alternated with several weeks onshore. Expanding work applications offshore may lead to different schedules, increasing comfort of the living facilities will motivate workers to invite their families offshore, gradually increasing the activity on the islands. Over time, the floating city will grow, adding functions and labour opportunities.

With this document we intend to inform about the Space@Sea developments and inspire others in the floating island industry. The floating island development and deployment roadmap consists of the following parts:

- The executive summary gives a brief overview of the overall Roadmap.
- Part I introduces the floating island concept and the results of the Horizon 2020 Space@Sea project. It summarises three years of development of the project which focussed on a technical design and four applications (living, farming, energy, and logistics). The focus of the applications has been on individual applications as well as combination of functionalities in multi-use applications.

- Part II gives the barriers and recommendations of floating island development which have come out of the Space@Sea project. For floating islands to become a reality some remaining technical issues need to be resolved as well as issues regarding regulations, legislation, and marine spatial planning.
- Part III provides a roadmap for the way ahead to bring floating islands to full application. Based on the recommendations given in Part II a roadmap with concrete actions is given including a discussion on possible funding for further research.

The Space@Sea project has come to an end in October 2020, the partners however, remain committed to bringing the concept of modular floating islands to a success. All partners are open for collaboration in further developments solving remaining barriers given in this roadmap.

Please get in touch with any of the partners to discuss any of the recommendations and actions following from these recommendations.

The Space@Sea team.

Figure 1: The Space@Sea partners at the project kick-off in November 2017

Executive summary

Executive summary

In November 2017 the Space@Sea multi-disciplinary partnership, consisting of 17 European partners, launched the three-year research project to develop a concept of modular floating islands. This document summarises the developments, the lessons learnt and the barriers which stand between the Space@Sea result and large-scale applications of multi-use floating islands.

Space@Sea developments

A modular approach of building up the total floating island was chosen by the Space@Sea consortium as it provides flexibility in expanding the floating island with new activities when needed.

The floater designed considered **shape and size optimisation** and an evaluation of the possible materials to be used. Initially a triangular floater was considered because earlier tests have shown triangles to have the least connection forces between the floaters. Triangles however, have a less efficient space utilisation compared to squares and rectangles. Preliminary model tests and numerical simulations showed that, although the connection forces between square floaters are higher, the occurrence of this was only very limited. Size optimisation was done based on sizing of present-day dry docks for fabrication of the floaters. The project concluded that, although **standardisation is crucial**, rather than standardising the shape and size of the floaters, **the location of the connectors should be standardised** as to connect different sizes and shapes.

Connectors between the floaters were considered. For flexible connectors a “simple” rope and fender solutions seemed to be the most feasible. A rigid connector was designed which turned out to still allow motions between the floaters in certain wave conditions. A full rigid connector will need to cope with extreme forces in harsh weather conditions, which will result in very heavy and expensive connectors. Future research should focus on innovative solutions to **reduce the maximum forces between floaters** in harsh conditions.

Numerical simulations have been done to study the mooring forces for a location in the Mediterranean and the North Sea. The combination of shallow water and harsh environmental conditions in the North Sea prevented a reliable catenary mooring design to be developed. For the Mediterranean, a **catenary mooring system** was designed where the outer ring of floaters would be moored to the seabed and other floaters connected to each other.

Transport and installation procedures were developed for the installation of a total floating island based on the mooring system designed for the Mediterranean. This includes the use of **standard vessels for mooring system installations and tugs for the installations** of the islands and connections to the mooring and each other. A **condition monitoring approach** was developed targeting the crucial parameters to be included in the monitoring systems.

Space@Sea has considered four applications on the floating island, energy hub, transport and logistics, aquaculture and living. These four distinctly different applications all have varying requirements for the floating island, making these four specifically interesting for the development of a generic floater. The **energy hub** provides support to offshore (floating) wind farms from which maintenance and support activities can be done and acts as a storage place for spare parts. The energy team furthermore developed smaller floaters fitted around the island acting as **wave energy converters**. **Transport and logistics hub** comprise of a floating port extension on floating islands can be either connected to the shore, and offshore floating hub or a disaster relief island. **Aquaculture** alternatives for mussels and sea brass has been studied. **Living** at sea developed housing on the floaters for offshore workers and for urban expansion.

Single-use **business cases** have been studied for the individual applications as well as multi-use combinations of these four applications. This showed that the energy hub as single-use floating island has a positive economic business case compared to alternatives on the market for deep water. For living and aquaculture the economic business case for single-use is negative.

Barriers for exploitation

Technically there are no major barriers for exploiting single-use and multi-use floating islands. The current design will allow first applications, although it will not be the optimal solution and probably too expensive, it is already possible. **Developments are needed to bring the costs down** which should focus on the mooring, rigid connectors between floaters, novel materials, and large-scale production processes.

Mooring has proven to be challenging in shallow water conditions combined with harsh weather conditions. Catenary mooring as studied in Space@Sea needs some water depth to be efficient or alternatively methods to reduce the drifting forces need to be developed. A combination of both will need to be applied to make floating islands also feasible for shallow water conditions.

Space@Sea has not considered **alternative materials** for the construction of the floaters. Material developments in the market show the potential for more durable materials, which will extend the lifetime of the floater, providing a more attractive economic business case.

Sizing of the floaters have been based on the current maximum size of dry docks for building. This has limited the size of the floaters, requiring rigid connectors between the floaters for instance for gantry cranes to move along the dock. Future developments should study **production facilities for larger floaters** as well as **rigid connectors** between floaters, which together will allow much larger fixed areas on the island.

Multi-use floating islands face governance barriers regarding, amongst others, maritime spatial planning, ownership of the island, floaters and buildings, and governing laws on the islands. Currently no regulations or guidelines are in place for the **settlement of a floating island**. Within the EEZ of a country the state having say over the sea space it is evident that this state has say of where floating islands can be settled. Outside the EEZ there is no governing body, which can allow the settlement. Within IMO and UN discussions on settlement of floating islands on the high seas need to be held.

Where for single-use floating islands the owner of the total island and/or floater is evident: the user of the island. For multi-use floating islands this is less evident. Also, for some applications such as living, or industry is perhaps not a natural choice to own the floating island. Governments, the EU, and member states, can play a role in **the ownership of multi-use islands**. Furthermore, current property law prohibits the ownership of an object on a floating object. For floating housing **property law will need to be adapted** to allow citizen to own a house on a floating island.

Business case evaluations have been done in Space@Sea for four applications being transport and logistics, energy hub, aquaculture and living. Single-use business case evaluations for the Mediterranean and North Sea have shown that only the energy hub and to a lesser extent transport and logistics have a positive economic business case. It should be noted though that although housing may not have a direct economic benefit, secondary benefits will still make floating housing a feasible alternative. Evaluation of the multi-use business cases show that combining applications also will create a more attractive economic perspective for floating housing. This is in line with the Space@Sea philosophy that living follows work.

Where local and national governments play roles in land reclamation projects such as the Maasvlakte II and Flevoland in the Netherlands, such role is yet to be considered for floating land expansion. Especially for land expansion which has no direct economic benefit but positively affects society and environment may need **a strong role of the local and national governments** in the deployment of the floating islands.

Way ahead

Two parallel streams for further developments towards multi-use floating islands are identified. **Technical developments** for moorings, rigid connectors, materials, and manufacturing procedures should start soon leading to full-scale pilot applications of single-use floating islands. Simultaneously **governance issues** which currently prevent multi-use applications should be solved. Governance issues regard, amongst others, regulations regarding the settlement and Marine Spatial Planning, ownership of floating islands and individual floaters, governing law and health and safety issues. Once the governance issues are solved, multi-use floating islands can make use of the technical developments for single-use floating islands. Large scale applications of single-use floating islands are expected between 2030 and 2035 and between 2040 and 2045 for multi-use islands.

Developments of **multi-use floating islands are still in a pre-competitive phase**. Single-use floating islands are making the transition to the competitive phase with first large scale pilot applications as part of the next steps. Both the pre-competitive and the early-competitive next steps will need financial support, for example from the Horizon Europe framework programme. Also, member state governments will need to take a role in addressing the governance related issues.

Solving the barriers currently preventing large scale applications of multi-use floating islands required a wide **collaboration of stakeholders** varying from future users, technology providers and research institutes to regulators and governmental bodies. With this roadmap we hope to inspire these stakeholders to see a green floating future and joining the floating movement. Space@Sea has been exemplary for the way completely different fields can and need to work together to obtain a common goal.

Part 1

Introduction to the floating island concept

Part I: Introduction to the floating island concept

Floating islands have been on the research agenda for quite a while, mainly providing application cases and business cases resulting in fancy artist impressions and well thought through economical concepts. Lacking was still a technical working-out of the concept of floating islands, including floater dimensions, mooring, installation and O&M procedures. Horizon 2020 project Space@Sea, funded by the European Commission, set out to provide a technical solution, meanwhile identifying topics for further research.

What is the issue?

Ever increasing population means that we require more space to live as well as more space to grow food and more space to generate renewable energy. Population growth in the EU (Figure 2) is ever increasing and hitting 450 million very soon. Most people in the EU live in coastal areas (Figure 3) as most of the jobs are there. Many countries are faced with a population shift from urban regions to the cities, putting extra pressure on the already densely populated cities. Climate change and sea level rise put these areas in jeopardy of flooding. Simultaneously an increase of offshore activities is noticeable. Harvesting energy from wind at sea is more efficient than on land because of the more constant winds and the sea itself is more and more seen as a source of food and materials.

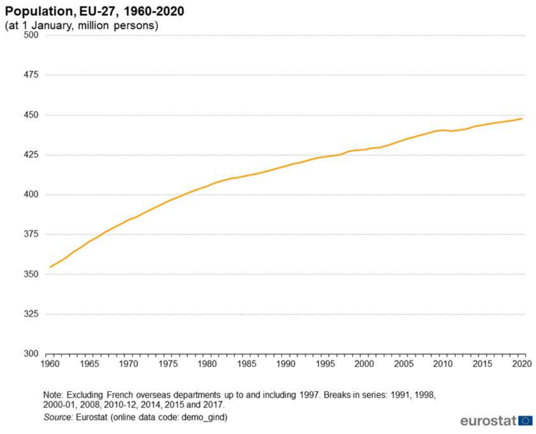

Figure 2: EU population growth[1]

[1] https://ec.europa.eu/eurostat/statistics-explained/index.php/Population_and_population_change_statistics#EU-27_population_continues_to_grow

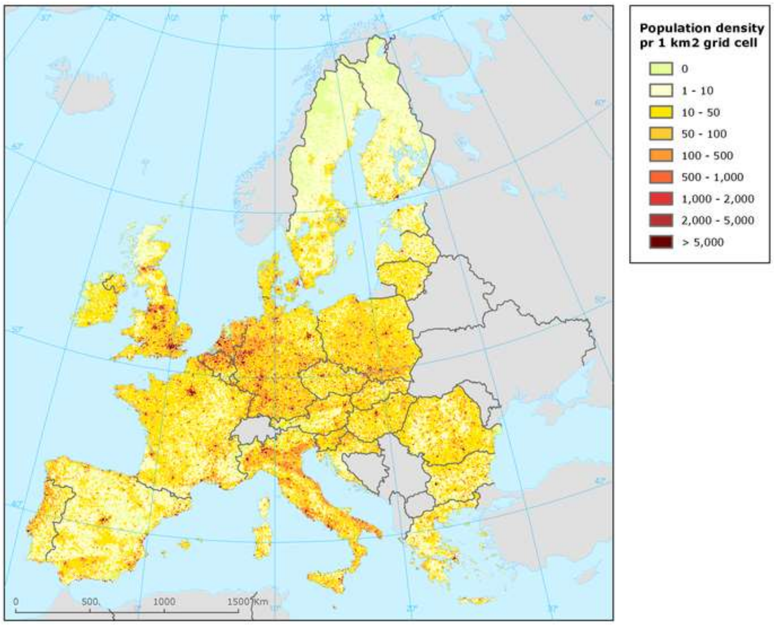

Figure 3: EU population density[2]

Together the trends of population grow, shift to cities and coasts, sea level rise and the increased activities at sea call for solutions of adding "space at sea". This can be either for urban expansion directly connected to the coast or space further offshore for people to work and live on. Creating land on sea is not new, both poldering and infilling have been used for a long time. Land reclamation however, is permanent and has a major ecological impact. Furthermore, land reclamation is only viable up to a limited water depth (±25 m) beyond which the costs and technical feasibility will become an issue.

Floating land space is a viable solution having a much smaller ecological impact. Also, once the land space is not needed anymore, it can be easily relocated leaving no long-term impact on the local environment. Floating is also a feasible solution for further offshore activities, requiring people to work and live offshore.

Why floating?

Floating islands are an elegant solution to the need for coastal and offshore land space, which has a low environmental footprint. Where artificial islands are permanent (of course they can be excavated and dredged, but not without large costs), floating islands can easily be relocated by towing the islands to another location in the same way they came to the original location in the first place.

A key challenge in floating islands is how to build such large structure. An island of any importance would have a size of at least several hundreds of metres each side. Currently no dock in the world can build floating objects of these dimensions.

2 https://www.eea.europa.eu/data-and-maps/figures/population-density-2

Producing the islands from one piece may also not be the most sensible from flexibility standpoint, modularity in the design and production of the islands is therefore called for. Modularity will provide flexibility in applications by adding or removing modules and functions when necessary. Furthermore, modularity will bring standardisation which in turn reduces the production costs.

The challenge for floating islands is in achieving a technical solution that resembles onshore conditions as much as possible. This contains a solution that is sufficiently stable with low motions which can be kept on its location in all environmental conditions. A design includes material choices, structural design, and shape optimisation capable of resisting all loads working on the floating island.

Space@Sea ambition

Many projects on floating islands to date have produced concepts of multi-use platforms, which resulted in economic evaluation and artist impressions. Much effort has been spent on creating multi-use business cases and preparing society for the future of living and working at sea. Now there is a need for a technical solution to accommodate the multi-use applications.

The Space@Sea project set out in 2017 to develop such technical solution, studying amongst others optimisation of the island shape, floater type and mooring. The main aim of Space@Sea was to provide sustainable and affordable workspace at sea by developing a standardised and cost-efficient modular island with low ecological impact. The technical designs of the floater are used in further evaluation of business cases for four example applications as well as concepts for installation, condition monitoring and maintenance and Health and Safety issues.

Following the basic design of the floaters, connectors, and moorings the Space@Sea concept was tested and demonstrated in a controlled environment at model scale. Space@Sea will deliver the floating island concept at TRL 5, in this document a roadmap is sketched to bring floating islands to reality.

Space@Sea concept

Space@Sea developed a modular concept to floating island. Modularity has proven to be successful in many fields from transport to buildings and large-scale manufacturing. Modularity in floating islands should focus on relatively small, standardised building blocks which together will form the total island. Here the consortium followed the example of shipping containers where most containers are so called twenty-foot equivalent units (see Figure 4). The location of the twist locks (connections) between the containers is standardised, making stacking easier. Through time however, the shipping container types have expanded to sizes which are not specifically a multitude of a smaller version. Also, the height of the containers can vary, not influencing the stacking and connections.

Figure 4: Twenty-foot equivalent unit[3]

Probably the most well-known concept of modular design is the popular Danish toy LEGO. Blocks of relatively few different shapes and sizes can be put together to build anything one can imagine. The design of the modules keeps production costs low while facilitating a wide range of designs and applications. Space@Sea have set out to design the "LEGO for multi-use platforms".

Objective of this document

With this document the Space@Sea consortium summarises the project developments and provides a sketch of the way ahead for floating islands. Space@Sea was not exhausting on all developments of floating islands, some topics were not or only slightly touched upon. Laws and regulations for instance were not considered, on purpose. We believed that the floating island society first needs a technical concept to talk about before we can discuss further barriers and challenges. The technical concept is here, and this document contains a start of further discussions and developments with the aim to fuse the discussions outside the consortium and accelerate developments towards the realisation of a first floating island.

This document consists of three main parts. In the first part the concept of floating islands in general and more specific the Space@Sea concept is further elaborated. A description of the project results and reference to more detailed descriptions is given to form a basis of the current state of the art of floating islands. In the second part the barriers for exploitation of floating islands are discussed. This includes problems which have not yet been solved and regulatory issues that will need attention in the coming years before a first offshore floating island will be achieved. In the opinion of

3 http://www.theinfolist.com/php/SummaryGet.php?FindGo=twenty-foot_equivalent_unit

the Space@Sea consortium these barriers are all barriers that can be solved. In the third and last part the roadmap towards the first floating island in given including milestones for the development and partners that need to become involved.

Floating island concept and Space@Sea design

Modular approach

The use of standard containers (Figure 5), to transport goods has dramatically reduced the costs of transport in international trade and was a major element in globalization. Containerization did away with the manual sorting of most shipments and the need for warehousing. It displaced many thousands of dockworkers who formerly handled break bulk cargo. Containerization also reduced congestion in ports, significantly shortened shipping time and reduced losses from damage and theft.

Figure 5: Picture of a standard 20-foot container

The idea behind the Space@Sea concept has been to take advantage of the concept of containers and to supports various activities for islands at sea through a standardised floater concept. By interconnecting modular elements, a flexible structure can be created. It has been the objective to design the modular floaters to support different activities at sea at low operational risks and costs. Nowhere the concept of standardisation has been proven to be as efficient as in the transport sector where the container was introduced to standardise general cargo. Space@Sea will introduce a similar game changer for multi-use platforms by standardising the floater to effectively reduce production and maintenance costs thus enabling crucial scale benefits. By applying a shared the mooring system and interconnecting mooring systems between multiple islands costs can be further reduced.

Floater design

The field of variables to be considered in the design of floating offshore structures is vast. Aspects to be considered include the structural integrity, operability of all functionalities, special characteristics of the deployment sites, mooring and more, which already forms a complex design process for stand-alone offshore structures. The complexity is further increased when considering the deployment of multiple connected floating bodies, as the design space is extended by the aspects of connections and integrability. Due to the novelty of the concept developed in the Space@Sea project, experience regarding the design and installation of scalable, modular floating islands is rare. Considering the large design space and scarcity of related research-based knowledge, the design process cannot be holistic and is therefore based on a heuristic approach.

In accordance with the heuristic approach, the design space is split into major categories, which determine the outline of the overall concept. Regarding the envisaged functionality of the Space@Sea island, each decision in one category will have an impact on the other categories. To understand the interaction of categories, one may consider a fundamental decision such as whether the main dimensions of a floating body should be of the order of a few metres or a few hundred metres. The choice will significantly influence the applicability of certain principles of floatation, as small objects are typically limited by their responsiveness to waves and the correspondingly experienced accelerations, whereas large floating objects are rather susceptible to structural failure due to large internal strains or slamming. It shall therefore be said that the choice of categories made here is not absolute, but rather a supporting frame to enhance the design procedure.

The most central aspects to be covered in an initial design should be based on a functional requirement analysis of the concept. Aquaculture and logistics, accommodation and sustainable energy all have different requirements to provide ideal operational conditions. What they have in common, is that they all require a minimum amount of space for their applications. Classic construction planning, plant layouts and port terminal design provide an idea about the most basic requirements in terms of general dimensions for the respective application. The first category to be evaluated was therefore defined to be module size which determines the overall dimensions including, but not limited to: draft, edge lengths and deck space. Closely related to the size is the module shape, referring to the curvature of the hull lines. This design category is of particular importance due to the modular approach followed by the Space@Sea consortium. In addition to the mere size and shape of the modules, the operability of the functionalities will also depend on environmental conditions and the response of the islands to the resulting external excitation.

While the response of the structures to these environmental loads naturally changes with shape and size, the behaviour may be significantly altered by choosing a different module principle. This category of design defines the chosen principle of floatation (barge, semi-submersible, etc.)

It was concluded that a model with a principal length of 50 m scores best. As modules with a maximum principal dimension of slightly below 50 m can be built in many places, the main dimension of the modules is defined as 45 m. The choice of this main dimension is largely based on the inherent advantages regarding modularity, building ease and transport and installation effort. Modules of this size may be handled by a single tug and can be built in all larger European shipyards. The deck space and quay length is deemed acceptable for three of the four functionalities, as presented by Schay and Otto (2017). Only the logistic hub would noticeably benefit from an extended quay length, since gantry cranes typically serve 100 m of quay for container vessels. The 45 m module design may, however, be considered a base size able to be coupled to larger modules of two, three or four times the module size. For the basic modules, a possible reduction in operational efficiency is accepted in exchange for the obtained increase in flexibility. Furthermore, since the scope of the Space@Sea project includes the design of a rigid connection technique for multiple floaters, the shorter quay length may be compensated by rigidly connecting multiple modules. Rigid coupling techniques of floating offshore structures have been proven to operate within acceptable limits for motion sensitive operation e.g. for the Mega-Float project, where a multi-module aircraft runway was deployed in Tokyo Bay, Sato (2003).

From a hydrodynamic point of view a triangular floater shape is preferred. This shape was therefore used as an initial design assumption. The advantages regarding the functionalities are, however, expected to outweigh the minor reduction in relative motion. It should be noted, that for each specific island configuration, the level on relative motion and connection forces will depend on the local environmental conditions and the shape of the island.

For the principle of floatation, all currently employed solutions in the field of offshore engineering were considered, as only a finite number of solutions is currently available for stationary floating platforms. On overview of the currently employed principles of floatation can be found in Lehmann, Östergaard and Clauss (1988). Computed relative motion amplitudes form the basis for the choice of a barge type floater. High rotational motion amplitudes of the modules, even within the island, must be considered for the devised installation sites. Under these conditions, in case of air cushion type modules, the air cushions underneath the modules are likely to lose a significant amount of air. The installation and operation of adequately sized fans to maintain the air cushion is costly. The construction of many such modules is deemed unfeasible, especially since this technique is also inherent with a loss of stability and displacement.

The computed relative motion also exposes a disadvantage of the semi-submersible principle. While the reduced water plane area of the surface-piercing columns leads to a reduced response to wave excitation, even for small roll motion amplitudes the relative horizontal displacement of the top structures will be significant due to the large lever arm. As a result, distances between neighbouring modules need to include a large safety margin, making joint application of multiple floaters unfeasible. This type of module further suffers from reduced accessibility. As the economic drivers of the Space@Sea concept, namely the logistic and energy hub, require an easy access to the platform for crew and cargo, an efficient transhipment procedure must be enabled. Current regulation requires the top platforms of semi-submersibles to be positioned several dozen metres above sea level (Lehman et al. (1988)). This complicates any kind of cargo transhipment or crew transfer. The TLP concept was deemed not applicable due to the high cost and the aspect of modularity, which either requires all modules to be connected to the group or require high pre-tension loads on module connections. In contrast, the barge type module is simple to construct, provides a stable platform for all applications, is easily accessible at sea level and requires low installation effort. As a downside, these types of bodies typically experience the highest motion excitation in waves. It is however, expected that the coupling of multiple such bodies will lead to a reduction of motion excitation.

Mooring

The definition of the module edge length provides the basis for the design of the mooring system. In deep waters, ropes, and chains of several 100 m lengths will be attached to the island coming from several directions to provide adequate position keeping ability. Under all circumstances, an entanglement of mooring lines must be prevented. This would become unavoidable when employing relatively small floater sizes and connecting each module to multiple radially distributed anchor points on the seabed. Consequently, dedicated mooring modules must form the connection between the Space@Sea island and the sea bottom. Several additional modules are connected either directly or indirectly to the mooring modules without having an own direct link to the seabed. This does not imply that the sole purpose of the dedicated modules is the mooring connection. They may serve for other applications if these do not interfere with the functionality of the mooring system.

The feasibility of a mooring system for coupled floaters is analysed with the aNySIM tool for two different cases defined within the Space@Sea project: North Sea case and Mediterranean Sea case. For each case the basis of design of the mooring system was defined, that included different island configurations, environmental data, soil data and other relevant data like available seabed area for the mooring system, available strong points on the island modules and capability of interconnecting elements between individual island modules.

The mooring design provides a station keeping solution for the floating island configurations relative to the seabed that could efficiently cope with the imposed environmental forces. As the floating island configuration could be of arbitrary shape or vary in size in time, the mooring system had to be developed modular and flexible.

Earlier basin model tests performed by Otto et al. (2018) (executed prior to the Horizon 2020 project Space at Sea) showed the global behaviour (in terms of horizontal motion) of a floating island. This global behaviour could be characterized as a slow drift motion. The tests also revealed that imposed horizontal drift loadings are mainly dependent on the global width of the island assembly.

The observations from these tests proved that mean wave drift theory can be applied in the mooring design to determine the global behaviour of the island for a given, width of the floating island configuration (and thereby fulfilling the modularity requirement due to the relation of width and number of modules) Furthermore, well-established second order diffraction theory in combination with associated heuristic methods could be applied.

The observations also indicated that the design of the connecting elements between the island modules should be based on the wave-frequent loads and relative motions between the individual modules.

The software tool applied for the mooring design is MARIN's software package aNySIM. The early stages of the Horizon 2020 Space@Sea project were used to enhance and expand the software to handle in an efficient manner large number of multi-body interactions in mooring simulations. Key modifications in the software includes modification to the diffraction and hydrodynamic databases. Furthermore, the capabilities of the software for analysis of multiple floating island modules were extended both in time-domain and frequency domain.

The aNySIM tool was applied to investigate the feasibility of a suitable mooring system and analysis of the station keeping capabilities of selected mooring concepts for the two business cases. Before the aNySIM simulation were execute, first an initial screening of suitable mooring systems was done using a first principles approach for horizontal surge drift loading. This mooring analysis work is implemented in spreadsheet calculations. The selected mooring configurations were further investigated in time-domain with aNySIM. The multi-body simulations in time-domain were however, very time-consuming, even with today's computer clusters.

The screening phase revealed feasibility issues for the North Sea business case. For the Mediterranean Sea business case a viable mooring system could be developed candidate based on catenary mooring system. In the analysis, the number of modules could be limited by grouping modules that acted as a skeleton. This grouping can easily be adaptable for future changes in the island configuration.

To further reduce the computational costs involved with multi-body simulations, the set of simulations was first run for an island platform with individual modules combined into an equivalent single body. A restricted, final, set of simulations was run with all island modules modelled individually.

The simulations confirmed the feasibility of the mooring system candidate, for which the design process was complemented with an anchor point design and installation method. Note that the mooring design solution applied standard industry available materials.

A finding related to the wave frequency behaviour of the modules was found in simulations with individual modules combined into rigidly coupled modules. These simulations resulted in reduced pitch motions.

The mooring system design for the North Sea was considered not feasible in the selected shallow water location for the floating island concept. A conceptual change to floating island structures with external breakwaters may be considered to reduce environmental conditions to which the islands are exposed. This would require further detailing of the environmental conditions within the breakwaters which is outside the scope of the present study. It is noted that the breakwaters would also limit the space to deploy a catenary mooring system and might require a different mooring configuration.

Transport and installation

In this project, the Transport & Installation (T&I) of the floating *Space@Sea* modules starts at the assembly port, where all assets (floating modules, top structures, mooring systems, installation equipment etc.) are being transported to and where the modules are being finalized, assembled, and commissioned before permanent installation offshore. The project is finalized when the final floating module is connected to the island configuration. However, this does not mean that no offshore operations are taking place anymore after completion.

The T&I of a floating island is divided into two (2) different sub activities, being the installation of the anchor foundation and mooring lines on one hand and the towage and offshore installation of the floating modules on the other hand. For the first activity, the project considers DEME's state-of-the-art heavy lift vessel Orion to install all 71-anchor foundations and to pre-tension the 750 m long mooring lines. Below figure shows Orion transporting all piles and mooring lines in one single trip.

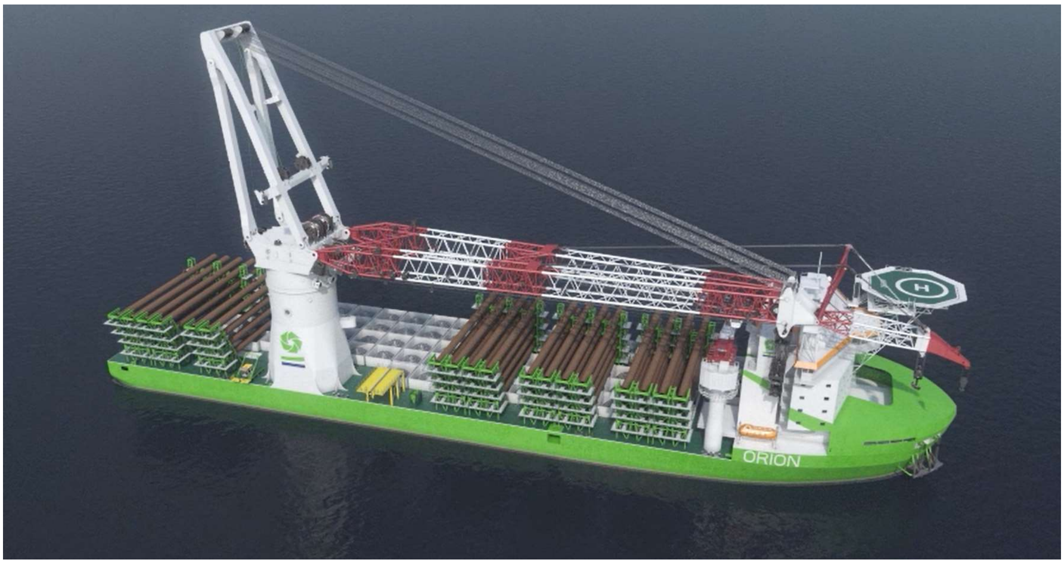

Figure 6: Heavy Lift Vessel Orion - DEME

The project considers vibro-piling as a promising technique to vibrate the anchor piles quick and efficiently 45 m deep in the seabed. Below figure shows the vibro hammer vibrating the pile into the seabed with support from a Remote Operated Vehicle (ROV).

Figure 7: ROV inspecting pile driving

For the second activity, an offshore construction vessel (OCV) in combination with tugboats are required to tow a single floater or a convoy, consisting of three pre-connected floating modules, to the offshore site and install. Performing a triple towage results in a quicker installation time and prevents the need of offshore assembly which is only applicable when wave heights are below 0.5 m.

Below figure shows a triple towage convoy at the assembly port.

Figure 8: Convoy at assembly port with offshore construction vessel and tugboats

It should be noted that both sub activities can't be executed simultaneously which means that the floating modules only can be towed and installed when all mooring anchor foundations and mooring lines are installed resulting in a total project execution time of at least 11 months including the mobilization, demobilization, and weather delays of all required marine equipment.

Due to its long execution time, it is highly recommended to divide the offshore works over two (2) or more years to perform the works during the good weather seasons, from April till September, limiting the amount of weather delays and associated T&I cost. Below figure shows the installation and connection of a 2nd convoy to a pre-installed convoy which is connected to one side the permanent mooring lines and to the other side auxiliary mooring lines to keep it in position during construction phase.

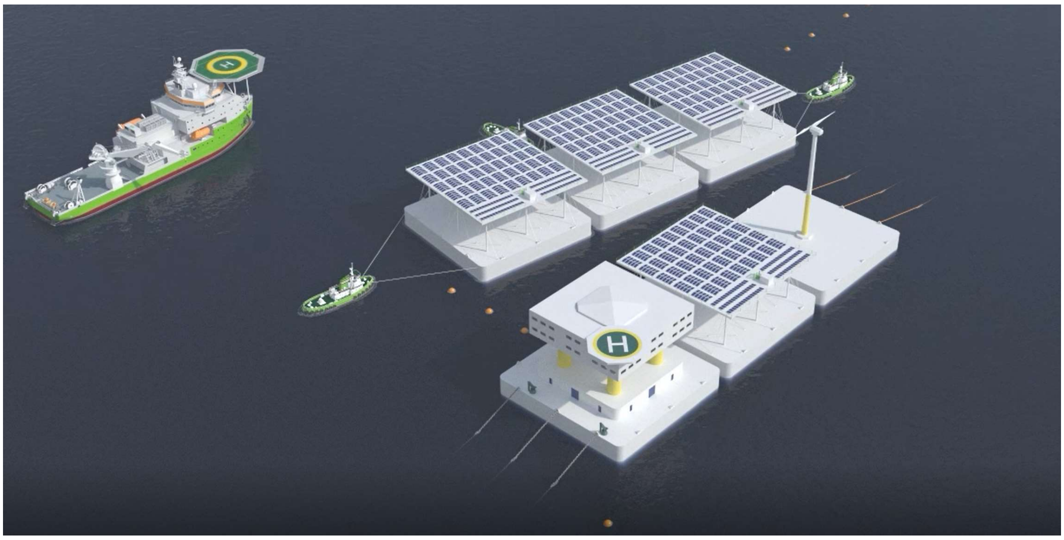

Figure 9: Installation of 2nd convoy

Maintenance

Operations and maintenance (O&M) of 'bottom fixed' offshore windfarms contribute with a substantial part of the total levelized cost of energy (LCOE). In general, the operational expenditures (OPEX) over a lifetime of 25 years equals the total capital expenditures (CAPEX) of an offshore wind, considering the engineering, procurement, construction and installation (EPCI). Additionally, the LCOE of an offshore 'floating' windfarm is currently higher than an offshore 'bottom fixed' windfarm, which means that keeping a floating structure operational is currently more expensive than fixed structures.

Developers of anchor foundations and mooring systems strive to design their products maintenance free. Even in case maintenance free design might be possible, it can be expected that this design is not economically feasible. Hence, O&M activities on future floating structure such as the *Space@Sea* floating island are required to ensure reliable operation throughout its lifetime. O&M activities of the *Space@Sea* floating island ARE based on the current O&M knowledge from offshore 'bottom fixed' and 'floating' windfarms.

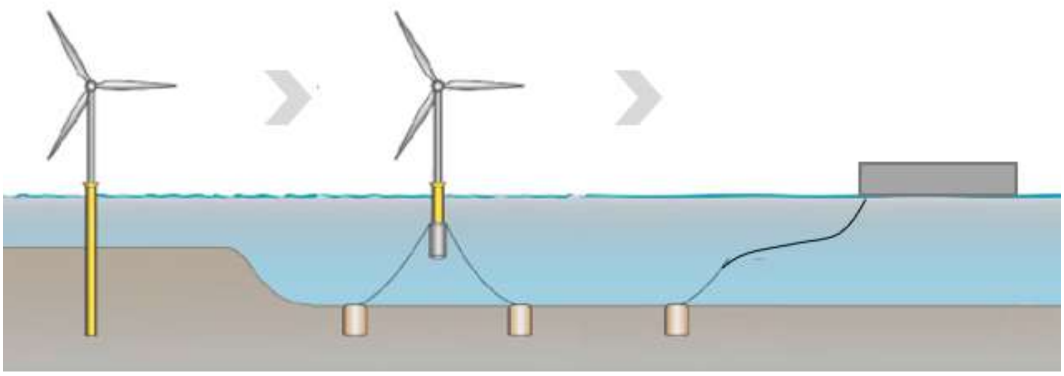

Figure 10: O&M activities Space@Sea floating island based on bottom-fixed and floating

The advantage of floating structures compared to fixed structures is the fact that they can be easily moved to (other) offshore locations, or even brought to shore for inspection and maintenance operations (e.g. at the quay side, in a dry dock). The latter prevents the use of large floating vessel performing floating to floating operations, which is a very risk full and challenging operation. Replacing floating modules out of the *Space@Sea* island configuration requires the same techniques and type of vessels as the Transport & Installation where an OCV is required to disconnect the mooring lines and tugboats for manoeuvring the floating modules out of the configuration and transporting to shore. Below figure shows an OCV disconnecting the mooring lines.

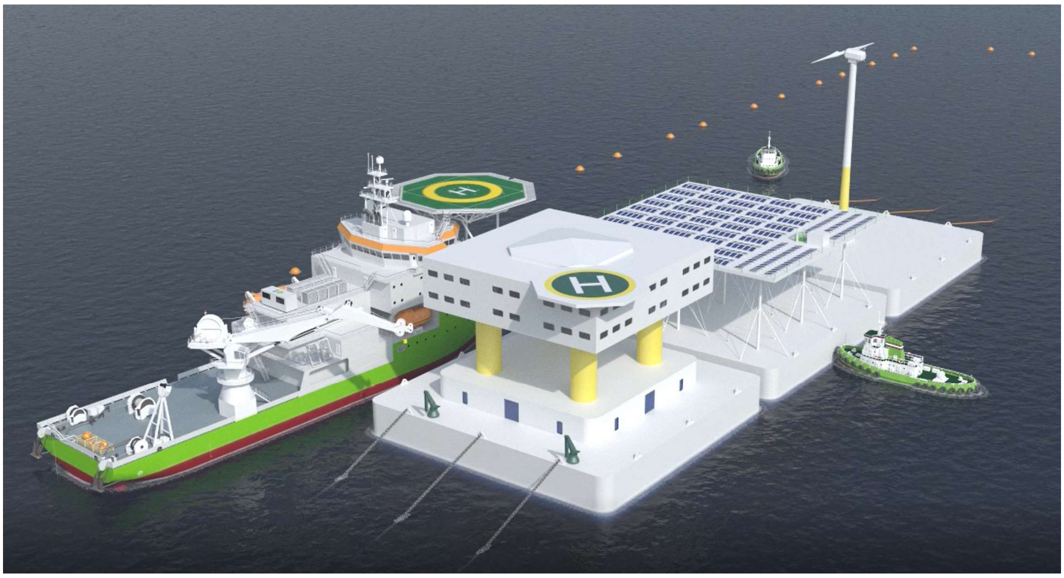

Figure 11: OCV disconnecting the mooring lines while tugboats are ready for towage

It should be noted that removing a floating module located in the centre of the island configuration requires more time and effort than floating modules at the outside. Below figure shows the island configuration where first the Wave Energy Converters (WEC) must be removed to be able to disconnect the mooring lines. Subsequently, the mooring lines needs to be displaced and kept afloat with buoys. From then on, a single or triple towage can be performed depending on which floating module needs to be removed. The operations for floating module replacements lies hand in hand with the design and layout of the island configuration.

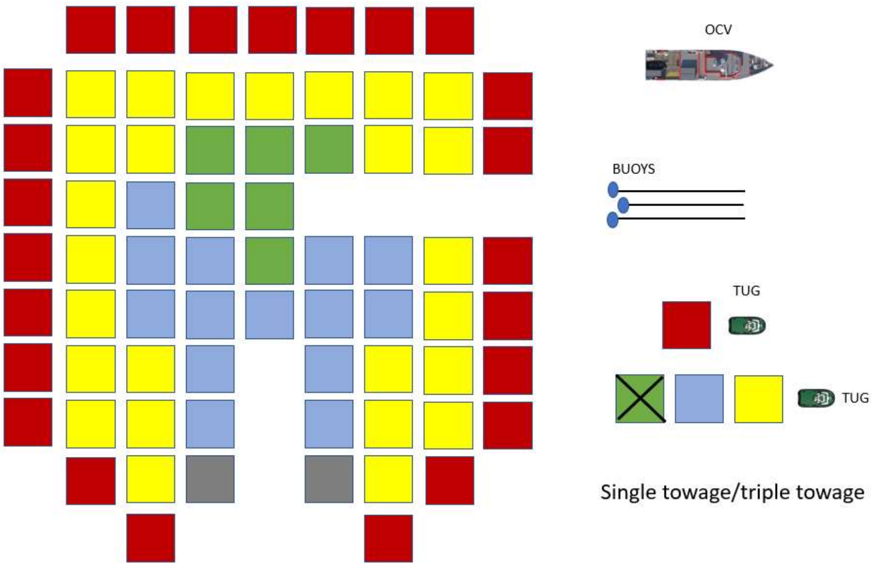

Figure 12: Removal of floating modules

Health, Safety and Environmental issues

Health, Safety and Environmental (HSE) requirements are very relevant aspects for the further development and future implementation of floating island constructions. The assessment of HSE issues is required to set standard preconditions for the floating island constructions. Particularly, the potential food and feed safety hazards as well as the associated environmental risks that may result from the multi-use platform environment is investigated.

The concise guidance presented by Space@Sea is based on different types of information:

- A hazard inventory (HAZID) elaborated in a risk register, and an evaluation of risks. This work is based on expert meetings and input from the four "application work packages" of the Space@Sea project, i.e. 'EnergyHub', 'Living', 'Farming' and 'Ports & Logistics'.
- An inventory of food safety issues in relation to multi-use of islands including aquaculture, based on literature study.
- An inventory of possible ecosystem-module interactions, i.e. the impact of the floating modules on the ecosystem, and the impact of the ecosystem on food production and the (integrity of) floating structures.

The issues considered in the HSE evaluation and their interactions are visualized in Figure 13.

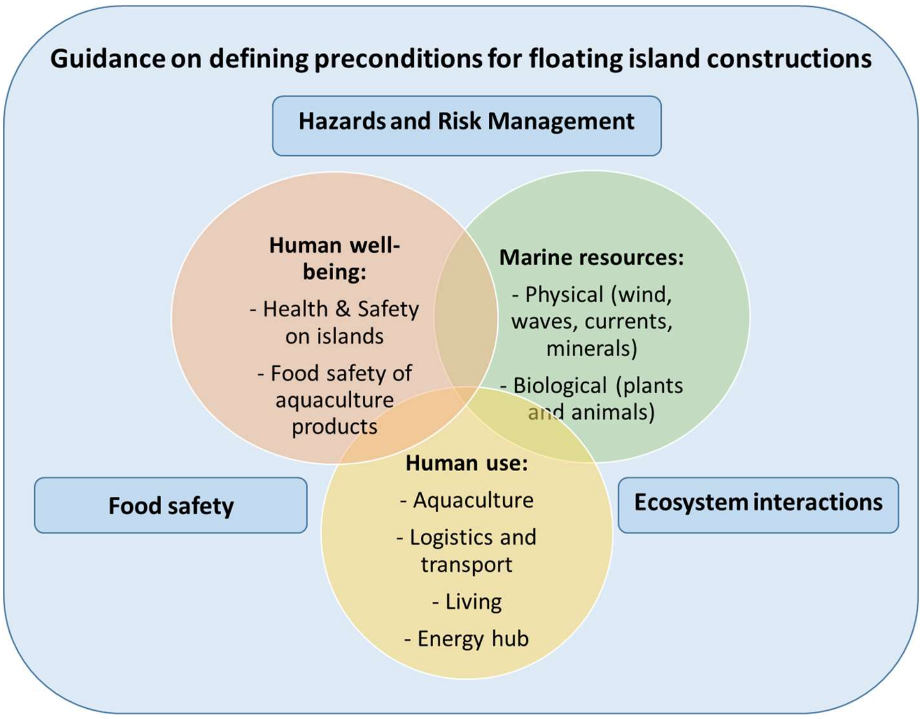

Figure 13: Guidance on defining preconditions for floating islands

Hazard and Risk Management

Reference is made to general and industry specific guidelines for HSE from the World Bank Group (www.ifc.org/ehsguideline) for all the applications considered within Space@Sea, i.e. the EnergyHub@Sea, Living@Sea, Farming@Sea and Transport&Logistics@Sea, and potential interactions between these activities.

As general and industry specific HSE guidelines are already available, the focus of this guidance document is on the hazards related to the unique aspects of the floating modular island for offshore applications:

- Motions, induced by the floating conditions.
- Distance, because of offshore applications.

On the basis of the HAZID, potential hazards related to the above mentioned aspects are identified and classified according to a Risk Assessment – Hazard Catalogue (BG RCI A017e)[4]

The hazards are evaluated for their risk potential and conceivable prevention and mitigation measures are discussed.

The nature of identified hazards is very diverse, and related to workplace design, mechanical hazards, electrical hazards, hazards related to spill of substances, fire and explosions, physical impacts, mental stress factors and others.

In general, preventive measures can be taken by limiting certain operations to environmental boundaries (low waves and wind conditions), by securing any lose equipment and tools, using clean and anti-skid floors, and installing handles and rails. Many, but not all, of these preventive measures can be included in the design of the floating modules and their applications.

Mitigating measures can be taken in several ways, such as the training of people for these special working and living conditions, including planned evacuations. Also, personal safety equipment may reduce the impact of incidents to people.

Food safety

The production of food at or in the vicinity of modular multi-use platforms may not only be facilitated but also be affected by other uses. This applies to the quality of food and feed products cultured at sea, where exposure to released materials and discharges may result in violation of quality standards. An overview of applicable standards is presented in this report. Standards apply to biological hazards, chemical hazards, and physical hazards.

4 https://downloadcenter.bgrci.de/resource/downloadcenter/downloads/A017e_Gesamtdokument.pdf

Discharge of wastewater and incidental spills from islands used for living and port operations may affect water quality. Also, other pressures like noise may affect the growth and well-being of cultured organisms, including fish.

Ecosystem interactions

Interactions with the environment include the impact of operations on the marine ecosystem, as well as the environmental provisions (e.g. nutrients for seaweed culture) and the impacts of the marine environment on structures (e.g. salinity, fouling organisms). An overview is provided of the potential pressures that may arise from the presence and functions of floating islands at sea on the marine environment.

The aquatic environment itself may or may not be a suitable place for the culturing of fish, mussels, and seaweed. This depends on the environmental preconditions that should be met, such as the range in water temperature, salinity, and food availability. For a selection of aquaculture species considered relevant to the Space@Sea project, an overview of these environmental preconditions has been compiled.

Two types of environmental impacts related to the lifetime and behaviour of offshore islands are relevant to consider: the effect of corrosion on the reinforcement of concrete, and the impact of fouling organisms. To minimize impacts on the structure, mitigating measures can be taken by setting up strategies for periodic inspection and maintenance of the floating structure and by covering of cracks in the concrete. Organisms attached to concrete structures, referred to as marine growth or fouling, may either protect or increase deterioration of their substrate. No clear conclusions can be drawn on whether fouling organisms should better be removed or not.

Business case evaluations

This section describes the economic business cases of the four individual applications and the two multi-use applications studied in the Space@Sea project. In evaluating the business cases a comparison between income and expenses was made from a business perspective. For some single-use cases this may be the right way to go, one application one owner. For many applications however, financing should be in line with creating of gravity-based islands where the government has a stake in the costs. A business case for governmental land development looks much wider at the problem considering also environmental, economic, and societal impacts which from a pure business economic point of view are seen as costs. In the discussion on future business cases the role of governments will be discussed.

Energyhub business case

When it comes to offshore renewable energy—from concept to product—is quite complicated by the challenges of the market. Getting the new technology or concept into the market requires a lot of upfront capital. It is always crucial for the developers to estimate the costs as accurately as possible at various stages for its entire lifespan. This section presents the research and findings of a business case study of a maintenance hub on a floating island developed in Space@Sea. The study evaluates the financial performance of the proposed Energyhub@Sea design.

The benchmark wind farm in this study is hypothetical and has a capacity of 100 units of 10 MW direct drive turbine. The lifespan for the energy hub is envisioned as 25 years. The energy hub consists of one floater with a concrete storage facility on top, as well as the living module for the workers. The virtue of robustness in the design will allow the maintenance hub downsizing and upsizing over time if needed. According to Soares (2018), the accommodation was designed to be minimalistic. Taking a regular 12 m^2 cabin for cruise-liners as a reference, the square metre prices for each room of the energy hub are extrapolated according to their size.

The business case study of the energy hub for the Mediterranean Sea site was conducted based on the available financial data. To highlight the benefits of the energy hub concept over other alternatives, costs comparison was further performed among the Energyhub@Sea, a fixed platform, as a few have been built for that purpose in recent years as per van der Heijden (2015) and a mothership, a viable alternative to fixed platforms as per Thomsen (2014). Looking at the cost comparisons depicted in Figure 14, it is apparent that zero opportunity energy costs brought about by the Energyhub@Sea and the fixed platform solutions phased out the mothership approach, which seems appealing at the first glance due to the lack of initial costs. The initial costs of the Energyhub@Sea are considerably cheaper with EUR 23.4 million compared to EUR 38 million for the fixed platform. During the design life cycle the Energyhub@Sea again performs better than the fixed platform. This is mainly due to higher expenses for maintenance and capital on the fixed platform side. Scrutinizing the total costs for these three different concepts, the Energyhub is outweighed by the least total costs in compared to other two solutions.

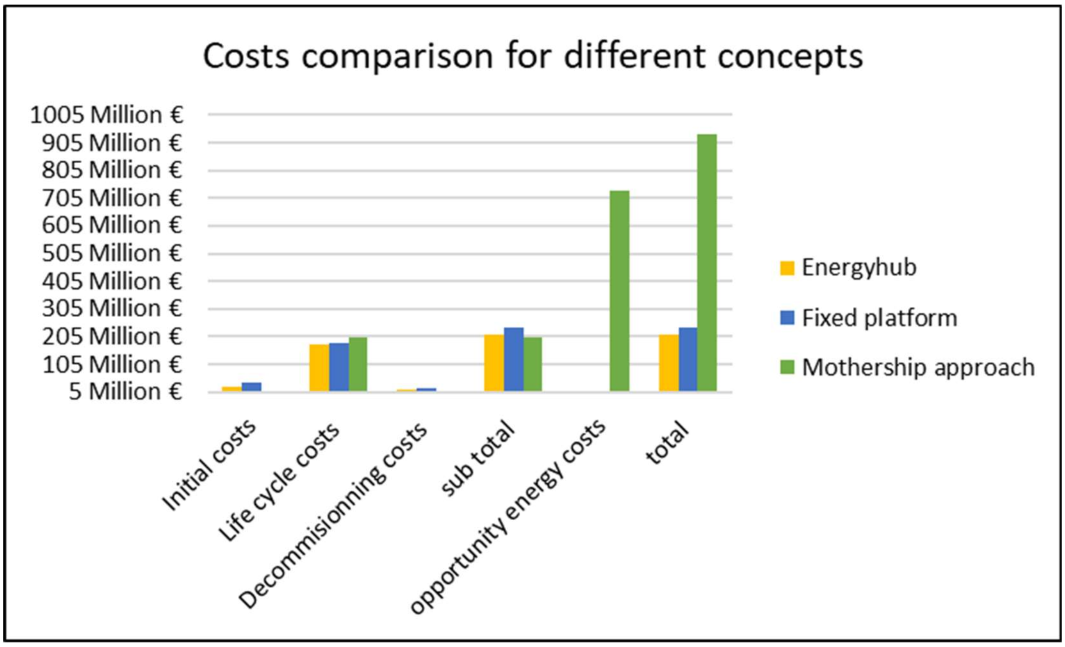

Figure 14: Costs comparison for different concepts

Besides these financial benefits, it is stated by Adam et al. (2021) that the energy hub overhauls the other two solutions by bringing other business benefits. These benefits involve:

- Provide maintenance basis: Energyhub@Sea solution serves as the operation and maintenance base for offshore wind parks and accommodate workers.
- Low costs: It offers a solution with both low capital and operational expenses.
- High wind park availability: It provides the highest possible wind park availability.
- Business flexibility: It could technically be moved to different locations.
- Innovation: It adopts new technologies and thus allows the company as a technological leader in that field.
- Best living conditions: Obviously the working and living conditions are influenced by the sea state. So, the energy hub could offer the best living conditions, provided that the sea state allow.

To sum up, the findings of the business case study prove that the energy hub solution is a commercially viable concept for the operation and maintenance of offshore wind farms. The innovations brought about by the Energyhub@Sea solution can accelerate the pace of progress in floating offshore wind farms, reducing the levelized costs of energy and downtimes.

Living business case

The Living@Sea business case investigates into the financial feasibility for the use of floating modular blocks developed for only living purpose at sea. A preliminary business case has been made for the Southern French coast, Bay of Montpellier, in the Mediterranean Sea. The objective is to analyse how the final designs of the modules, connectors and mooring systems developed within the Space@Sea project could provide justification for a possible investment proposition for Living@Sea at this location. Two scenarios or case studies have been formulated and used as baselines in the study: "Case I: Offshore Industrial Floating Accommodation" and "Case 2: Nearshore Urban Floating Community". By collecting and analysing info of both monetary and non-monetary indicators from floating development and other common practices such as offshore accommodation barges and land reclamation, a relative comparison has been made. It should be noted that the focus of the costs lies on the acquisition and implementation phases as they were presumed to make up the largest part in the calculations.

The results of the business case have shown that floating development appear to be financially more interesting than land reclamation for near-shore conditions, and more interesting than accommodation barges for offshore conditions. Living@Sea makes an appealing business case when placed near coastal cities where real estate values are high, and where connectivity to mainland is possible. Its flexibility creates room for innovative urban planning and its adaptivity to changing water level is another important asset. In comparison to land reclamation, floating uses much less sand/materials, creating much less negative environmental impact. Moreover, floating has faster building time (thus faster return of investment). In the urban or nearshore environment, the unit price of floating per Usable Floor Area (€3,037/m^2) could be competitive to that of which land reclamation costs (€4,335/m2). The costs for the newly created land, only the space of the modular floating platforms without any superstructures is €2,951/m^2 and respectively €5,203/m2.; whereas, in offshore environment, floating is also found to be more cost efficient (€4,062/m^2) than offshore barges (€5,000-€10,000/m^2). To optimize this business result, one could either decrease the time needed to build, certify and install the platforms from 4 to 3 years, so as to speed up paying back for the loan, or increase the unit sales price from €5,000 to €6,000/m^2.

Based on the preliminary designs of modules and their sub-systems for Space@Sea, it has been concluded that Living@Sea could yield a positive business case. However, many uncertainties and unknowns still need to be investigated further. For instance, the manufacturing strategy, the means of transport and installation process the floating structures, regulations ownership issues, insurance as well as the market value of these units. These all need to be found out to generate more accurate financial projections.

Aquaculture business case

Within Farming@Sea options are explored for the possibilities of offshore production of various groups of species (micro-algae, seaweeds, mussels, fish) by making use of floating modules as being developed in Space@Sea. The purpose of the business cases described here is to assess the economic feasibility of producing mussels and sea bream offshore by making use of floating modular islands.

North Sea – Mussel farming

Considering mussel farming, the business case elaborated here could encourage mussel farmers to expand their business to offshore areas. The mussels are cultured on longline systems, suspended in the vicinity of the floating island. The floating island is used as a processing site, and as an area for operation and maintenance activities. The business case intends to expand the production volume of mussels and to transpose (part of) production from the nature conservation area of the Wadden Sea to the coastal North Sea. There is a high biological potential for the offshore culturing of mussels, but the sector is still reluctant to invest for several reasons, including the high costs for technology and ships that can withstand offshore conditions. The floating modules as developed within Space@Sea could remove part of these constraints by providing suitable workspace in the operation and maintenance of mussel culturing. By applying the multi-use aspect to the floating islands investment costs can be shared with other industries.

Different types of information have been collected from several sources to assess costs and revenues, these included biological data on growth and production of mussels, capital investments needed for the culturing systems, and costs for the processing of mussels. Relevant information was mainly found for the ongoing bottom culturing of mussels in the Netherlands, longline systems in Denmark, and additional publications from international aquaculture sources such as STECF. A period of 25 years was taken into account for this business case, since a longer term would introduce too much uncertainty is the estimates.

With overall costs of €236 million and total income of €247 million, the profit would amount to €11 million over the entire 25-year period of time, excluding the costs for the use of floating modules. The activities for this business case would require 4 modules and the costs of modules should not be higher than this to achieve a profitable business case. Further reductions of costs should be further studied in relation to the multi-use of floating islands. Cost savings could possibly result from sharing space, facilities, and activities with other use at the island.

The price of mussels appears to have a major impact on the financial performance of the offshore Space@Sea farm. Therefore, negative impacts on the growth and quality of mussels pose a high risk to the business case. Also, incidents, such as severe storms events, may not only damage the culturing systems for which a re-investment is needed, but also reduce the revenues by destroying part of the production of mussels.

Applications in sheltered areas such as fjords and bays will off course reduce these risks.

The assessment shows that the business case may well be viable in case costs savings could be achieved, e.g. by profiting from multi-use benefits. However, also additional costs may become evident from such an analysis. Apart from the financial performance of a mussel farm, the offshore production of mussels also has additional benefits to nature and environment and stimulates economic development in the vicinity of the farming location.

Mediterranean – Sea bream farming

For culturing of Gilthead sea bream, we assessed the economic feasibility of using recirculating aquaculture systems (RAS) in the Mediterranean Sea placed on top of a floating modular island. The use of closed systems would considerably reduce the environmental footprint of the aquaculture of finfish. Furthermore, an offshore location would have less interferences with other human activities in the coastal zone. For the business case a high fish production volume was chosen as it would contribute to the aim to increase food production derived from marine waters. By making use of a multi-use set-up of a modular floating island, faming of sea bream in a RAS system could benefit from facilities and activities related to energy supply, accommodation for workers and transport and logistics.

The designed aquaculture facility requires many modules. It is estimated that about 150 modules each measuring 45x45 m are required to produce the aimed 50.000 tonnes of sea bream per year. Even without considering the costs for modules (either rent or purchase), the business case appears not to be profitable.

Given the assumptions made and the many uncertainties that are involved it is unlikely that culturing of seabream on floating modules in offshore areas will become profitable in the future.

Transport and logistics business case

The business case of the Transport&Logistics@Sea (T&L@Sea) hub is a detailed comparison between the modular floating (T&L@Sea) hub that is being developed in the Space@Sea project, and respective container terminals situated onshore. Considering that the Port of Antwerp (PoA) is already considering expansion further along the river Scheldt the T&L@Sea hub is examined as a potential alternative to normal onshore expansion or via land reclamation. The question to be answered was whether the T&L@Sea hub can fulfil the purposes of a container terminal, and under which circumstances it can be more beneficial than the two major alternative solutions, an onshore terminal and a terminal situated on reclaimed land. Additionally, two other locations are examined as potential deployment sites with different characteristics.

A smaller T&L@Sea hub outside the Port of Genoa which has limited inland expansion opportunities and is situated at deeper water depths compared to the North Sea, and a much smaller scale disaster relief effort off the coast of Africa that is operated for 1 month rather than years and does not require a lengthy installation process like the long-term alternatives.

The T&L business case is explored from the point of view of the two main stakeholders related to the development and operation of a port terminal – the relevant port authority and the terminal operator. The port authority is the one that is shouldering the investment costs for all civil works related to a terminal, while the terminal operator will procure the equipment, is responsible for the operational and maintenance costs, and usually leases the land (where applicable) from the port authority.

Based on the results, the T&L@Sea hub cannot achieve lower costs than either of the 2 alternatives, resulting in 1,8 to 4,1 times higher Financial Net Present Values (FNPVs) in all cases. The main reason is the high construction costs of the modules that comprise the platform, and the constraints of the modules requiring an equipment unit present on each module, leading to significant equipment acquisition and maintenance costs. However, if the module related costs and the on platform handling of containers can be improved via smarter design (leading to a reduction in equipment required), the T&L@Sea hub can potentially become an attractive alternative for land reclamation onshore terminals.

Looking at the T&L@Sea hub as an independent project, it is clear from the results throughout this business case that efforts need to be focused on reducing the cost of modules, try to secure high EU contributions and/or low public and private loans, and a low discount rate for the duration of the project, since these factors have the most significant impact on the FNPVs in all cases.

The results from two smaller cases examined a smaller scale T&L@Sea hub off the coast of Genoa and as a temporary disaster relief effort, still not favour the T&L@Sea hub as a direct competitor of onshore ports. However, in cases of deep water and extremely limited possibilities for expansion, such as the Genoa port, or for short-lived specialized operations, a T&L@Sea hub might be the best available choice, as currently there are no feasible alternatives.

However, the T&L@Sea hub offers numerous non-monetary benefits (or non-direct monetary benefits), which may make it a viable option for certain cases, either as an extension of the Antwerp port or as a standalone project. Reduced vessel turnaround times, flexibility in size/operations, low environmental impact and opportunities for temporary deployment may be deciding factors for the realization of such a project.

Multi-use business case North Sea

The multi-use business case evaluated for the North Sea has as main function a transport and logistics hub for the container terminal of the port of Antwerp. The port function is complimented with functions for aquaculture (mussels), offshore energy service hub and living facilities. Figure 15 shows the location of the North Sea multi-use island in the Southern North Sea just outside the mouth of the Schelde river. Figure 16 shows the layout of the island which is composed completely of the 45x45 m floaters. A total of 109 floaters completes the island, 96 of these are for the floating port, 4 each for living and farming and 5 for the energy hub. The total surface area of the island is 221,000 m^2.

As main purpose the island functions as an extension of the port of Antwerp's container terminal. Large vessels will not have to navigate the narrow locks and can call at the floating island from which the cargo is distributed to the Port of Antwerp and/or the hinterland. This makes it close to the single-use business case on transport and logistics described before.

Environmental conditions in the North Sea can be harsh. The average wave height is 2.2 metres with a zero up-crossing period of 9.9 seconds. The water depth at this specific location is approximately 25 metres. A mooring design was evaluated for this case; however, it was found that the water depth was insufficient to use catenary mooring system. It was decided to use a floating breakwater to reduce the wave height at the floating island. The costs for the breakwater are not included in the business case evaluation. Costs for the mooring were extrapolated from the mooring design for the business case in deep water in the Mediterranean Sea.

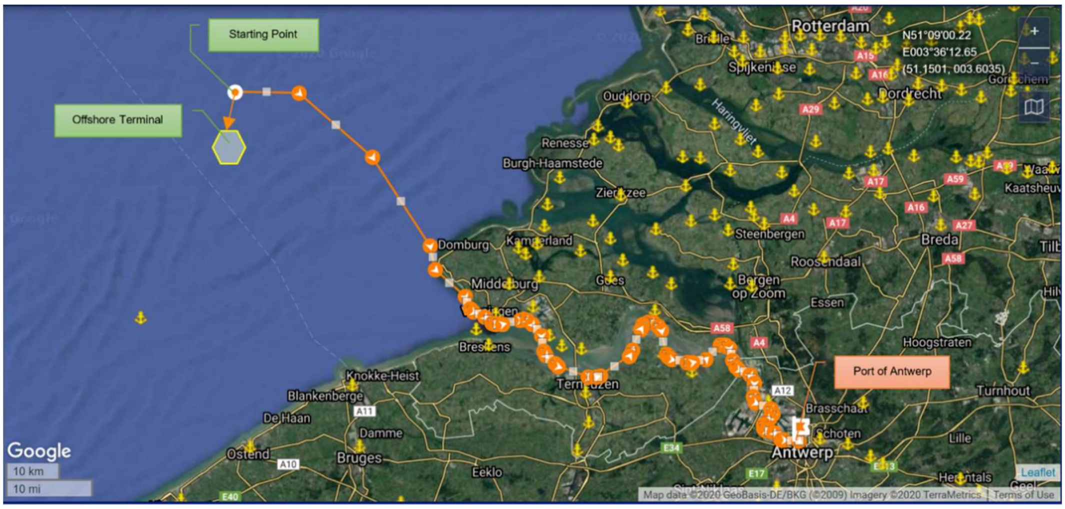

Figure 15: Location of North Sea multi-use island

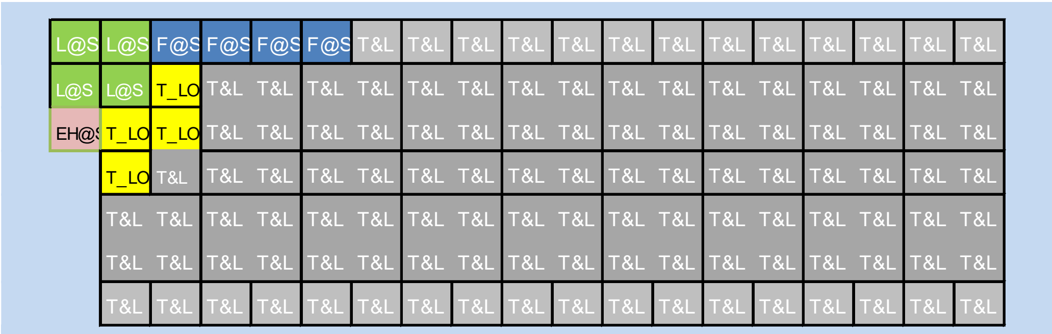

Figure 16: Layout of North Sea multi-use island

To place the business case of the floating multi-use island on the North Sea in perspective, a comparison is made to land reclamation as industry standard. Land reclamation is a feasible and often used approach for relatively shallow water conditions and can be done by poldering or infilling. In this case, infilling was chosen as approach which was also the approach used in case of the nearby located Maasvlakte II.

For both alternatives the CAPEX and OPEX are calculated based on the input from the single-use applications described above. Financial assumptions made in this business case are extensively described in Space@Sea Deliverable D1.1 (Ahrouch and Breuls (2020)).

Table 1 shows the results of the CAPEX and OPEX calculations for the North Sea multi-use island. This clearly shows that both from a CAPEX and OPEX point of view the floating solution is inferior to land reclamation for this location. It is expected that for increasing water depth the costs for land reclamation increases drastically, resulting in floating solutions being more attractive.

Table 1: Results of business case comparison for North Sea multi-use island

North Sea multi-use island Comparison				
	CAPEX			
Module Type	S@S [M. €]	Landfilled [M. €]	Delta [M. €]	Ratio [-]
T&L@Sea	1438,8	794,6	**-644,2**	**1,81**
Living@Sea	78,7	38,5	**-40,2**	**2,05**
EnergyHub@Sea	18,4	10,0	**-8,4**	**1,84**
Farming@Sea	53,0	25,7	**-27,3**	**2,06**
Total	1588,9	868,8	**-720,1**	**1,83**
	OPEX			
Module Type	S@S [M. €]	Module Type	S@S [M. €]	Module Type
T&L@Sea	76,1	49,1	**-27,0**	**1,55**
Living@Sea	3,9	3,4	**-0,5**	**1,15**
EnergyHub@Sea	5,9	5,8	**-0,2**	**1,03**
Farming@Sea	17,5	16,7	**-0,8**	**1,05**
Total	103,4	74,9	**-28,5**	**1,38**

Multi-use business case Mediterranean

The Mediterranean multi-use floating island has as main function the energy hub, supporting the maintenance of nearby floating wind farms. The location is of the coast of Montpellier in the south of France as shown in Figure 17. As can be seen from Figure 18, the island is built up of 51 floaters for energy which consists of 1 storage and maintenance building, 25 floaters with solar panels and 1 floater with a wind turbine. Additionally, 7 living floaters, 2 transport floaters and 15 aquafarming (sea brass) floaters complete the multi-use island.

As main function the multi-use island acts as a service station to (future) wind farms in the vicinity. This has great overlap with the single-use application studied for the EnergyHub@Sea and reduces the travel time for maintenance crew to and from the wind farms. The living facilities are meant for the maintenance personnel and for the personnel operating the aquaculture function.

The water depth at the location is approximately 100 metres with a significant wave height of 6.1 metres. For these conditions a mooring system was designed and reported by van Rossum and Otto (2020). A catenary based mooring solution was chosen with large diameter chains (157 mm) with 3 mooring legs attached to the mooring module (and a spacing of 15 m between the mooring legs) as shown in Figure 18.

Figure 17: Location of Mediterranean multi-use floating island

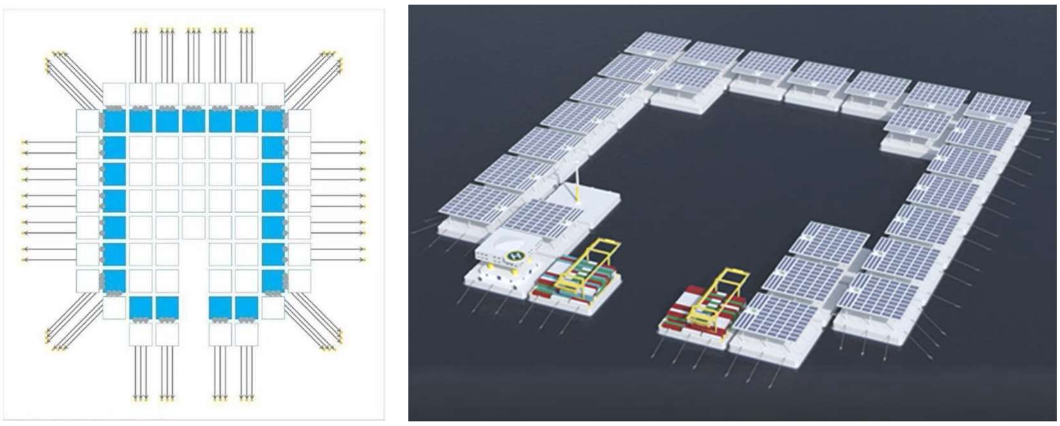

Figure 18: Layout of Mediterranean multi-use floating island

To place the business case of the floating multi-use island on the Mediterranean in perspective, a comparison is made to a commonly used Fixed Jacket. A jacket is often used in the offshore oil and gas industry up to a water depth of approximately 150 metres. A fixed jacket is a steel frame supporting the deck and the topside in a fixed offshore platform which is located several metres above the water surface. As the deck of the jackets is located several tens of metres above the water surface, it is questionable if it is operable as transport and logistics platform. Mooring a (large) vessel is not possible as it generated high bending moments in the jacket structure. In the oil and gas industry, loading and unloading of goods is done with the vessel keeping position using its propellers and bow thrusters (Dynamic Positioning (DP)). Most transport vessels however, do not have an expensive DP system, greatly impacting the number of ships being able to call at the jacket type port.

For both alternatives the CAPEX and OPEX are calculated based on the input from the single-use applications described above. Financial assumptions made in this business case are extensively described in Space@Sea Deliverable D1.1 (Ahrouch and Breuls (2020).

Table 2 shows the results of the CAPEX and OPEX calculations for the Mediterranean multi-use island. This shows that the floating solution in this case is substantially more attractive from both the CAPEX and OPEX perspective. The CAPEX of the floating island is 50% lower than for the Jacket solution while the difference for the OPEX is much smaller. Only for the transport and logistics application the OPEX for the floating island is higher. On the other hand, as discussed above, it is questionable if a Jacket is a suitable solution for transport and logistics.

Table 2: Results of business case comparison for Mediterranean multi-use island

Mediterranean Sea business case Comparison				
	CAPEX			
Module Type	S@S [M. €]	Fixed Platform[M. €]	Delta [M. €]	Ratio [-]
T&L@Sea	33,3	69,8	36,5	0,48
Living@Sea	149,7	258,5	108,8	0,58
EnergyHub@Sea	542,8	1026,6	483,8	0,53
Farming@Sea	164,2	459,6	295,4	0,36
Total	890,0	1814,5	924,5	0,49
	OPEX			
Module Type	S@S [M. €]	Module Type	S@S [M. €]	Module Type
T&L@Sea	1,5	1,1	-0,5	1,42
Living@Sea	10,9	11,3	0,4	0,96
EnergyHub@Sea	160,0	160,8	0,7	1,00
Farming@Sea	18,2	18,2	0,0	1,00
Total	190,7	191,4	0,7	0,997

Development of the roadmap

The floating island development and deployment roadmap is the result of the Horizon 2020 research project Space@Sea. The results of 36 months of research, development, and many inspirational talks within the consortium and with stakeholders form the basis of this document. Work Package (WP) leaders of the project have contributed to the contents of the roadmap reviewing the results of their WPs as well as an outlook to work still to be done on these topics.

As a first development in the Space@Sea project focussed on the modular floater design, optimising size, shape, and floater types. Furthermore, an approach to mooring the islands was developed and Health Safety and Environmental issues were studied. For the generic floater design efficiency of the design for the applications considered in Space@Sea was accounted for.

Following the first design of the floaters the individual applications of floating islands were designed. Applications for floating islands are vast and wide, Space@Sea focussed on housing, aquaculture, offshore ports, and a maintenance hub for offshore energy. Developments on the offshore energy maintenance hub also included the development of a wave energy converter (WEC) attached to the floating island which also will contribute to damping the motions of the island. For each application a business case for a selected location or for multiple locations have been studied assuming single-use of the island. Subsequently, multi-use business cases have been studied for the application of a floating port in the North Sea and an energy hub in the Mediterranean Sea. Table 3 shows which applications are involved in these two multi-use business cases.

Table 3: Multi-use business cases

Business case	Housing	Aquaculture	Port	Maintenance hub
North Sea floating port	4 floaters	4 floaters	100 floaters	1 floater for maintenance.
Mediterranean energy hub	7 floaters	15 floaters	2 floaters	27 floaters for maintenance.

In parallel to the design of the applications and the business cases the installation and maintenance procedures were developed. Installation should be done as much as possible with standard vessels and adding or removing floaters to the overall island should be made easy. For the maintenance a remote monitoring approach was developed to monitor the condition of the critical components of a floating island.

The project partners have worked closely together with great interest in the overall developments. The multi-disciplinary team, all with different backgrounds, did a great job in getting the work to be concluded in this roadmap.

Space@Sea involved stakeholders from the maritime industry, offshore energy, and multi-use development sector. These stakeholders were involved through the Advisory Board which contributed to the half yearly General Assembly meetings.

Part 2

Barriers and recommendations of floating island developments

Part II: Barriers and recommendations of floating island developments

During the developments of Space@Sea recommendations for further work became apparent based on the experience gained. Furthermore, barriers have been identified which prevent multi-use floating islands to become reality. In this part these challenges are divided in technical challenges, regulatory challenges, and business case related challenges.

Technical challenges

One of the major challenges for the transport and installation of the floating *Space@Sea* island is the offshore connection of the floating modules to each other. WP5.4 has considered the rigid connectors which has an installation limit of maximum 0.5 m wave height, meaning that it is not possible to install the connectors when the waves are reaching this limit. Based on weather data on the considered location (e.g. Mediterranean Sea), wave heights below 0.5 m are very rare resulting in a large amount of weather delays.

Another challenge is that transport and installation, and especially the first sub activity 'anchor foundation and mooring line installation' is not a common use but is very dependent on the offshore location. Each location has its own weather conditions, soil type, water depths etc. and requires different type of marine and installation equipment. The proposed T&I method is based on the Mediterranean Sea location but cannot be taken as guideline for other potential locations.

As stated above, the floating *Space@Sea* island configuration should be designed such that each module can be reached with a crane type vessel and/or easy to be disconnected and pulled away from the island. Extra attention should be made on the centre modules which requires a risk full and challenging operation to remove them out of the island configuration.

Floater / Module design

One aspect about the floater design was, that it needs to fulfil all the applications' requirements. These applications – Living-, Farming-, Energyhub- and Transport&Logistics- @Sea – have quite different requirements that need to be respected throughout the development process. The requirements towards the floating island modules were of quite different nature. To streamline these requirements, they were categorized to foresee their impact on the floater design.

With regards to the required deck space, it became clear that some of the applications will not be feasible with the initially proposed equilateral triangular floater design. Especially the applications Living@Sea and Transport&Logistics@Sea emphasized the importance of large, uninterrupted deck space to accommodate all aspects of their applications. Large structures with more than 50 m side length are currently not manufacturable in European shipyards and global availability is also scarce. Considerations were made, that in case an industry standard of modular floating islands is successfully developed, shipyards will adapt and make the manufacturing of such large structures available.

Therefore, the decision was made to have a base size of 45 m side length, while bigger island modules could be integrated with the requirement to have a side length of x times 45 plus x-1 times gap size.

Regarding the shape of the modules, it was concluded that triangular shapes have a significantly smaller ground space index (GSI) compared to rectangular shapes. GSI describes the proportion of space covered by buildings in relation to the overall space. Within the Living@Sea application different hexagonal urban plans, based on a triangular grid were analysed – namely New Delhi and Detroit. While the Detroit layout features triangles of 760 m side length, both concepts failed as the hexagonal plan was only applied to the very city centre and all subsequent city expansion was done in an orthogonal manner. However, urban development is not the only system that would be challenged by a hexagonal plan of limited proportions. High-yield agricultural systems are also organized in a linear, orthogonal fashion as are manufacturing plants and many other industrial sites. As every triangle has three pointy parts, a lot of the created Space@Sea would end up unusable.

Therefore, it was decided to have a quadratically base shape of the modules.

Mooring

Several factors influenced the mooring design, which are elaborated below and were mainly due to the (limited) time-schedule, typical for these types of projects.

E.g. the offshore industry projects mooring design can only start if the moored object is known and extensive data is collected on metocean and geotechnical aspects. These data were not readily available in the Horizon 2020 Space at Sea project, requiring conservative assumptions. It is recommended to have realistic data available in an early stage of a future project.

The complex floating island configurations were analysed with numerical and analytical methods and only very limited experimental basin data was available. Further validation and calibration basin tests are recommended to ensure that the simulations are sufficiently validated.

The calculations required for the design of a mooring system for the floating island configuration, given the number of individual modules in combination with a huge number of mooring lines, are exceeding today's desktop computer power and require large scale cluster-based CPU power. It is recommended to do further research in methodologies and algorithms that enable desktop computer calculations or initial estimates of the mooring system.

The first order loadings of the individual modules were independent of the global, second order behaviour. It is recommended to further optimize the sizing and clustering of modules, also in terms of width, to reduce unfavourable first order pitch motions and their impact on module interconnection loads.

The mooring system design for the North Sea conditions was not feasible in the selected shallow water location for the floating island. For these harsh conditions, it is recommended to investigate the impact and feasibility of fixed external breakwaters to reduce environmental conditions to which the islands are exposed. This involves detailed and complex site-specific environmental and coastal modelling of various hydrodynamic phenomena. It is noted that such breakwaters also affect the vessel manoeuvring area, which is relevant for island modules that include a port function.

Connectors and relative motions

Different types of connectors, having different levels of rigidity, can be envisaged. In principle, the less stiff the connector is the lower the module interaction forces are. On the other hand, a low stiffness of the connector implies larger relative motions between the modules. As part of the Space@Sea project two different approaches were investigated, a rigid one and a flexible one. Due to the higher relative movement, a flexible connector is capable of withstanding higher sea states. However, the higher relative movement makes it harder to build bridge constructions between the elements. Figure 19 shows an illustration of the biomechanical inspired flexible connection. The connection is made by running cables through the modules and placing fenders between the modules. This reflects for instance the human spine.

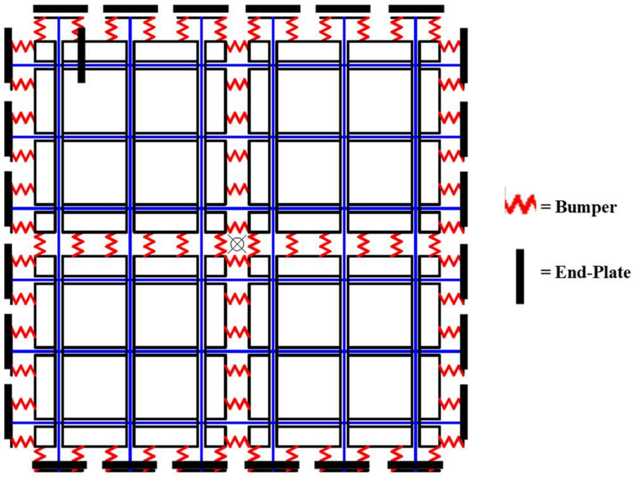

Figure 19: Illustration of the flexible connection

A rigid connector constrains all degrees of freedom leading to zero relative movement between the modules. For numerous applications this is desirable but comes with the disadvantage of high forces on the connectors as well as on the platform elements. During the Space@Sea project the rigid connection was investigated. It was concluded that forces in a fully rigid connection become so large that this type of connectors are only useable on locations with no risk of rough sea states or for the inner parts of big platform arrays, where the waves have already been damped by the outer modules. For future research there are still outstanding questions to be answered. Nothing is purely rigid. A concrete barge with a footprint of 90 m times 90 m has a certain inherent flexibility. When connecting four barges with a 45 m times 45 m footprint the rigidity in the connection does not have to be larger than the rigidity of the larger module. Furthermore, thorough specifications are necessary as to degree of rigidity that is required for different applications. The answer that it should be rigid is too simple here.

Moving toward a more rigid connection, the smart-flexible connector was developed. The developed is a combination of articulated steel components (yellow part in Figure 20) and cable connections (part left and right of the red plates in Figure 20). The cabling is placed inside the module and is under pretention. The connection itself allows for rotation around the vertical and one horizontal axis. The X shape of arms was chosen to decrease the forces components in the arms. Thus, the resulting force transmitted through the connection is bigger than each individual load in the X shape arms.

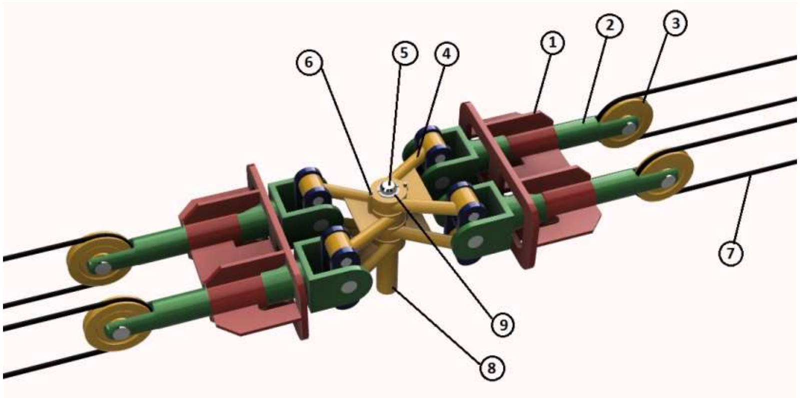

Figure 20: Illustration of the smart-flexible connector

The connector has two degrees of freedom that are free. However, when placed in a setup with multiple connectors between multiple modules, as illustrated in Figure 21, and in realistic wave conditions these degrees of freedom will inherently be restricted as well.

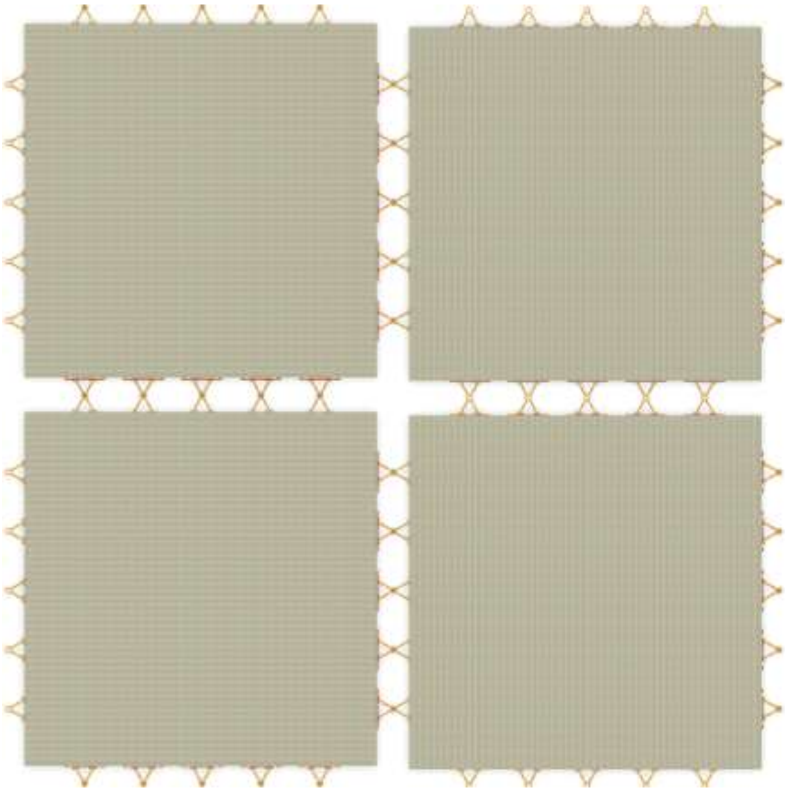

Figure 21: Illustration of four island connected with smart-flexible connectors

Regulatory challenges

One of the main bottlenecks which stifles the development and deployment of large-scale floating city/island development has to do with regulation and governance. Work Package 7 (WP7): Living@Sea investigates regulatory framework of floating city development from two key perspectives: offshore and urban. In its effort to collect the most relevant technical requirements for floating city development from these two distinct worlds, WP7 discovers that the most fundamental and important question needs to be answered first prior to being able to identify these requirements. That is, the definition and legal status of a floating city/island. The legal definition of a floating city determines what the legal rights and obligations are primarily of the coastal states, on the presumption that such floating island would be situated in the internal waters, the territorial sea, or the Exclusive Economic Zone (EEZ) of a coastal state. In this chapter, the definition of a floating city/island and general challenges are described shortly from different levels of law, followed by urban regulatory framework, maritime law and regulatory framework, rules and regulations regarding health and safety.

Definition in international law

A floating city consists of the substructure and superstructure. A superstructure refers to the part of the structure that is constructed above the "ground level" (i.e. the buildings); whereas, a substructure refers to the "foundation" (i.e. floaters). While the superstructure of a floating city can resemble buildings on land, it remains ambiguous what the substructure is legally. From the perspective of international law, it has been concluded that currently the term “floating cities/island” do not exist in the international Law of the Sea Convention (LOSC). None of the following labels could be attached to floating cities: “artificial island”, “installation or structure”, permanent harbour works”, “ship” or “vessel”. It also remains possible that floating cities may have different status when in different state (e.g., static, or dynamic). Although there is the possibility that floating cities could be regarded as “barges” as they float, such term does not exist in the LOSC and thus is as yet unregulated.

A more general definition of a floating island, which goes beyond the city / urban function, is from Flikkema et al (2021): “*an artificially created floater, or set of connected floaters, moored to the seabed of which the topside can be used for activities similar to activities on land*”. In this definition, the floating island can either be moored offshore or connected to shore as an urban extension.

Another highly relevant question still needs to be answered, on whether floating cities which situate close to the coastline and artificially connected to land territory will become an integral part of the mainland and artificially enlarge a coastal State’s land territory? This is important to find out to enable large-scale floating city development.

Definition in national law: case study of the Netherlands

The Netherlands is used as a case study country as it has long been prestigious for its water infrastructure and has a long history of experimenting with living on water. From the perspective of Dutch property law, the size of the platforms does not matter; however, the legal qualification of a floating house being regarded as a movable or immovable property does play a role in determining whether it is possible to design floating platforms that hold several buildings. Due to the Woonark Decision made by the Dutch Supreme Court in 2002, all floating houses fall under the definition of a ship and are regarded as movable property. This is an important factor which complicates and hinders floating development on a larger scale (more than one house per floating platform). Based on this principle, it is not possible to be the owner of a component part of a movable property. In other words, ownership cannot be divided, and it would not be possible to transfer one of the dwellings to a third party. Nor is it possible to establish a right of mortgage or pledge on behalf of a bank or financier. As a result, a floating platform with several houses on it is not or hardly financed. There is a solution to this, which is a legislation amendment and is currently ongoing in the Netherlands; however, such amendment will not solve all issues. Other practical challenges still need to be investigated, such as the possibility of 3D land registry, allowing floating structures to be registered as an immovable property.

Building regulations in the urban context

Building Decree, Building Code or Building Regulations are usually referred to when designing/building on land by architects and engineers. These legal instruments specify the minimum standards for the design, engineering, and construction of a safe, comfortable and/or efficient building. In recent years, there is an increasing amount of floating real estate being developed and built. The Netherlands is one of the front-runners that further defines regulations for floating urban development. Upon realising the benefits, needs, trends as well as risks of building on water, both the central and local Dutch governments have conducted studies or commissioned third parties to investigate into several technical aspects of floating structures over the course of time. The goal is to come up with standards to regulate the design and construction of buildings and ensure safety and comfort of inhabitants. These general standards have also led to amendment to the Building Decree 2012, particularly with regards to safety, healthy, usability, accessibility, escape route, plot boundary, constructive safety and spatial quality. It is speculated that more details will be filled in the future, depending on the urgency and necessity considered by the government.

Maritime law & Regulatory Framework

Regulations defining the framework for shipping environments has a prime focus on safety. Safety of marine operations in shipping is addressed by the International Maritime Organisation (IMO). IMO formulates and maintains a multitude of conventions that are ratified by the member states. A more general and legal framework to ensure not just the value, but also the safety of life at sea, was adopted after the disaster with RMS Titanic in 1912. This was the SOLAS or Safety of Life at Sea convention (1914-01-20). SOLAS states minimal requirements for construction, equipment, and operation of merchant ships. It has a focus on principal safety. In particular, the structural integrity of the ship structure and the equipment on board to be fit for purpose with respect to the sailing environment. SOLAS has been ratified by 164 member states in IMO and has been maintained by IMO since 1948. SOLAS is nowadays regarded as the most important of the international treaties concerning the safety of merchant ships.

Over the recent history, IMO introduced further conventions, STCW, MLC and MARPOL. STCW focuses on the required level of training for crew in order to maximize reliability of man-made decisions and minimize hazard of human error related incidents. MLC has a specific focus on the rights and wellbeing of seafarers on board ships. It is by origin from the International Labour Organisation but is organized by IMO. MARPOL has a focus on the preservation of the marine environment with a specific interest in limiting oil and exhaust emissions by ships. Together with the SOLAS convention these are referred to as the four pillars of the international Maritime Regulatory Regime. They affect the basic safety of operations at sea by:

- Requiring a structurally sound structure
  - **SOLAS** (International Convention for the Safety of Life at Sea)
- Have properly trained and certified staff operating them
  - **STCW** (International Convention on Standards of Training, Certification and Watch keeping for Seafarers)
- Making sure the on-board crews have good secondary terms of work
  - **MLC** (Maritime Labour Convention)
- Ensuring that risk of damage to the environment is minimized
  - **MARPOL** (International Convention for the Prevention of Pollution from Ships)

The offshore oil and gas industry introduced new players, technology, hazards, and risks to the maritime environment in comparison to merchant shipping. Different procedures were adapted, but the generic concept of regulatory framework remained like that in shipping. Both addressed the interests related to “Working at Sea”. The offshore industry originates from the (land based) oil and gas world. The asset values and risks that come with handling hydrocarbon energy products are higher than for merchant shipping.

Therefore, stricter regulations on health, safety and environment are usually applied than in shipping industry. While the topic of “Living@Sea” may now add another new branch to the scope of the more general “Life at Sea”, the outline of a regulatory framework for that new branch will likely be similar, but not identical to that for shipping and offshore.

The concept of “Living at Sea” on larger scale floating islands is a new kind of human activity on the oceans. Although the existing maritime regulatory framework does not seem to apply directly to “Living@Sea”, there does seem to be some structures and principles that can be extrapolated to the marine structures for permanent residential purpose. It is in line with the historical facts that the “urgency” of having marine structures for residential purpose will call for regulatory frameworks to be adjusted, in a way that will meet specific usage conditions instead of imposing a priori restrictions onto them. The development and introduction of the offshore industry in the 20th century brought new challenges with capital intensive assets, highly hazardous operations, and combined risks. Consequently, a different regulatory framework was adopted to match the need of the profitable offshore energy industry with corresponding strict safety requirements. The present four main “pillars” that form the maritime regulatory frameworks are related to:

- Safety of the structures,
- Limited impact on the environment,
- Properly trained and educated staff, and
- Wellbeing of workers.

These pillars support the coverage of financial risks by insurances and stakeholders, and operational risks by crews, passengers, and coastal communities. They should also be applied on the standards for Living@Sea.

Health and Safety

Offshore Health and Safety rules have been established for either offshore working conditions or leisure. Offshore working conditions are either from the shipping or oil and gas sectors, which represents different working conditions than other applications on floating islands. Offshore oil and gas health and safety regulations are focused on an industrial application requiring the use of coveralls, hardhats, and steel tipped shoes. These regulations are fit for its purpose in the oil and gas industry; however, they will be inconvenient for living conditions.

Nonetheless, health and safety regulations on a floating island intended for living will be different than for onshore living. Houses will move due to the motions of the sea, although the islands should be designed to minimize the motions, some motions will be inevitable in given conditions. This calls for health and safety regulations to prevent objects falling unexpectedly and prevent people falling over or falling in the water.

Health and Safety regulations on floating islands will need to be formulated based on zones such as living areas, public areas, working areas and hazardous working areas. These regulations should include maximum inclination angles in seaway as well as maximum vertical and horizontal accelerations. Also, guidelines and regulations regarding seafastening of objects needs to be in place. As motions are expected to be much less severe than on ships, no permanent seafastening of furniture is needed but they will need to have the possibility to be secured.

Finally, health and safety regulations should also include guidelines on what to do in case the maximum allowable values are exceeded. Emergency procedures need to be in place to in the ultimate emergency case evacuate the island or move all personnel to the safest area on the island. It is also required for inhabitants on the floating islands to keep in mind some safety rules, and for the entity that manages the floating island to establish and implement a Safety Management System.

Maritime Classification Rules

No regulatory framework is available for the design and verification of mooring systems of floating islands. As a starting point, the framework of rules, industry practices and standards as applicable in the oil and gas offshore industry is used. These are based on typical offshore structures as e.g. FPSO's which have a different reliability philosophy and background. However, the risk profile of an oil-gas floating platform with pollution risk and explosion risk from hydrocarbons differs from the applications in the business cases. The risks for these applications will be much lower, resulting in for example lower required safety factors. Furthermore, the floating islands are moored with many more mooring lines than typically used in mooring oil-gas floating platforms, having impact on the required redundancy and safety levels of the mooring systems.

For example, the standard approach for intact and one-line broken situations might need reconsideration. The involvement of a class society in these matters is highly recommended.

Due to the size of the islands, the uncertainty in the mooring calculations have increased. This uncertainty is not recognized in the existing framework of rules and regulations. New rules and guidelines are required for floating islands to mitigate this uncertainty and to ensure sufficient safety levels in their mooring systems. Furthermore, these new rules and guidelines should reflect differences related to design life maintenance plans, corrosion and abrasion of mooring and connecting elements, marine growth and protection.

For near coastal floating islands, local regulatory rules could become more important, certainly with respect to marine life requirements, dismantling requirements etc.

Maritime Spatial Planning

With increasing offshore activities for shipping, fishery, aquaculture, tourism, and renewable energy maritime spatial planning (MSP) is becoming more and more important. On the North Sea for example traffic lanes for shipping are in place to regulate the location of ships, outside these traffic lanes wind farms and other offshore activities arise.

The seas can be subdivided in three regions, territorial waters bordering coastal states within 12 nautical miles (nm) of the coastal; exclusive economic zones (EEZ) up to 200 nm from the shore where nations have extended rights; and the high seas where no claim of ownership is done. In the territorial waters and EEZ it is the nations having the rights who can mostly determine the location of activities, sometimes together with other bodies such as the EU. On the high seas there is no ownership and little regulation regarding placement of activities is present.

Floating islands on one hand are regarded as urban extension and planned close to the shore and existing activities mostly in the territorial waters and EEZ. For these activities member states and the EU will need to develop guidelines for the placement of floating islands and regulations for shipping in the vicinity of these islands. Placement of the island close to existing maritime activities is the most obvious as the already existing activities may also benefit from the presence of the island and the services on the island.

For the high seas regulations are needed governing which laws apply to the floating islands, perhaps a flag state approach as for ships can be considered. Furthermore, regulations are needed for where floating islands can be placed. From safety perspective it is desirable to have regulations on placement of floating islands.

It is imaginable that a country will not allow a floating island of a country with which they are in conflict just outside the EEZ in the high seas. Although Space@Sea did not design floating islands for military use, it is also not unrealistic that this will be a future use.

Additionally, a floating island just outside the EEZ on which goods will be produced against very low wages is undesirable as it can compromise the economic development of the country. Countries will need to get measures to protect themselves against unwanted settlement of a floating island close to their shores or EEZ.

For floating, multi-use, island development to be brought to the agenda, several stakeholders need to be involved such as local and regional governments as well as global institutions such as UN and IMO. Agreement is needed on regulations or guidelines for MSP for floating islands in the high seas and the governing regulations on floating islands outside territorial waters. The EU is well situated to take a leading role in these developments as much knowledge and experience on the topic is developed here.

Business cases and preferred applications

A technical solution is nothing without a business case for its applications. Space@Sea has studied four single-use business cases and two multi-use business cases consisting of these four applications. The Space@Sea solution specifically and floating islands in general are not limited to only these applications studied in this project. In general, a floating island is artificial land on which you can do the same activities as you could do on land. Although there are some limitations, the design is such that the motions of the island are limited and do not affect the activities.

Competitors of the technical solution of a floating island are artificial islands through landfill and fixed jacket structures as used in the offshore oil and gas industry. Landfill is economically more attractive for shallow water conditions, however, the environmental impact of creating new land is very large. Fixed jacket solutions are feasible up to larger water depths, however, not all applications are possible, for one because a vessel cannot be moored to a fixed jacket. For water depths beyond approximately 50 metres, a floating solution in any way is economically more attractive as was shown in the Space@Sea project (Ahrouch and Breuls (2020)).

First near shore applications are expected to be small scale urban expansion while first offshore applications are expected to be single-use renewable energy support structures. In the following sections there are further elaborated.

Single-use business cases

In this section the future potential for single-use business cases is described for four applications studied in the Space@Sea project. Although multi-use islands are more beneficial, it is expected that as a first step a single-use floating island will be developed to gain experience. In this case it is important to already account for the possibility to extend this single-use island with additional functions, making it a multi-use island. Modularity in the island and floater design therefore is also essential for single-use islands.

Living

A preliminary Living@Sea business case has been developed as a stand-alone application for the Southern French coast in the Mediterranean Sea. The business case was developed based on the designs of modules, connectors and mooring systems developed within Space@Sea. Living@Sea makes an appealing business case when placed near coastal cities where real estate values are high, and where connectivity to mainland is possible. Its flexibility creates room for innovative urban planning and its adaptivity to changing water level is another important asset. In comparison to land reclamation, floating uses much less sand/materials, creating much less negative environmental impact. Moreover, floating has faster building time (thus faster return of investment). The unit price of floating (€3,037/m^2) could be competitive to that of which land reclamation costs (€4,335/m^2). In offshore environment, floating is also found to be more cost efficient (€4,062/m^2) than offshore barges (€5,000-€10,000/m^2). Quite a few scenarios showed that Living@Sea could yield a positive outcome. However, many uncertainties and unknowns regarding regulations or the price that clients are willing to pay still need to be found out to generate more accurate financial projections.

Transport & Logistics

The T&L@Sea hub offers numerous non-monetary benefits, which may make it a viable option for certain cases, either as an extension of the Antwerp port or as a standalone project. The reduced vessel turnaround times, the flexibility in size/operations, the use in deep sea areas where a land extension would be more costly or even impossible, the low environmental impact and the opportunities for temporary deployment only may be deciding factors for the realization of such a project.

Despite higher costs, the existence of such a project may be an inevitability due to insufficient land for expansion. To enhance the business case for the T&L@Sea hub, future research must focus on optimizing module construction and relaxing some hard constraints relating to module connectivity, in order to reduce platform and equipment initial costs and maintenance. Additionally, the numerous qualitative benefits must be given appropriate weight in the decision to materialize such a project.

In cases of deep water and extremely limited possibilities for expansion, such as the Genoa port, or for short-lived specialized operations like disaster relief, a T&L@Sea hub might be the best available choice, as currently there are no feasible alternatives.

Aquaculture

Single-use floating aquaculture does not prove to be economically attractive from the single-use business case evaluation of Space@Sea. The reason for this is the relatively high price for the infrastructure compared to current aquaculture in sheltered water basins. Further offshore aquaculture is not specifically more beneficial than close to shore from a growth perspective.

The application of aquaculture is better fit to an existing floating island to make the floating island self-sufficient. Even in that case it is questionable if the aquaculture should be done on or connected to a dedicated floater or that floating cages close to the floating island are better suit. This will vary per location and per species which will need to be further studied when an opportunity arises.

Energy

The offshore energy sector is one of the most probably first sectors where floating islands will be applied. Renewable energy is moving further offshore as the near shore locations are becoming scarce. With the shift to further offshore comes an increase in water depth and a shift from bottom fixed wind turbines to floating wind turbines. To date supporting infrastructure for the wind farms such as converters have not been made floating, expensive sub-sea solutions are sought for. As shown in the multi-use business case for the Mediterranean, floating solutions at larger water depths are more attractive than Fixed Jacket solutions and most probably also for sub-sea solutions.

Wind power park owners and Transmission system operators (TSOs) will benefit from a floating solution for the support infrastructure. Case studies will need to be done to show the benefit of the floating solution and should include modularity and a view on the future. Where on the short term the focus will be on support infrastructure, the longer term will create the possibility for instance to include hydrogen generation plants on the floating islands to store and ship the generated energy.

Wind power parks which could benefit from the developments of Space@Sea and the applications are in the deeper waters for instance of the coast of Ireland, France, and Portugal in the Atlantic Ocean.

Multi-use applications and locations

Space@Sea partners believe that multi-use applications will follow single-use applications. These single-use applications will attract other activities, gradually moving from single-use to multi-use platforms. To facilitate this growth, floaters need to be modular so that other functions can easily be added.

As described in the previous sections, energy, logistics and living are expected to be the most feasible applications on the short term. For further offshore applications, the latter is a support function rather than a leading function as creating a settlement in the middle of the ocean without any activities does not seem feasible. For urban expansion, living is expected to be the main purpose of the floating island, although also here additional activities will be possible.

Further applications beyond the ones studied in Space@Sea are industry, energy production (for instance a floating nuclear power plant propose by Pater et al. (2020)) and tourism. For these applications, industry and tourism would primarily focus as extension of an existing island while energy production is promising as single-use starter for a multi-use floating island.

Locations for future multi-use islands are dictated by the location of the multi-use activities which will be the initiator of the floating island. This can be a coastal area requiring urban extension, a floating wind power park requiring support infrastructure or a port or airport requiring extension. Starting the first floating island application in the middle of the ocean however, is not the most obvious first application. Small-scale solutions will need to be initiated in “good weather area’s” to gain experience in floating solutions.

Key issue to be solved in the first multi-use applications is the governance and ownership of the general infrastructure. These issues will be addressed in the roadmap in Part III.

Benefit of multi-use

Combining applications in a shared island formation as discussed in the previous section has multiple benefits. Sharing of maintenance and assets will lead to a reduced costs per application. Management and organization of one large island is easier than management and organization for multiple small islands with each their individual use. With multi-use also transport of people and good to and from the island can be combined. Combining applications does not start from day one. Offshore applications will need to seek synergy advantages, for instance aquaculture and energy to be extended with high quality living arrangements for the workers. These activities will require port facilities for goods and people, production and repair facilities, grocery stores and leisure facilities all requiring workers for which housing is needed.

Gradually a city will start to form as workers luxury living facilities will be attractive for them to take their families. The creating of an offshore community with the potential to be expanded to a town or city is very likely. Multi-use of offshore space and offshore platforms (MUS and MUP) is inevitable in this philosophy. Key to this approach is the modular approach to floating islands where it is easy to extend the size of the island once new applications and services join the island formation.

Multi-use does not come with only benefits, there will also be some drawbacks. Currently we see attempts to share ocean space between aquaculture and wind energy. The latter is reluctant as adding functionalities increases the risks and liabilities while investors aim for keeping the risk as low as possible. This however, is a state of mind that has to be overcome with growing confidence in the technologies. Another drawback is that the applications will need to adapt to each other. For instance, housing next to a fish processing plant is not a good idea. “Urban” planning of the floating city is needed where applications are not in each other’s way like is being done on land. Again, the modularity can help here, if the floating island grows certain new applications can be placed as barrier between, in this example, living area’s and the fish processing plant.

In all multi-use of ocean space and platforms is inevitable for making floating islands a success. The opposite is also true, multi-use will only be a success with modular floating islands.

Role of governments in business cases

In the Space@Sea project individual and multi-use business cases have been made from a business economic point of view. This may however, not always be the right way to look at the viability of floating islands, societal and environmental impacts may be sufficient reason for governments to (also) take a role in floating islands.

For a single application such as an offshore energy support hub an economic business case evaluation is a viable approach as there is one main application that can be compared to current approaches. It would then be a joint business case for the Transmission System Operator (TSO) and the Wind Power Park (WPP) owner.

For governments other drivers such as societal and environmental impact are more important than the economic business case. Societal impacts such as the creation of jobs or (space for) housing are worth investing in for a government, like investments of governments in the creation of artificial lands by poldering or infilling.

In the Netherlands many local governments purchased agricultural ground surrounding their city for rapid urban expansion due to the scarcity of affordable housing. Local governments were tasked with creating space for houses and provided the ground to estate developers to create houses. This is what is called an active ground policy.

At the time of writing this roadmap, the Netherlands again is faced with a scarcity of housing, this time however, combined with an increasing scarcity of land. Not only has much of the country been built on, but the remaining natural areas should also be kept nature. This greatly increases the stress on the already existing urban areas, local governments should also be looking to the water for a solution. To challenge the housing scarcity, these governments can consider an active ground policy for floating ground.

Relation to multi-use of ocean space

The European Commission aims at strengthening the sea and ocean related economy called Blue Growth. Figure 22 shows the employment and economic potential of the European waters. Blue growth focus areas for further development are:

- Blue energy: generating renewable energy from ocean resources such as tidal, wave, ocean thermal and offshore wind energy. This sector will have a significant impact into achieving the Paris agreement climate goals. It is the objective of the EC to give further effort to reinforce research and development in the field of ocean energy are needed with the objective to further reduce costs.
- Aquaculture: growing fish, seafood, and marine crops to be used directly as food or feed for other animals. The EC aims to increase the aquaculture production by informing member states of sustainable aquaculture solutions.
- Maritime, coastal and cruise tourism: attracting people to make use of the coast and seas for leisure such as cruises, leisure craft, swimming, sailing, diving, and snorkelling. It is the objective of the EC to boost the tourism industry by boosting maritime and coastal tourism.
- Marine mineral resources: advances in technologies and concerns regarding security of supply of minerals have urged mining companies to consider what minerals the sea can provide. By 2020 5% of the world's minerals could come from the ocean, not only looking at shallow water sources but also exploring the deeper seas. EU support could include measures to ensure that European companies are not squeezed out of the value chain for marine minerals by state-supported competitors.
- Blue biotechnology: exploring underwater life has the potential to uncover a great deal of yet unexplored capacity of marine organisms. Research is needed to further investigate the potential of marine biotechnology; the EU can support this acceleration by a combination of basic and applied research.

Drivers for most of the above-mentioned focus areas are cost reductions. Synergy advantages through multi-use of ocean space or multi-use of platforms will contribute to reducing the costs of individual applications.

The above list shows the European Blue Growth ambition which will increase activity at sea next to the already existing shipping, fishery, energy, and mining activities.

Multi-use of ocean space, meaning multiple activities to take place in the same space possibly at the same time, is inevitable. Some activities require a static ship or platform for parts of the envisaged activities. Sharing assets such as ships or platforms is called multi-use platforms and has a large potential to reduce the overall costs.

A floating island provides deck space for multiple activities in parallel from which the above-mentioned blue growth activities can be done. Although a floating island may be costly, sharing the infrastructure costs over multiple stakeholders and activities on the island will reduce the costs per activity. Selecting the optimal location of the island is important and needs to be a weighted optimum between the various activities and stakeholders.

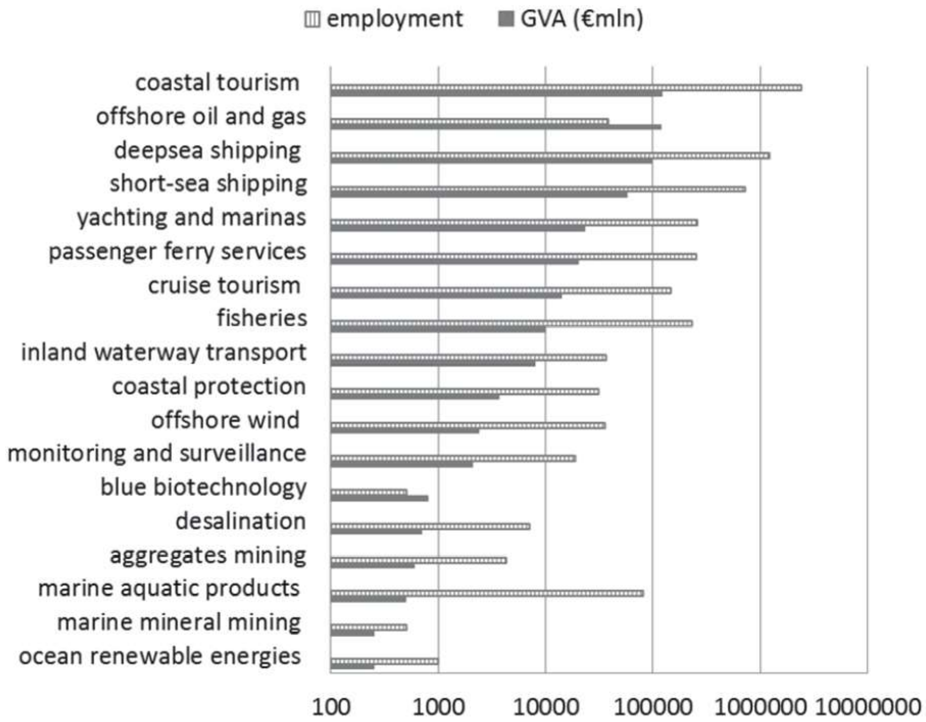

Figure 22: Scope of EU Blue Economy[5]

The Horizon 2020 project MUSES has delivered an extensive "Ocean Multi-Use action Plan" (Schultz-Zehden et al. (2018)). In this document multiple multi-use combinations are discussed focussing on tourism, fisheries, environmental protection, aquaculture, offshore wind, wave energy and oil and gas decommissioning. Although the focus here is on multi-use of ocean space, some combinations will benefit from a multi-use platform. According to the action plan *Multi-use needs to be proactively facilitated and incentivised*, which calls for an active role of regulatory bodies and governments.

5 European Union, 2012, *Blue Growth Opportunities for marine and maritime sustainable growth*.

In the Horizon 2020 project UNITED several pilot applications for multi-use platforms is studied on the topics of renewable energy, aquaculture, bio-resources, tourism, and maritime transport. UNITED focusses on the business potential of several locations for multi-use platforms and is thereby complimentary to the work done in Space@Sea.

Floating islands can contribute to accelerating sharing of ocean space for multiple activities by sharing (costs for) assets. Many of the activities will need a central point, either for storage of spares, as based for support activities or to perform the activities from. Space@Sea has shown that for aquaculture single-use islands are too expensive, if the main infrastructure however, can be combined with for instance support services for offshore energy installations the overall costs will go down greatly.

Multi-use furthermore has the potential to attract further activities, once a shared platform is initiated, other industries operating in the area will investigate the possibilities of joining. Modularity of the floating island will then ease the expanding of the island and growing of the number of activities on the multi-use floating island.

The Space@Sea project developed a floating island solution with a floating city in mind for the future. A floating city per definition is a multi-use platform and as any other city activities and functions will come and go. Flexibility in the design of the floater supporting floating islands is essential in providing support for real multi-use applications. In modularity, standardisation of connection and anchoring points is essential, other aspects such as draught and activities on top of the floater are secondary.

Part 3

Roadmap and way ahead

Part III: Roadmap and way ahead

In this third and final part of the Floating Islands Development and Deployment Roadmap the way ahead is sketched giving required developments, priorities, roles, and a timeline. This roadmap is the view of the Space@Sea consortium and is meant to inform stakeholders a possible way forward and evoke their (re-)action.

There are many stakeholders in the process to multi-use floating islands ranging from owners / operators of the applications, builders / developers of floaters, governmental organisations and regulators to future inhabitants or workers. All stakeholders hold part of the puzzle that needs to be completed to create the first multi-use floating island.

The outcome of Space@Sea is a first step to a technical solution for floating islands. We are very much aware that this will not be the only possible solution for floating islands. Moreover, the Space@Sea concept is under development and remaining technical challenges need to be addressed. Some main challenges, as will be discussed below, focus on governance and regulatory issues. Many of these non-technical issues are not solved if there is not technical solution to solve it for, the Space@Sea solution can be used as initiator and accelerator for these discussions.

Future developments

Space@Sea has delivered a technical concept to Technology Readiness Level 5, to go beyond this to full commercialisation further developments are needed. Lessons learned from the technical developments have directed towards future developments needed to reach commercialisation. In this section these headline developments are discussed.

Technical

Technical developments are obtained from the design work of Space@Sea which is an iterative process. The last iteration in the project has resulted in the concept design. This design has left room for further optimisation in the next iteration. The following technical developments are needed according to the Space@Sea consortium:

- Durable materials for the floater structure need to be studied, Space@Sea considered existing materials such as steel and concrete. Innovations in materials such as the buoyant concrete (Veenendaal et al. (2020)) may have a beneficial influence on the lifetime of floaters and on the costs.

- A rigid connector between the floaters which can cope with high loads needs to be developed. Rigid connections are needed to ease the transfer of people and goods between the floaters. Although in most conditions the connection forces for a rigid connection are limited, some conditions may induce excessive forces. A solution in which the connector is rigid in mild conditions but can be made to act flexible under heavy load or storm conditions would be beneficial to reduce the loads in the structure.
- Space@Sea approached modularity by introducing two sizes of similar shaped floaters, assuming also the height of each floater would be equal. In seeking the optimal shape, it became apparent that different applications may have different requirements regarding the shape and size of the floater. To facilitate these different requirements but still conforming to modularity, an approach is proposed in which the type and location of the connectors is standardised as well as the height of the deck above the water surface. In this way, different shapes and sizes of floaters can be connected to form a complete floating island. Doing this will make the layout design (urban planning) of the floating island more challenging, but it will better facilitate the different requirements of the different applications.
- As mooring for the island, a relatively standard catenary mooring system was designed to cope with the environmental conditions. The mooring design was optimised allowing for only limited motions. If we would allow more horizontal motions, alternative mooring systems may become feasible. A study is needed into the maximum allowable horizontal motions, which will depend on the applications, and the resulting design space that opens for the mooring design.

Regulations

Although technical developments are needed to optimise the concept of modular floating islands, technically it is already possible at this moment. Barriers for multi-use as discussed in Part II of this roadmap call for the following actions on regulatory aspects:

- As all other offshore structures, building requirements for the floater structure are needed. These requirements will include minimum strength requirements for the structure and requirements regarding relative motions and angles between connected floaters.
- Per application regulations are needed regarding the maximum allowable motions and accelerations. These requirements will vary per application and will need to be included in the regulations regarding floating islands. Requirements on motions and accelerations depend on many factors such as operation limits of cranes, machinery requirements, human tolerance and health and safety for working and living conditions.
- Further health and safety regulations for working and living on a floating island will need to be elaborated considering risk of objects moving or falling, slipping hazards, and risks of falling of the island.

Governance

Another barrier mentioned in Part II of this Roadmap concerns governance and clarity about who has decisive power on the island and in the waters around it. Required development in this field contain:

- One of the key questions is where to locate multi-use floating islands and which rules or guidelines should apply to this settlement. Within the territorial waters and EEZ of countries it is evident that this country can decide where to place floating islands, considering always other use and shipping lanes as well as requirement of neighbouring countries. Nonetheless, it is urged that the EU provides its member states with guidelines in locating floating islands. On the high seas ownership and control of settlement is not placed with one organisation or governing body. Establishing rules regarding settlement of floating islands in the high seas therefore needs to be done at a global level such as International Maritime Organisation (IMO) or the United Nations (UN). It is highly recommended that the EU initiates on global level such as IMO and UN discussions regarding rules and guidelines for the settlement of floating islands in the high seas.
- Procedures and standards regarding ownership of the floating island and individual floaters needs need to be considered for multi-use floating islands. Where ground release on land is governed by local or national governments, a similar role for governments can be considered for floating islands. Stakeholders such as national government, future users of floating islands, offshore asset owners and investors need to agree on procedures for ownership, also considering possible expansion of (already existing) floating islands.
- Linked to the ownership of the total island is the governing law on the island. A possible solution is the use of flag states as it the case for shipping where the state may not be the owner of the island, but the island is registered in a certain country, flying the flag of that country, and subsequently having the national laws of that country prevail on the island. IMO will need to decide on flag state approaches for floating islands.
- Ownership of property on a floating island is currently prohibited under Dutch national law (and possibly also for member states). For the future users of floating islands, it may be interesting to own property on the floating islands. This can be a house for floating housing or a factory of office building for work activities. Currently each individual floater can have individual owners, but the floater cannot sell part of the island to third parties. National governments need to develop laws allowing for people and companies to own property on a floating island.
- Insurance of the islands, individual floaters, buildings on the floaters and people will need to be considered. As risks may be different for floating islands than for on shore, insurance companies will need to consider dedicated insurances for sub-components, activities and people.

Applications

Applications that have proven by Space@Sea to have high potential for floating applications, both in single-use and multi-use, are energy, living and transport and logistics. Aquaculture has a potential but more as support to an already existing island than as an initiator for a floating island. Further applications are tourism and environmental research which can benefit from a stable offshore station. Additional applications such as industry, hydrogen generation and a floating airport are feasible in the future. Each application will need to be individually studied on feasibility and limits regarding the motions and other limiting criteria for the floater design. Future research should focus on the technical requirements of additional high potential applications for floating islands and their possible impact on governance issues.

Single-use applications will be needed to initiate floating islands and accelerate the development of multi-use islands. Single-use floating islands will then be used to further develop the floaters, moorings, connectors, and other technical issues. In the meantime, governance can be addressed for multi-use and the single-use island can be extended to become a multi-use island or dedicated multi-use islands can be erected.

List of priorities

Based on the remaining barriers and the list of further developments, priorities are formulated. Two parallel processes are needed to arrive at multi-use floating islands. A technical process focussing on further development of the technical concepts and making steps towards large scale production facilities for floating island components and a governance process tackling governance issues which mainly apply for multi-use islands.

Technical priorities should be developed and tested, and first real life pilots and applications should be done for single-use floating islands. The priorities to be considered are:

- Mooring and rigid connections of which the development has started in the Space@Sea project, but further developments are still required for mooring in shallow water and harsh conditions as well as completely rigid connectors.
- Materials have been studied on a high level in the Space@Sea project where mainly a comparison was made between steel and concrete. Developments in the materials sector such as new types of salt resistant or buoyant concrete [REF] are crucial in further reducing the cost of floating islands.
- The current sizing of the floaters was based on the maximum dry dock size in the EU. For large scale rollout of floating islands new manufacturing facilities and processes will be needed. Industry will need to develop efficient and durable production and manufacturing processes for the standardised floaters.

- Pilot applications of single-use floating islands will need to be initiated. The offshore wind industry is expected to be one of the industries leading the developments for floating solutions for support infrastructure for floating wind turbines.

Governance and legal priorities to make multi-use floating islands a commodity will need to be considered in parallel. These priorities are:

- Maritime spatial planning and regulations or guidelines for the settlement of floating islands need to be discussed at high level.
- Issues regarding law and ownership of the island and of property on the island need to be considered at EU and at member state level.
- Demonstrations of multi-use islands and cohabitation of various activities on a multi-use floating island need to be done.

Timeline

At time of writing of this roadmap the Space@Sea project has just been completed and next steps are considered. The priorities mentioned in the previous section can all be categorised in technical, governance, pilot applications, production, and operation. Figure 23 shows the timeline of these categories making a distinction between single-use and multi-use floating islands. This clearly shows that the single-use applications focus on technical solutions while multi-use islands focus on governance and organisational issues. It is the firm belief of the authors of this roadmap that floating islands will become a commodity as from 2045.

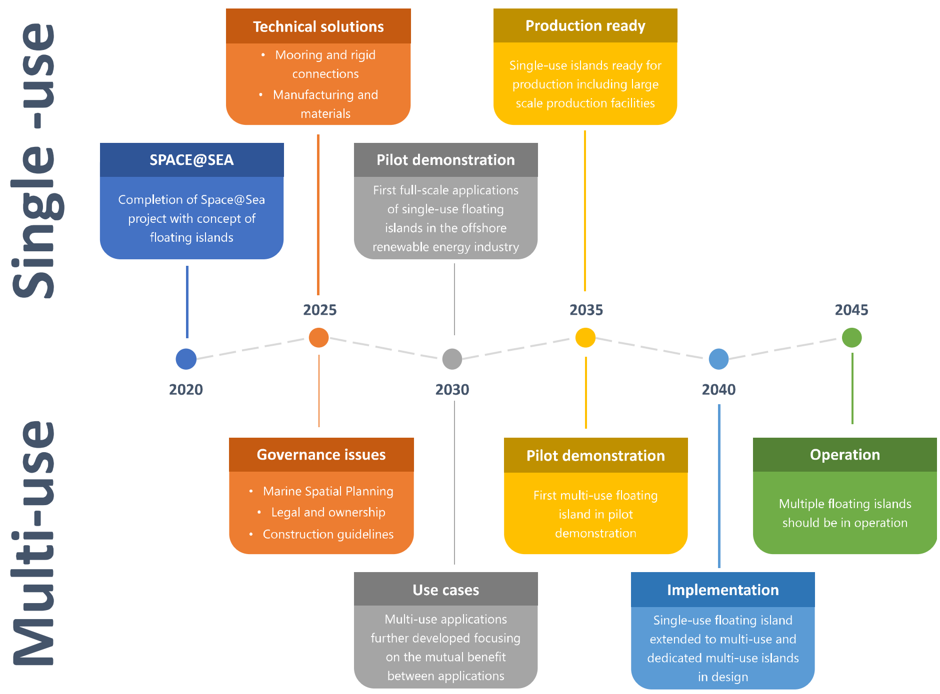

Figure 23: Floating island development timeline

Finances

Multi-use floating islands are still in a pre-competitive phase where collaborative research is needed to address the remaining barriers. Industry, research facilities and universities will need to invest in further research to bring floating islands to the water. Funding for this research is increasingly needed from industry and future floating island owners. The challenge in this is that governance issues for multi-use floating islands need to be solved regarding ownership and possible shared ownership. Governance related issues as shown in the timeline will need to be developed and (mostly) funded by governments, regulators and stakeholders involved in the governance issues.

Development of single-use applications is essential in the process towards multi-use applications. Fist single-use applications will need external funding for pilot applications such as support infrastructure for offshore floating wind and floating housing applications. Governmental funding or funding in the Horizon Europe programme will accelerate the process and should also include actions for upscaling to multi-use islands. Research funding should call for the following scope / impact:

- Bring together relevant stakeholders to address maritime spatial planning, ownership, and governmental role in multi-use floating islands.
- Study the application of new materials and new types of concrete in floating islands and the effect of this on durability and costs.
- Develop large scale production procedures and production sites capable of coping, if needed, with larger floater sizes than currently possible with dry docks.
- Further detail and engineer a rigid connector between floaters.
- Perform pilot application of first single-use floating island where the island is ready for expansion to multi-use.

Consortia addressing a call for further research and development should consist of companies with the capacity to bring a pilot application to the water and continue the exploitation of the floating island beyond the project.

Concluding remarks

From 2017 until 2020 Space@Sea developed a concept of modular floating islands to create additional space for living, working and transport. The project was supported by the European Commission as part of the Horizon 2020 research programme. The multi-disciplinary consortium consisted of companies, universities, and research institutes with a wide experience. A strong collaboration was built based on mutual respect and an astonishing level of interest in each other. Not only strong business relations for the future were built but friendship between team members have grown strong.

With this Roadmap for the Floating Island Development, Space@Sea partners want to set the agenda for further research into floating islands because we are convinced that floating islands will have a significant role in the green and blue future. Sea level rise and increased activities in coastal areas and offshore will inevitably call for floating solutions as gravity-based islands have a large environmental impact.

We hope to have inspired the readers of this roadmap with the work done so far and the outlook to the future. We are aware that probably not everyone agrees with our views and invite partners to challenge our opinions and together bring floating islands to the future. The floater design developed by Space@Sea should be a step towards the final design where shape, material and size can be further improved in the following steps. Future developments should not be bound by the shape and size of the floaters developed in Space@Sea but developed are to be inspired by the choices we have made.

Space@Sea was a technical oriented project focussed on a technical solution and the technical aspects of the applications considered. Governance, law, financing, and other essential disciplines to bring the concept to the market were underexposed due to the nature of the project. From the start we have positioned ourselves as the team that will provide a first technical solution which the other disciplines can use as baseline for detailing their contribution.

This roadmap is also directed at EU policy makers and their counterparts at the member states. Many of the remaining barriers for large-scale exploitation of floating islands and floating cities run into governance and law issues that need to be addressed at EU level. We are happy to further discuss with policy makers the steps to be taken.

The consortium is not blind for possible misuse of floating islands which we cannot ignore in this roadmap. As currently no regulations are in place for settlement of floating islands on the high seas, we see a risk of low labour cost countries placing production facilities on floating islands just outside the EEZ of EU member states. This will have a direct consequence for the economic development and jobs within the EU and is therefore undesirable. An even darker scenario would be that aggressive forces would initiate a floating island with military facilities just outside the EEZ. Although we are sure that most of the applications are friendly and have a positive economic impact on the EU, we need to be aware of negative effects.

At the very least we have inspired the team of 17 international companies, research institutes and universities and the partners we have touched through the three-year project to think differently and out of the box about land scarcity. We all believe in a green floating future.

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