Floating Modular Houses as Solution for Rising Sea Levels

A case study in Kiribati island

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Many island states, due to rising sea levels, have a problem with losing inhabitant homes. One of those countries is Kiribati island. Nowadays, this problem is solved by applying floating architecture, so life on the land is transferred to the water surface. Building settlements of this type is very complex. This paper proposes a unique concept for architectural and urban design using computational intelligence methods and the principles of regular tessellation. It is necessary to define the architectural program, ie. input data for the design process based on the general and special needs of users in terms of the functional organization of space. Each data will be represented by a module of unique dimensions, and the connections between the data by parameters, which result in a functional Bubble diagram of a modular floating house. By setting the requirements for the minimal perimeter and maximum area, the most optimal design of each of geometric shapes of regular tessellation will be chosen and evaluated by objective and subjective parameters of the design quality to find out which one is the most suitable for the modular floating house and then sustainable floating settlement.

Keywords: *floating architecture, regular tessellation, parametric design, architectural optimization, Kiribati island*

INTRODUCTION

Global warming is a characteristic of the modern world. According to the Panel on Climate Change (IPCC 2018) [1], population growth, economic activity, lifestyle, energy use, land use templates, technology and 21st-century climate policy initiate almost all greenhouse gas emissions and lead to catastrophic changes in nature, which are seen and felt every day. According to the research of the author team Slater et al. (2021), in the period from 1994 to 2017, 28 trillion tons of ice melted, which affected the rise of the average global sea level by 3.5 cm and this trend will continue.

Small island developing states are particularly vulnerable to rising sea levels due to low altitudes (Balesh 2015). These problems of the modern world have encouraged architects and urban planners to reject the paradigm of building on the ground, broaden their horizons and adopt the principle - to start associating with water and not always consider it an enemy. At the beginning of the 21st century, a new typology of architecture called aquatecture developed, as architecture shaped in the aquatic environment (Piatek 2016), so that the change of context led to changes in the understanding of architecture.

Floating structures, as a type of aquatecture facilities (Piatek 2016), stand out due to the possession of special mooring systems, which allow free vertical movement by providing synchronization with water level fluctuations, adaptation to natural conditions and thus, impose as an effective solution to sea level rise challenges (Simović et al 2019, El-Shihy and Ezquiaga 2019, Endangsih 2020). The floating house is an innovation, which is currently recommended for housing needs (Endangsih 2020) in terms of energy independence, sustainable development and environmentally friendly solutions. The advantage of the application of these facilities is the possibility of a modular system design and construction, which is conducive to low cost and construction time.

PARAMETRIC DESIGN THINKING MODEL AND OPTIMIZATION FOR FLOATING HOUSES

The modular floating house is an optimal solution to the consequences of rising sea levels whereby, its multiplication can result in a system of modular floating houses, ie. a sustainable floating settlement. Designing a settlement of this type is not easy, so it is necessary to find a unique concept/algorithm by which this can be achieved and thus optimize the process of architectural and urban design (Cubukcuoglu et al 2016, Caetano et al 2020).

Designing modular measures in architecture and urbanism requires the application of auxiliary design modular grids. An auxiliary grid is a guarantee against arbitrariness. The auxiliary grid satisfies the spirit. An auxiliary grid is a tool, not a recipe. Its choice and its expressive modalities are an inseparable part of architectural creation (Corbusier and Claudius-Petit 1977). The geometry of the auxiliary design modular grid can be identified with the geometry of two-dimensional plane tessellation because they are based on the multiplication of basic geometric shapes without overlaps and gaps using isometric operations of translation, rotation, axis and symmetry of sliding reflection (Chang 2018). If the two-dimensional plane of tessellation is identified with the water surface, tessellation polygons with three-dimensional models of floating objects for residential, public and commercial purposes, a modular floating house and a later settlement can be designed, but the definition of connections between modules is missing. ie whether tessellation polygons have common edges and what isometric operations enable them, in order to create a compact whole with maximum utilization of the water surface. These connections can be materialized into parameters based on the general and special needs of space users in terms of the purpose of space, number and layout and communication connectivity of functional units, ie. defined design process program (Zawidzki and Szklarski 2020).

The design process, which is based on algorithmic thinking, ie. the one that uses rules and parameters as constraints, is called parametric design. In the process of parametric design, after the rules and parameters are changed, an unlimited number of alternative solutions can be generated in parallel (Oxman and Gu 2015). By applying parametric design thinking, architectural optimization and generating plans in software Rhinoceros and Grasshopper, an orderly formation can be created (Cubukcuoglu et al 2016), i.e. the universal concept of architectural and urban design and iterations choose the shape with the maximum area and minimum perimeter (Egor et al 2020). A polygon that possesses the ability to tessellation can obviously have infinitely different shapes, but by imposing serious limitations on the composition and task of classification and enumeration, tessellation is reduced to something that can be managed. Based on the parameters of evaluating the quality of the solution (parameter of nature and urbanity; functional; constructions and materialization; social and psychological needs of users; financial profitability), an optimal geometric shape can be selected and an architectural and urban design solution developed. Finally, the application of mathematics will avoid empty modularity.

A CASE STUDY KIRIBATI ISLAND

One of the states facing the consequences of rising sea levels is Kiribati, located in the central part of the Pacific Ocean with the highest absolute elevation of the terrain currently 2 meters (Qu et al. 2020). The population of Kiribati has a problem with territorial loss, health, infrastructure and economy, which will ultimately result in the disappearance of the indigenous people and state. According to The Pacific-Australia Climate Change Science and Adaptation Planning Program (PACCSAP 2011-2015) [2], the sea level can increase to 87 cm by 2090 and about 50% of the island's surface will be underwater, which implies that a long-term solution to the problem in the shortest possible time with a smaller financial budget is necessary for the state's survival. According to El-Shihy and Ezquiaga (2019), Donner and Webber (2014), immigration to an artificial island is imposed as a solution with moderate to high financial resources, high durability, longer lifespan, moderate to longer construction time, positive impact on the environment and total impact of 72.5%. Therefore, the advantages of this proposal are the retention of coral reefs, the culture and identity of the people, and the disadvantages cost and time of implementation, which are the main parameters of valorization of solutions in small island developing states such as Kiribati. This state imposes itself as a good example of a case study, where the problem can be solved by applying a floating architecture.

The subject of research in this paper will be the parametric design of modular floating houses and their system (floating settlement) with limitation to the design network of regular (Platonic) tessellation in order to find out which geometric shape of the module base (equilateral triangle, square or hexagon) will suit to the state of Kiribati and its population. In this way, a universal architectural and urban solution (concept/pattern) can be offered to all island and coastal states, which are facing the consequences of climate change.

Research methodology

This research has the following methodology:

Stage 1: Architectural program as a list of input data for research. The program in the architectural design represents a clearly defined need and conditions for a certain new architectural space. By their nature, needs can be general and special, where the human needs as a biological and social being are general, and special needs represent needs for a certain type of built space.

The general needs of the population in Kiribati are not fully met. As one of the countries with the lowest standard of living and high birth rate, only 20% of the population has access to the sewage system, and 64% of them do not have a bathroom in their homes (Balesh 2015). Uncontrolled discharge of wastewater leads to pollution of groundwater, which is the main source of drinking water on the islands of Kiribati.

Limited available resources and technical-technological development have resulted in emphasizing the functionality and simplicity of the shape and volume of buildings (Whincup 2010). The foundations of the buildings are in the form of raised rectangular platforms, while the volume is represented by large oblique planes covered with local materials. A large percentage of residential buildings is open-ended, ie. covered space that is accessible from all sides. It is used only for sleeping, and other activities are performed outdoors. Although nature is their natural habitat, the population must be modernized.

Agriculture is the main activity of the population. Almost every household grows fruit and vegetables for its needs, keeps animals, and 70% of the population is engaged in fishing. According to The 2015

Population and housing census [3], fishing and local crops are the primary food source of almost every household in accordance with the standard of living.

Taking social needs into account, *mwaneaba* is extremely important for the inhabitants of Kiribati, as a place of tradition, rituals and significant social events. *Mwaneaba* is the largest single cultural artifact in Kiribati and its size signals community significance (Whincup 2010).

Therefore, the functional units that must be provided by the program in the new floating settlement are functional residential zones (basic housing unit for a minimum of 4 people with a flexible structure in terms of expanding household members and contact with the natural environment, gardens and animal storage areas in their immediate vicinity nearby) and functional public areas (areas for gathering the population-*mwaneaba*, pools for fishing, walkways, large areas of greenery). As a special part of the program, the necessity of appropriate technologies in terms of energy independence and ecological construction can be singled out. *Note: The floating island must have a connection to the mainland due to other public facilities.*

Stage 2: Defining a basic floating object module with a unique area. Dimensioning of prefabricated buildings requires coordination of measures in order to achieve simplicity, efficiency and economy of construction, but also speed in the design process. With the aim of realizing the above, the modular grid of architectural and urban design is being identified. Therefore, each of the functional zones of the basic housing unit (modular floating house), ie. the entrance, auxiliary, main and open areas zones are represented by a module of unique dimensions, area and volume. This would mean that the basic floating object module must be of such dimensions that each of the rooms of the corresponding zone can be accommodated in its predetermined boundary size. By studying all the rooms of functional zones on the basis of the area occupied by the furniture element, the area for access and performance of activities, as a single area of the basic floating object module is defined as an area of 10 square meters. Within the modular floating house, the following modules can be distinguished: entrance zone (free space), main zone (dining room and living room, bedroom), auxiliary zone (kitchen and bathroom) and open areas (animal shelter, vegetable garden). It can be noticed that the communicative zone is omitted because its area is redistributed to the premises of other zones and in that way their area is increased.

Stage 3: Defining connections between functional zones of a modular floating house in the form of tessellation geometry parameters in parametric design software. The basic housing unit of a four-member household [3] (modular floating house) contains 7 basic modules: one module of the entrance zone (free space), 3 modules of the main zone (two modules with a bedroom, one module with a dining room and a living room), one module of the auxiliary zone kitchen and bathroom) and two modules of open areas (one vegetable garden and one animal shelter). The way of grouping the basic modules of functional zones will depend primarily on the purpose of space, the complementarity of functions and the tessellation grid, which will cause grouping around the center area, corridor or surface assembly without a clear constitutive motive. Mutual relations of individual zones from the program, ie. modules for residential purpose, which should be adhered to in the process of designing a modular house, are defined in the form of tessellation geometry parameters in parametric design software (Rhinoceros and Grasshopper) (see figure 1):

Figure 1
Bubble diagram of functional layout for floating modular house (Space Syntax)

Figure 2
Regular (Platonic) tessellation: (a) equilateral triangle; (b) square; (c) hexagon

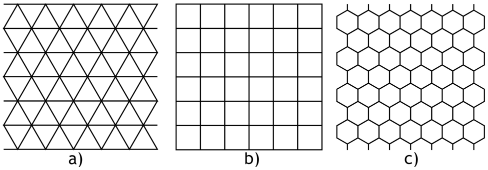


Figure 3
Triangle modular floating house: (a) Functional layout, (b) Floor plan design

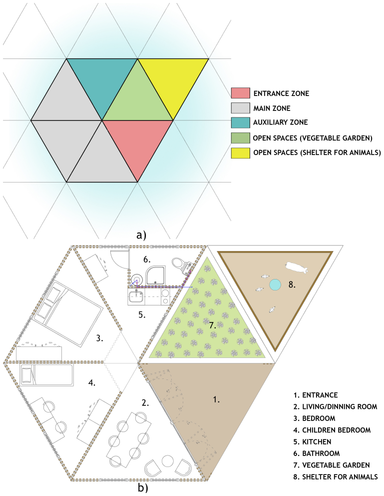
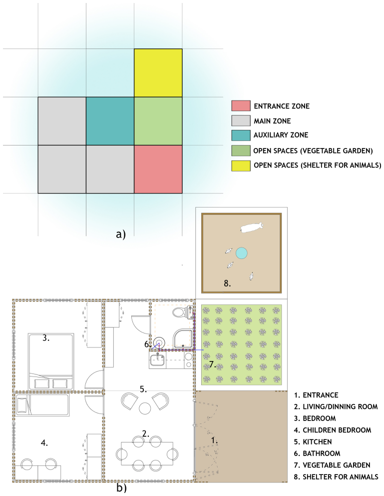


Figure 4
Square modular floating house: (a) Functional layout, (b) Floor plan design



- the position of the auxiliary zone is of exceptional importance due to the application of self sufficient technologies;
- main zone modules must be connected to the auxiliary zone (*edge to edge*);
- the zone of open areas is connected to the entrance zone (*edge to edge*);
- modules of open areas zone, ie the vegetable garden and the animal shelter must be next to each other (*edge to edge*);
- the vegetable garden, as a module of the open areas zone, must not be covered;
- the vegetable garden, as a module of the open area zone, must be positioned next to the auxiliary zone module due to watering with technical water (*edge to edge*);
- the animal shelter, as a module of the open area zone, must have a special rainwater collection system and
- the entrance zone module does not have to be covered by a full structure.

Stage 4: Setting conditions / constraints: Design with the minimum perimeter of a modular floating house. Based on the scheme presented using the Bubble diagram, it can be concluded that the auxiliary zone module and the vegetable garden, as a module of open areas zone, have the most common edges with other modules. Therefore, the positioning of the polygons of these modules is the initial step in the design process. Then, the parameters can be used to make an algorithm of the modular floating house on the water surface for each of the geometric shapes of regular tessellation (see figure 2) and by evaluating many combinations, an adequate way of grouping residential modules within an auxiliary modular grid of regular tessellation can be chosen. On the end, the condition is set: the design with the minimum perimeter of the modular floating house (see figure 3-5).

Stage 5: Defining connections between functional zones in the form of tessellation geometry parameters in software for parametric design of floating settlements. The space that unites modular floating houses into a sustainable settlement on the water surface is the public space. The modules that are planned for public purpose are pools for fish farming, walkways, greenery and a space for gathering residents- mwaneaba. The number of modular floating houses is limited to 12 (about 50 inhabitants). The large shape of the floating settlement means the application of symmetry. Tessellation planning of a floating settlement is facilitated by the following geometry parameters and isometric operations (see figure 6):

- the space for gathering residents (*mwaneaba*) occupies a central position (center of symmetry);
- walkways rely on the space for gathering residents (*edge to edge*);
- greenery and walkways are alternately placed (*edge to edge*);
- pools for fish farming are connected to walkways (*edge to edge*);
- the module of the entrance zone of the modular floating house is connected to the walkways, as modules of public purpose (*edge to edge*);
- the animal shelter, as a module of the open area zone of the modular floating house, must be positioned towards the open sea (*there are no common edges with the modules that are planned for public purpose*);
- at least one module must be omitted between individual modular floating houses and modules for a public purpose (*modular floating houses do not have a common edge, all functional zones of a modular floating house, except the entrance and vegetable garden, do not have a common edge with public modules*) due to the insolation of each of the houses and the privacy of the residents.

Stage 6: Setting conditions / constraints: Design with the minimum perimeter of a floating settlement. Based on the scheme presented using the Bubble diagram, it can be concluded that mwaneaba must be positioned in the center of the settlement, and then connected to the modular floating houses

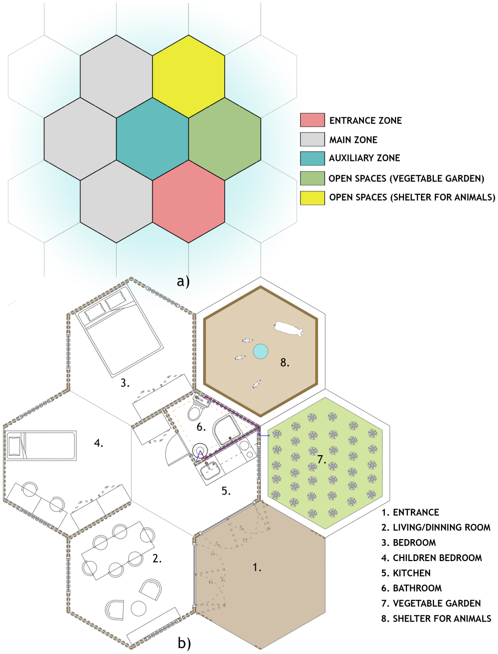


Figure 5
Hexagon modular floating house: (a) Functional layout, (b) Floor plan design

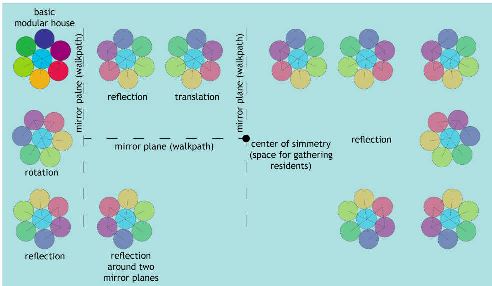


Figure 6
Bubble diagram and applied tessellation operations for floating settlement

by modules of walkways and greenery. The parameters can be used to create an algorithm of settlement on the water surface for each of the geometric shapes of the regular tessellation and by evaluating many combinations, an adequate way of grouping modular floating houses with the minimum perimeter and modules of public use within an auxiliary modular grid of regular tessellation can be chosen. On the

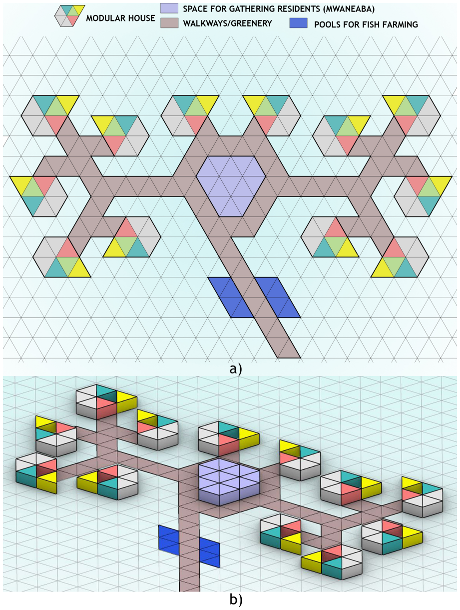


Figure 7
Triangle modular floating settlement: (a) 2D model, (b) 3D model

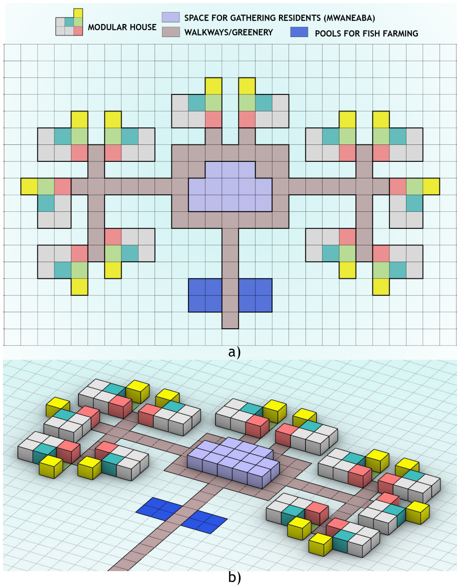


Figure 8
Square modular floating settlement: (a) 2D model, (b) 3D model

end, the condition is set: the design with the minimum perimeter of the floating settlement (see figure 7-9).

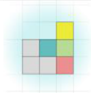
RESULTS AND DISCUSSION

Each geometric shape will be evaluated on the basis of realized parameters of urbanity and nature, functional (purpose of space, layout and number of functional zones, a communicational connection of zones), construction and materialization, psychological and social needs of space users and financial profitability (see table 1).

Based on the research results, it can be concluded that the triangle is unsuitable for all parameters, due to insufficient surface utilization.

A square is a geometric shape that is very favourable in terms of function, constructive stability, social and psychological needs, flexibility in designing and creating ordered formations. However, the position of the rainwater harvesting system does not give good results, as well as the position of the vegetable garden due to insufficient insolation of the whole structure. The author team of Czapiewska et al. 2013 [4] uses a pentagon and a square in the urban design of settlements because they consider the circular formation to be the most stable structure, and with their combination, it is possible to achieve that.

El-Shihy and Ezquiaga (2019) in their research present two models of a floating module in the form of hexagons and squares, emphasizing them as a perfect combination for solving the consequences of sea-level rise (the case of Abu-Qir) because the square module allows linear expansion and formation of the traffic network while the hexagonal module enables a strategy of dynamic expansion of the island. In this research, however, the hexagon proved to be a suitable geometric shape of the module, because it meets all the parameters and is a polygon that can make the most of the area with the smallest perimeter. The auxiliary zone with the rainwater collection system has an ideal position because it is possible to collect rainwater from all roof planes evenly. Another advantage of the hexagon is the possibility

	Floating modular house								Floating modular settlement						
Shape	Length of polygon side a (m)	A (m²)	p (m)	Urbanity and nature parameter	Function parameter	Construction and materialization parameter	Psychological and social needs of space users	Financial profitability	A (m²)	p (m)	Urbanity and nature parameter	Function parameter	Construction and materialization parameter	Psychological and social needs of space users	Financial profitability
	4.8	70	33.6	L	VL	VL	VL	L	1930	686	VL	M	L	M	VL
	3.2	70	38.4	M	VH	M	VH	M	1590	678	M	VH	H	VH	M
	2	70	36	VH	H	VH	VH	VH	1490	580	VH	VH	H	VH	VH

H: High, VH: Very High;M: Moderate; L: Low; VL: Very Low.

Table 1
Evaluation design matrix for equilateral triangle, square and hexagon modular floating house/settlement

of dynamic organic (bio-inspired shape) expansion of the floating house and settlement in case of expansion of families and households. Lister and Muk-Pavic (2015) offered a hexagonal community of six triangular modules to solve the Kiribati problem and presented an artificial island by its tessellation.

We can conclude that the hexagon with an area of 10 square meters on the side of the 2 m polygons is suitable for the geometric shape of the Kiribati floating house module. By multiplying this shape an ordered formation is formed, ie. a floating settlement with the smallest perimeter and the largest area. This data is extremely important for the population of Kiribati because the perimeter of the modular house multiplied by the height of the building gives the area of the module panel, which is, financially, the most profitable here due to the smaller area. The research team Donner and Webber (2014) in their study points out that the construction of an artificial island is a solution to the problem of Kiribati and its popula-

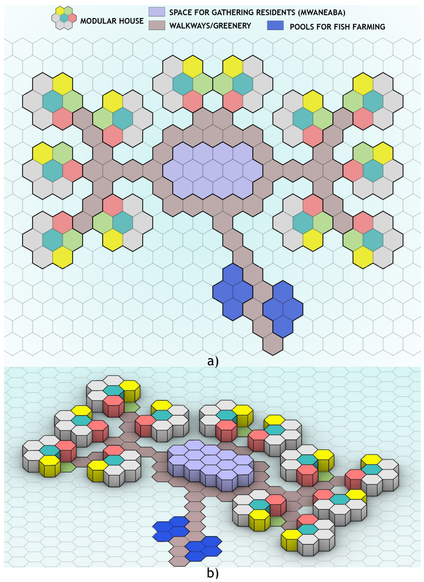


Figure 9
Hexagon modular floating settlement: (a) 2D model, (b) 3D model

Figure 10
Concept design

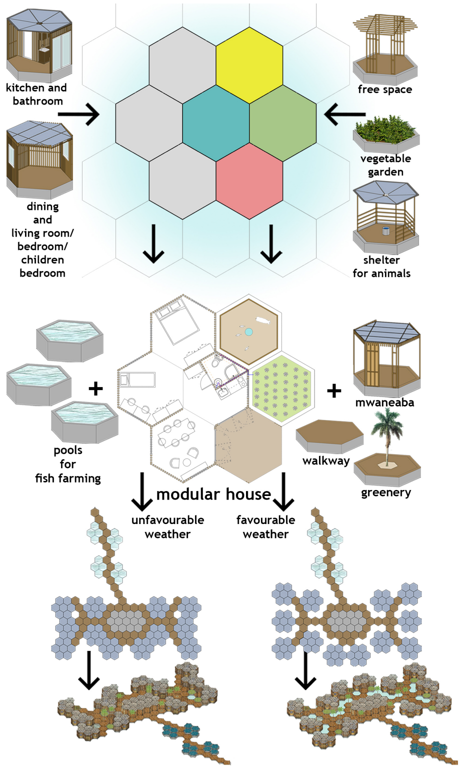
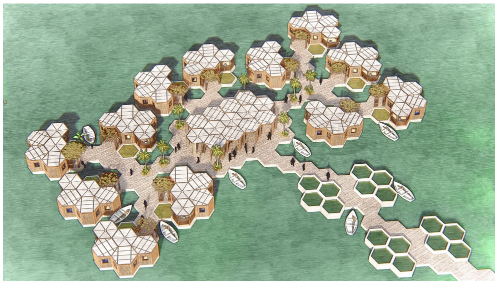


Figure 11
Architectural visualization



tion, where the speed of implementation and financial profitability are cited as defects. This study eliminates these defects by applying a modular hexagonal design and expands the understanding of previous studies. This solution is also suitable in terms of the mobility of the floating house because the hexagonal floating settlement can have a combination of houses both when the weather is favourable or unfavourable. All this is made possible by the application of parametric design so that it can be used in the education of students and other architects for the design of floating houses and settlements on the water.

At the end of the research, the elaboration of the concept and visualization can be further developed (Figure 10,11).

FUTURE RESEARCH

Parametric design is a good tool for forming settlements with different types of houses so that the final design would be less symmetrical. This paper presents one type of modular floating house for a family of 4 members because according to statistical data [1] it is the minimum number of members of one household in the state of Kiribati. Future research would focus on the development of floating houses for several household members and a study to check the suitability of the same geometric shape due to the larger number of different floating houses in the settlement.

CONCLUSION

Floating architecture is the architecture of the modern age. With its potential, it can help solve global problems such as the consequences of rising sea levels with which the island and coastal states are facing. Defining the parameters, as a connection between the necessary functional zones, will facilitate and speed up the design process. By applying the hexagon module, isometric operations of the tessellation procedure and parametric design, a modular house can be designed, and after that, a floating settlement as well. This concept can serve as a universal architectural and urban solution.

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