EL-Shihy *City, Territory and Architecture* (2024) 11:8
https://doi.org/10.1186/s40410-024-00228-6

City, Territory and Architecture

RESEARCH ARTICLE

Open Access

# A new approach for configuring modular floating cities: assessing modular floating platforms by means of analytic hierarchy process

Ahmed A. EL-Shihy[1*]

**Abstract**

Floating cities have emerged as an efficient long-term solution over unsustainable practiced solutions to combat the rising seas problem; nevertheless, the world lacks an international, official, and comprehensive framework regarding floating cities. Although previous research approached modular floating city design; however, resulted in configurations with various critical design restrictions mainly regarding interlocking capabilities and space utilization. The purpose of this paper is to offer a new systematic strategy for configuring modular and expandable floating cities without such restrictions. This paper explores Euclidean tilings as a strategy to offer numerous configurations based on regular, semi-regular, and demi-regular tilings. Selecting the ideal configuration is complicated; therefore, both quantitative and qualitative data methods were implemented to attain the objectives. Via an extensive literature review, this research derives key factors for configuring floating cities, then sets a brainstorming session with experts for group decision making before providing findings upon calculations via analytic hierarchy process, one of the most used quantitative data methods of multiple-criteria decision analysis. Through comprehensive literature review: seakeeping, modularity, zoning and circulation, and feasibility have been identified as the most significant criteria in floating city research. It explores the qualities and limitations of triangular, squared, hexagonal, octagonal, and dodecagonal platforms. Regarding criteria, seakeeping was the most significant criterion for platform selection by 53.6%. Regarding platforms, the hexagonal platform scored the highest with 25.31%. Relying on this method and the design considerations presented, numerous dynamic configurations can be offered and assessed through specific contexts without any of the past restrictions.

**Keywords** Euclidean tilings, Geometric Urban Planning, Modular floating city configuration, Climate Change

## Introduction

The Intergovernmental Panel on Climate Change (IPCC) states that constraining the adaptation measures to the challenges of the rising seas without considering real economic, social, political, and industrial adjustments, may lead into higher costs and damages (IPCC 2023). For instance, improving a city's infrastructure in order to guard its built assets may be rather expensive while temporary solutions may not cover the growing costs or risks and yet, some of the most vulnerable low-lying regions still practice unsustainable short-term solutions (Piyapong et al. 2019). Recent studies on sea level rise (SLR) suggested floating houses as an efficient strategy for managing SLR risks (Setiadi et al. 2020; Baumeister et al. 2021). The demand on various floating applications including floating cities

*Correspondence:
Ahmed A. EL-Shihy
ahmed.shihy@ngu.edu.eg
[1] Architectural Engineering Program, School of Engineering, New Giza University, Giza, Egypt

have produced an extensive amount of research in the last few decades such as Suzuki et al. (2006), Ko (2015), Baumeister et al. (2021), Stankovic et al. (2021), and Drummen and Olbert (2021). Very Large floating structures (VLFS) are categorized by having a long lifespan from 50 to 100 years and being the largest-scale structures in terms of their expense and resources, building technology, and modular and adaptable formations (Suzuki et al. 2006). As 40% of the Earth's population resides within 100km of shorelines (NASA Socioeconomic Data and Applications Center (SEDAC)) and as the United Nations report says that 90% of the largest cities will be impacted by SLR (UN-Habitat 2019), it is believed that waters can be our last resort for human settlement (Kirimtat et al. 2020). Moreover, the idea of floating cities as a sustainable solution against SLR has been reviewed lately by the United Nations which has raised the awareness of people, architects, and governments globally (Mohammed 2019). Therefore, apart from retreating from the coastlines as the situation worsens, VLFS is a resilient proven solution that needs to be considered which do not echo the same past mistakes in urban planning and conventional construction methods (Lin et al. 2019).

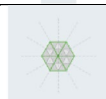
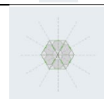
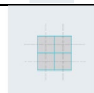
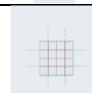
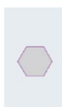
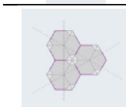
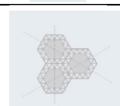
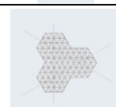
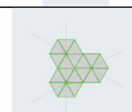
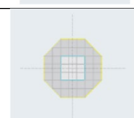
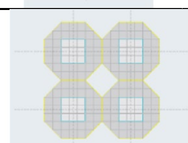
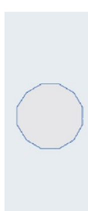
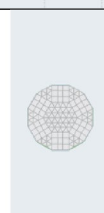
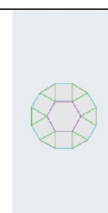
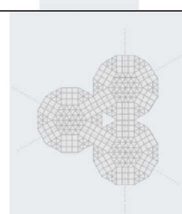
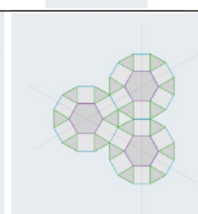
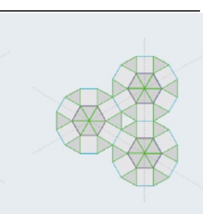
From an urban perspective, an official and comprehensive framework concerning urban strategies and considerations for modular floating projects does not exist. Thus, systematic research regarding configuring modular floating cities through different urban configurations highlighting their potentials and limitations is required. Previous research such as Stankovic et al. (2021), Ko (2015), Drummen and Olbert (2021), Piatek (2016), Cubukcuoglu et al. (2016), Endangsih and Ikaputra (2020), Chen et al. (2021), Dong et al. (2020), and Kizilova (2019) mainly focussed on configurations relying upon triangular, squared, pentagonal, hexagonal, crossed, or circular platform shapes when addressing modular floating cities. Moreover, such previous research assessed floating city configuration relying on one shape or a combination of them resulting in configurations with limited design capabilities and/or gaps between platforms. Thus, this paper attempts to address such limitations in a manner that has not been previously approached to offer novel and valuable results. Such goal is attained through offering a systematic approach relying on Euclidean tiling by convex regular polygons for modular floating city configuration. Euclidean tiling is a tessellation approach where planes are configured via symmetric processes resulting in unlimited expansions without any overlapping problems (Otero 1990). Thus, this paper explores a new approach in designing complete floating cities and claims that there are a lot in this subject that is yet to be explored.

Various engineering fields utilize Euclidean tiling (Otero 1990; Gomez-Jauregui et al. 2021). Such tilings can be achieved through Cundy & Rollett's (C&R) (Cundy and Rollett 1981) or GomJau-Hogg's (GJ-H) (Gomez-Jauregui et al. 2021) notations for producing any of the three tiling categories of regular, semi-regular, and demi-regular tessellations (Gomez-Jauregui et al. 2021). As shown in Table 1, only three regular tilings exist which rely on only one equilateral polygon shape, where every vertex is encircled by the same polygon shape (vertex-transitive) which could be achieved through six triangles, four squares, or three regular hexagons all meeting at one vertex (Gomez-Jauregui et al. 2021). Through semi-regular tilings (Archimedean or uniform), eight vertex-transitive tessellations that could be resulted via introducing octagonal and dodecagonal polygons to regular polygons (Gomez-Jauregui et al. 2021). Through demi-regular tilings (k-uniform), twenty non-vertex-transitive 2-uniform and sixty-one non-vertex-transitive 3-uniform tessellations could be resulted via all five mentioned polygons (Gomez-Jauregui et al. 2021).

The main drive of this study is to produce a dynamic approach that solves the previous challenges with modular floating planning design through systematically exploring the pros and cons of platform designs based on Euclidean tiling as a strategy for configuring adaptable floating cities. This research suggests that if a modular floating city is configured relying on a combination of five platform shapes, architects, urban designers, and planners can configure a modular floating city without the limitations of previous studies which are limited to shapes that created forced gaps between platforms if not relying on same regular shaped platforms. Although some research analyzed modular floating platforms such as Stankovic et al. (2021), Ko (2015), Drummen and Olbert (2021); however, no research on modular floating city planning has been based on Euclidean tilings. Several influences should be explored in the early stages of design development since a lot of factors are influenced by platform shapes. In this paper, the performance of each platform design is analyzed and ranked through some of the most significant criteria in floating city research to recommend the optimum platform and offer urban considerations for planning modular floating cities.

Since it is difficult to take such decision without a tool for assessing numerous information on different designs through different criteria; therefore, both quantitative and qualitative data methods were implemented to attain the objectives. Initially, this paper conducts an extensive literature review to derive key factors for configuring floating cities. This paper executes a brainstorming session with experts for Group Decision Making (GDM) then provide findings upon calculations via

**Table 1** Platform dissections based on GJ-H (Gomez-Jauregui et al. 2021) and C&R (Cundy and Rollett 1981)

| Platform | Configuration | Shape | Middle vertex dissection | 2 middle vertex dissections | | Original vertex dissection | |
|---|---|---|---|---|---|---|---|
| Tri-angular | Discrete |  |  |  |  | | |
| | Ring | |  |  |  | | |
| Squared | Discrete |  |  | |  | | |
| | Ring | |  | |  | | |
| Hex-agonal | Discrete |  |  |  |  |  | |
| | Ring | |  |  |  |  | |
| Oct-agonal | Discrete |  | | |  | | |
| | Ring | | | |  | | |
| Dodec-agonal | Discrete |  | | |  |  |  |
| | Ring | | | |  |  |  |

analytic hierarchy process (AHP) to assess such criteria on all platforms to judge and rank these designs accordingly. Therefore, this research objective is to answer these questions:

1) Against SLR, particularly in low-lying regions and island countries, what are the criteria for assessing modular floating cities from an urban planning standpoint? How are they prioritized?
2) How can the proposed systematic strategy of Euclidean tiling for floating platforms configuration (ETFPC) offer unlimited adaptable and expandable floating cities? What are the potentials and limita-

tions of each platform design? How are they prioritized?

3) How does such approach work? How can it solve previous design restrictions in interlocking capabilities and challenges in maximum space utilization? What are the design considerations for using such approach for planning floating cities?

This paper is structured as follows: materials and methods, results and discussion, and conclusions, implications, and future research.

## Materials and methods

### Materials

Standardized modular design decreases the construction time and costs (Chen et al. 2021). Therefore, instead of creating a VLFS, the concept of breaking down a structure into smaller modular interlocking segments allows the structure to be assembled and disassembled easily which as a result promotes faster construction and implementation (Ko 2015). Standardized modular platforms designs can offer transportable and upgradable platforms (Wang et al. 2008; Dong et al. 2020). Moreover, it provides great possibilities in configuring floating cities because of their ability to expand limitlessly (Kizilova 2019).

The geometry of the floating structure should be addressed in designing any floating structure since each platform shape influence a city's configuration (Endangsih and Ikaputra 2020). However, previous research and implementations regarding configuring modular floating cities relied on shapes that produce gaps between platforms and/or configurations with limited capabilities due to using on regular platform design. Thus, this paper offers a novel and systematic approach to address such restrictions and fill this gap in research as well as offering design considerations for such approach.

Through some of the most assessed criteria on floating city research: seakeeping, modularity, zoning and circulation, and feasibility, the proposed ETFPC approach is assessed. Thus, regardless of any context this approach relies on five platform shapes: triangular, squared, hexagonal, octagonal, and dodecagonal.

#### *Criteria for modular floating platforms*

Seakeeping refers to the unallowable movement of floating platform when exposed to strong waves and the resultant consequences on people and the structure. The seakeeping of platform differs regarding each platform design. Platforms should be durable yet flexible in order to resist high sagging and hogging movements in order for the living conditions on the floating city to become acceptable (Ko 2015; Suzuki et al. 2006). The stability of a platform impacts the configuration in various ways (Wang et al. 2008; Wang and Tay 2011). However, depending on the required platform shapes for any configuration and depending on the city's location whether coast-by or in high seas, the seakeeping attributes of the floating city can be precisely measured (Wang et al. 2008).

Modular capabilities refer to how a platform shape directly impacts the configuration. Floating platforms should have the ability to fit into various configurations to accommodate different sites. Having the ability to be adjusted to different future purposes, and being transportable if transportation is required for any reason (Ko 2015). Moreover, the mobility feature of floating structures is impacted by platform shape, size, and where it is located in the configuration (Piatek 2016).

Unlike building on land, the floating platform acts as a vacant piece of land for the residents. Thus, it is crucial to have a platforms that promote higher zoning attributes (Wang et al. 2008) regarding land use distribution on each platform without negatively impacting the horizontal circulation from one platform to the adjacent platform and vice versa (Cubukcuoglu et al. 2016). On foot circulation should be highly considered for sustainable floating city design (Cubukcuoglu et al. 2016). Platforms are expensive to construct; thus, platforms that promote sharp angles can result in unused areas (Ko 2015). Space utilization is based on what platforms offer individually and not only in configuration. Therefore, maximizing the buildable area on the platform should be one of the main objectives (Piatek 2016).

The end users would greatly benefit from such modular architectural solution which could offer a rapid solution and ease the transition of their relocation. Cost, time, and complexity are impacted by each other through the size and shape of the platform design (Wang et al. 2008; Suzuki et al. 2006). Considerations should not only include optimum space utilization as a priority, but also the maintenance costs, time for transport/relocation, and complexity of construction and assembly/disassembly.

#### *Modular floating platform shapes for ETFPC approach*

Triangular shaped performs offer good hydrodynamics and average connection forces; nevertheless, maximum forces was almost the same in triangular and squared formations (Drummen and Olbert 2021). It is one of the most dynamic platform shapes for modular floating city configuration. However, it is unfeasible approach since its the lowest performing platform regarding insufficient space utilization (Stankovic et al. 2021) which results in less zoning and circulation capabilities due to its three sided geometry especially if both circulation and superstructures are to be integrated on the same platform.

Squared platforms perform better than triangular ones in terms of functional distribution, stability, social needs, and design flexibility (Stankovic et al. 2021). It is limited to orthogonal growth which can be handy in parallel formations to coastlines. Its better in zoning and circulation since it performs better regarding higher useable space (Drummen and Olbert 2021) due to its right angles. As prefabricated units are mostly rectilinear, it is more suitable for superstructures as its difficult to build on steep or wide angles (Ko 2015). Moreover, it offers economical, rapid, and simple construction making it an attractive option.

The hexagonal platform is a universal urban solution offering the most regarding all criteria like optimum area to its perimeter and offering simple tessellation that modularly expand on its edges (Stankovic et al. 2021). Hexagonal configuration offers stable ring configurations promoting dynamic growth. Due to the symmetry, the city can simply expand in any direction, eliminating any interlocking challenges (Ko 2015). Modular hexagonal platform configurations are the best approach due its symmetrical characteristic which offers flexible zoning and circulation (Ko 2015) as it offers usable space for superstructures and dynamic expansion and circulation through its six sided geometry.

Integrating both squared and hexagonal platforms configurations allow their orthogonality and flexibility attributes respectively; thus, maximizing zoning, circulation, and minimizing traffic time (Ko 2015)since such configuration combines the pros of both polygons which as a result decreases the cons of each. Although not as simple and rapid solution as the squared platform, it is the largest regular platform offering the highest expanding dynamics in a regular configuration relying only on its own.

Although no scientific research has been found on the octagonal or dodecagonal platforms, they are essential for the proposed approach for semi-regular and demi-regular configurations. They share similar seakeeping and feasibility attributes with the hexagonal floating platforms to VLFS for their shear size. Floating platforms are considered VLFS when any side exceeds 60 m (Wang et al. 2008). Since VLFS are categorized for their immense size (Suzuki et al. 2006), they are typically built in modules (Wang and Tay 2011). Regarding modularity, and zoning and circulation, the octagonal platform shares many attributes with the squared platform while the dodecagonal platform shares many attributes with hexagonal, triangular, and squared platforms respectively.

According to the literature, the hexagonal platform appears to be ideal regarding its universal attributes (Stankovic et al. 2021), while the squared one appears to offer logical zoning and horizontal circulation but expands only orthogonally (Ko 2015), whereas the triangular one is flexible and dynamic in expansion but with low area usage to its cost and horizontal circulation attributes (Ko 2015). No research has studied the octagonal or the dodecagonal platforms; however, they share many of the VLFS attributes besides that the octagonal platform share many attributes with the squared and hexagonal platforms whereas the dodecagonal share many attributes with hexagonal, triangular, and squared platforms respectively. However, as discussed, previous research is limited to regular tessellations or impacted by forced gaps like in configurations which rely on the squared and the hexagonal platforms.

## Methodology

Through utilizing different research methodologies, research methods could be categorized as either qualitative or quantitative (Umar and Egbu 2018). Such mixed research method utilizing both methods was assumed to be ideal for the research problem.

### *Analytic hierarchy process*

Developed by Thomas L. Saaty (Saaty 1980, 2008), relevant studies implemented the AHP method to test and rank alternatives through multiple criteria in order to conclude objective results. A research by Golbabaie et al. (2012) successfully used the AHP method to assess configurations of container terminals (Golbabaie et al. 2012). Moreover, research by Miszewska et al. (2020) concluded the mooring cables as the most favourable anchoring system using the AHP method (Miszewska et al. 2020). Díaz and Soares (2021) state that using the AHP method helped in increasing objectivity when evaluating offshore wind farms (Díaz and Soares 2021). Ko, (2015) analyzed the pentagonal, squared, and hexagonal platforms using Multiple-criteria decision analysis (MCDA) (Ko 2015).

This method is implemented to assess and select between the options set based on various criteria via a methodical analysis to efficiently evaluate several sources of different data objectively to realize the intended objectives. Therefore, this study executed the MCDA method which is called AHP (Saaty 2008) that will lead into setting urban considerations for modular floating cities. The general structure of the hierarchy to the research problem is demonstrated in Fig. 1. The AHP, is a quantitative comparison technique which relies on many pair-wise comparisons set to identify the most significant option via comparing their performance through the criteria set (Golbabaie et al. 2012). It transforms such assessments into numerical values in order to measure and rank such options (Saaty 2008). Such method is relied upon since we cannot make complete judgements but relative ones (Igor and Ramadan

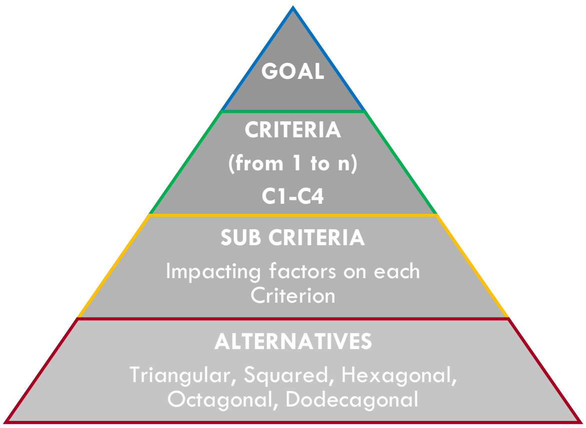



**Fig. 1** General structure of the hierarchy to the research problem

2004). Therefore, the conclusions are based on the findings of the AHP method were accomplished as following (Saaty 2008; Golbabaie et al. 2012):

1) Initially, framing the problem in a hierarchy consisting of the objective of the decision, identify the participating experts, possible options for accomplishing it, and criteria set for assessing such options. This happens through pairwise comparison matrix where all criteria are compared, and the findings are gathered in a matrix. For any two items compared, every comparative score set for one item, a relative score is set to the opposite item.
2) Ranking the significances of criteria to form hierarchy through sequence of decisions and judgements by the experts based on pair-wise comparisons. The rank for each criterion is set via geometric mean where the average of every row in the matrix is divided by the number of sum of the geometric means of all criteria analyzed (Golbabaie et al. 2012).
3) Synthesizing the findings to set the accurate significances for the hierarchy.
4) Finally, examining the consistency of the resulted judgements. Both Consistency Index (CI) and Consistency Ratio (CR) measures are calculated in order to assess whether the results of the comparisons are consistent or not.
5) Conclusion based on the findings.

To calculate CI and CR, Eqs. (1) and (2) were used in terms of *n* criteria (Golbabaie et al. 2012) while the RI was based on the constant value as shown in Table 4. The λmax was calculated in through averaging the total sum. This process was executed six times, once for all criteria with one another, and once with each of the five platforms with all criteria.

**Table 2** Rating system for preferences (Saaty 2008)

| Scale credit | Preference definition |
|---|---|
| 9 | Row is extremely significant |
| 8 | Row is very highly to extremely significant |
| 7 | Row is very highly significant |
| 6 | Row is highly to very highly significant |
| 5 | Row is highly significant |
| 4 | Row is moderately to strongly more significant |
| 3 | Row is moderately more significant |
| 2 | Row is equally to moderately more significant |
| 1 | Row and Column are of equal significance |
| 1/2 | Column is equally to moderately more significant |
| 1/3 | Column is moderately more significant |
| 1/4 | Column is moderately to strongly more significant |
| 1/5 | Column is highly significant |
| 1/6 | Column is highly to very highly significant |
| 1/7 | Column is very highly significant |
| 1/8 | Column is very highly to extremely significant |
| 1/9 | Column is extremely significant |

$$CI = \frac{(\lambda\mathrm{max} - \mathrm{n})}{(\mathrm{n} - 1)} \tag{1}$$

$$CR = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2}$$

***Group decision making***

AHP method is often implemented as a GDM where either behavioural or mathematical methods are relied upon while the main behavioral methods generally undertaken are debate and brainstorming method, six hats, focus group method, and Delphi (Miszewska et al. 2020). On the other hand, the mathematical methods are a collection of judgements made by experts which are geometric mean, arithmetic mean, weighted average which includes both the arithmetic and the geometric means, median and the mode (Miszewska et al. 2020). Furthermore, in the calculated aggregation of judgements of the participated experts in the multi-decision-making process for the AHP, two approaches are categorized as aggregation of individual priorities and the aggregation of individual judgements (Lin et al. 2022).

In the context of this study, the brainstorming method from the behavioural methods is undertaken which is a qualitative method. It is a method within the heuristic methods that involves both creativity and brainstorming new ideas and arguments (Agustini and Rimantho 2018). It starts with selecting a lead to guide the assembly with the following tasks: classifying the problem, selecting members where five to ten is recommended, selection of

**Table 3** Criteria for platform assessment

| Criterion | Definition | Considerations | Main references which experts made key decisions upon | Secondary references that experts debated upon |
|---|---|---|---|---|
| C1 | Seakeeping | Formation behind breakwater<br>Individual platform performance<br>Platform area ratio to adjacent platform<br>Connection to area ratio<br>Superstructure loads on platforms | (Wang et al. 2008);(Wang and Tay 2011);(Suzuki et al. 2006);(Ko 2015) | ;(Miszewska et al. 2020);(Wang 2017); (Díaz and Soares 2021) |
| C2 | Modularity | Dynamic expandability of urban configurations<br>Compatibility and forced design decisions | (Dong et al. 2020);(Kizilova 2019);(Tsaltas et al. 2010);(Ko 2015); (Endangsih and Ikaputra 2020) | (Stankovic et al. 2021);(Drummen and Olbert 2021); (Cundy and Rollett 1981);(Gomez-Jauregui et al. 2021);(Piatek 2016);(Wang et al. 2008);(Wang and Tay 2011);(Suzuki et al. 2006) |
| C3 | Zoning and Circulation | Optimum usable space to area ratio<br>Circulation qualities | (Cubukcuoglu et al. 2016); (Wang et al. 2008);(Wang and Tay 2011);(Suzuki et al. 2006);(Tsaltas et al. 2010); | (Piatek 2016);(Cundy and Rollett 1981);(Gomez-Jauregui et al. 2021); (Stankovic et al. 2021);(Drummen and Olbert 2021) |
| C4 | Feasibility | Platform size on construction time, complexity, and mobility<br>Efficient cost per square meter<br>Complexity and speed of assembly and disassembly | (Piatek 2016);(Chen et al. 2021);(Ko 2015);(Wang et al. 2008);(Suzuki et al. 2006);(Dong et al. 2020);(Wang and Tay 2011);(Endangsih and Ikaputra 2020) | ;(Miszewska et al. 2020);(Díaz and Soares 2021); (Wang 2017) |

length where 45 min is recommended, selection of location of the assembly to perform a session, demonstration of guidelines, interpretation of outcomes (Miszewska et al. 2020).

#### *Evaluation criteria for platform assessment*

Initially, the AHP method was implemented to assess the criteria; however, since not all criteria are valued the same in exploring the qualities of each platform; therefore, based on the sum of the scores from each criterion, the weight factor was set for each criterion so that each platform design can be adjusted accordingly. To identify the significance of each criterion, the rating system for preferences comparing each criterion is demonstrated in Table 2.

Since such field is multidisciplinary with main focus on urban planning, a multidisciplinary team of experts is assembled to have all rounded discussion and to produce sound judgements on the research subject, Therefore, a university was asked to take part in the brainstorming session. Since this is multi-disciplinary research, a team of seven experts is assembled. Three of them are professors and four are associate professors. Five experts were from the Architectural Engineering and Urban Design department with practical experience in sustainable urban development projects whereas two experts are from the Civil Engineering Department with practical history in offshore construction projects. The sessions were set in a meeting room in the university, in an appropriate time for all members where only the team of experts and one member of the authors as the lead were present. Upon demonstrating the guidelines and all the required information, the session started; nevertheless, lasted for over the intended. Consequently, a consensus was reached where all members are on common ground when undertaking the form by means of the 9-grade scale set by Saaty for the research subject. Since group-thinking usually happens in brainstorming process (Kunifuji and Kato 2007), any argument from any member had to supported with reference especially when members have different arguments hence the input of the member is decreased if they do not have a scientific argument or cannot support their arguments on a particular item with the arguments of other members. All of such references are included in this research while the main references provided by the members regarding important points in decision making are demonstrated in Table 3. This issue has been minimalized through choosing members of similar experience and rank, and who have professionally collaborated whether in academia or in practice.

While shape of the platform is impacted by various factors, various literature considered multiple factors for affecting floating cities, this paper combined them under four categories and assumed that they are the four pillars to discuss with the experts of in the brainstorming session to judge modular floating platforms and reach consensus. Thus, to achieve a more precise assessment, this paper applied the evaluation through four criteria which are: seakeeping, modularity, zoning and circulation, and feasibility, as shown in Table 3.

Before meeting with the experts, through the literature, it was observed that criteria are can not be measured without further considerations as demonstrated in Fig. 2. Thus, considerations were set to guide the evaluation process objectively. For instance, seakeeping is influenced via different considerations as shown in Table 3. A higher score is credited for a design which offered higher seakeeping attributes both individually and in configuration as it impacts breakwaters, adjacent platforms, connection number, and superstructures.

Modularity is influenced by some factors; thus, a higher score is credited for a design that offered higher modularity attributes regarding dynamic expandability and compatibility in a configuration of same shape.

Spatial qualities of any platform design are essential for getting the most out of each platform. A higher score is credited for a design that promotes optimum circulation and usable space to area ratio when/when not configured and promote higher circulation qualities. To analyze platforms geometrically, as shown in Table 1, analysis of middle vertex dissection, 2 middle vertex dissections, or original vertex dissection has been performed on each platform.

Cost, time, and complexity are influenced by each other and by any platform design. A higher score is credited for a design that offered higher efficiency for cost per square meter, complexity and speed of assembly and disassembly, and platform size on construction time, complexity, and mobility.

While some research, such as Umar (2020) considered sustainability factors for designing floating cities through using central sustainability drivers such as energy, water, food, waste, mobility, and habitat regeneration; however, this paper addresses sustainable floating cities from an urban planning standpoint for modular and expandable floating platforms based on the ETFPC approach. This approach is guided by sustainable design and tested through configurations based on Euclidean tilings to solve two main issues. The first is to maximize compatibility with other platform shapes for almost limitless configurational possibilities without forced gaps that may cause forced design decisions and affect circulation paths, create longer travel distances, and increases carbon footprint as a result. The second is to minimize wasted spaces on platforms with sharp edges which result

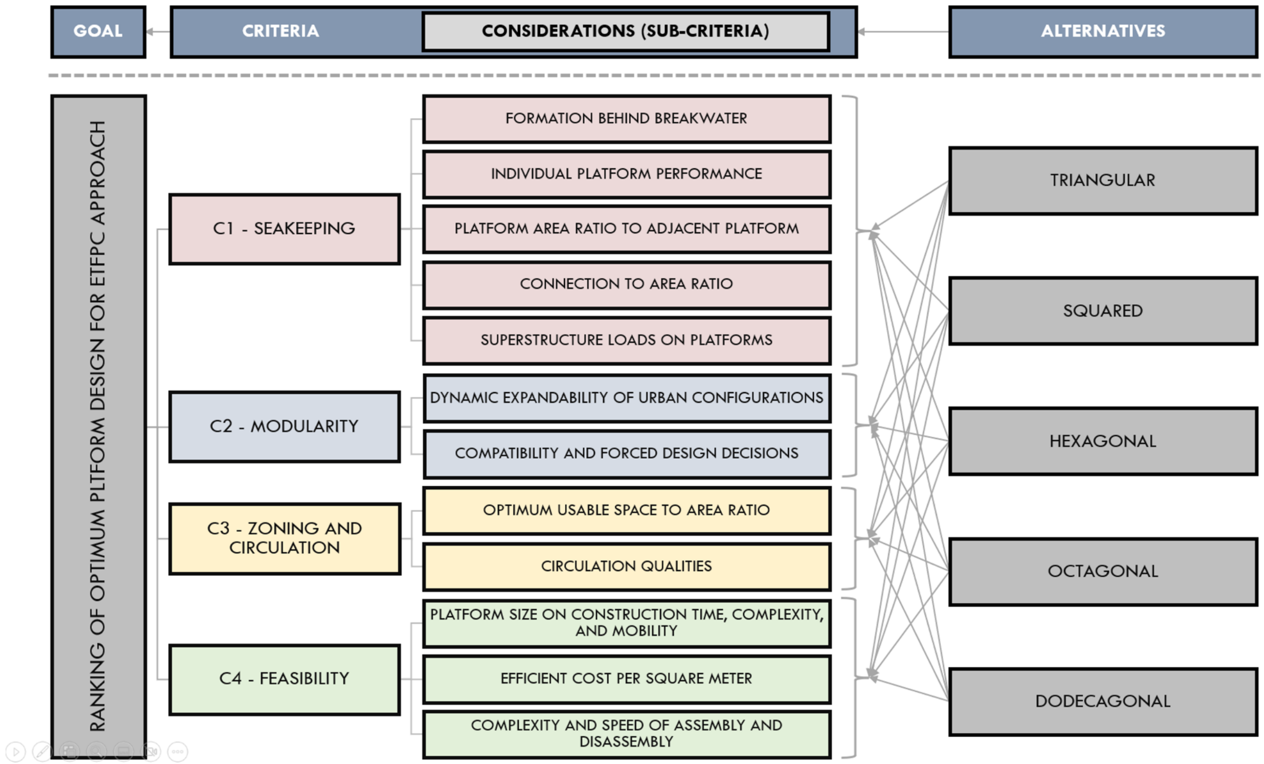



**Fig. 2** Construction of hierarchy tree for platform shapes for ETFPC approach applying AHP

**Table 4** Criteria for platform assessment values of Random Index (RI) for matrices (Golbabaie et al. 2012)

| Size of Matrix | RI |
|---|---|
| 3 | 0.58 |
| 4 | 0.90 |
| 5 | 1.12 |
| 6 | 1.24 |
| 7 | 1.32 |
| 8 | 1.41 |

in unbuildable areas by maximizing optimum usable space to area ratio for more sustainable and efficient cost per square meter, least connections to platform area ratio which decrease speed and complexity in manufacturing process and complexity and maintenance frequency to result in less carbon footprint. Thus, sustainable urban development is the core of the ETFPC approach.

After executing this process, measuring the consistency is based on Saaty's values of Random Consistency Index for matrices is shown in Table 4. If the consistency result was reasonable, the process is executed for each of the four criteria to assess all five platform shapes required for the ETFPC approach.

### *Evaluation of modular floating platforms for ETFPC*

The whole AHP process has been implemented for all five platforms. The average resulted from each platform regarding standardized matrix for weighting each criterion is then multiplied with average resulted from the standardized matrix from the same criterion in the original AHP to adjust the result for each platform regarding the significance of the criterion. The qualities of each platform design can lead into either favorable or dictate unfavorable design decisions when configuring modular floating cities such as limiting the circulation and zoning qualities.

In Euclidean geometry, any regular polygon is equiangular and equilateral meaning that all angles and all sides are equal respectively. An assumption that each edge is 30 m has been taken. Three of which are based on regular geometric tilings for configurations which are the triangular, squared, and hexagonal platforms. While the other two are the octagonal and dodecagonal platforms which are required for semiregular and demi-regular configurations. Since the scale of this field is rather significant; consequently, making it impossible to be covered in one research. Therefore, this paper

**Table 5** Pairwise comparison matrix for the criteria

| Criterion | | C1 | C2 | C3 | C4 |
|---|---|---|---|---|---|
| C1 | Seakeeping | 1.000 | 4.000 | 4.000 | 3.000 |
| C2 | Modularity | 0.250 | 1.000 | 1.000 | 0.500 |
| C3 | Zoning and Circulation | 0.250 | 1.000 | 1.000 | 0.500 |
| C4 | Feasibility | 0.333 | 2.000 | 2.000 | 1.000 |
| | Sum | 1.833 | 8.000 | 8.000 | 5.000 |
| CR = 0.008 | | | | | |

explores such approach from an urban planning level; therefore, this paper does not focus on the legality of placing floating platforms in any sovereign territory but focuses on producing a method that provides unlimited dynamic configurations. Moreover, it does not go in-dept regarding the specifics of materiality since the development of construction methods and materials is in constant change but rather focuses on minimizing material usage regardless of which material is used in the number of connections to area ratio; optimum usable space to area ratio; platform size on construction time, complexity, and mobility; efficient cost per square meter; complexity and speed of assembly and disassembly. The literature relied upon to evaluate floating platform shapes was based on their similarity to the platform shapes addressed to this paper. Evaluating the pros and cons of each platform is achieved through exploring the design potentials and limitations through each criterion. For each shape, the sum of the adjusted results from all four criteria produced the results required to judge platform shapes and configurations accordingly. This led into defining the design considerations.

## Results and discussion

Upon identifying and defining the four criteria and the five platforms designs which forms the ETFPC approach for the ETFPC as well as explaining the AHP process in the materials and methods section, this section discusses the results on such method to rank all criteria and all five platforms with the criteria for the ETFPC to achieve the research objectives. As demonstrated in Fig. 2, the hierarchical structure tree is based on the criteria set via the comprehensive literature review and assessed by the experts at the Brainstorm session. As mentioned, the AHP analysis for the optimum modular floating platforms for configuring modular floating cities is based on Euclidean tilings and the four main criteria set are seakeeping, modularity, zoning and circulation, and feasibility. Each criterion has further impacting factors as demonstrated in Fig. 2.

Initially, this section discusses the pros and cons of criteria and prioritize them. Then, it proceeds to discuss how can such systematic approach offer unlimited adaptable and expandable floating cities via identifying, discussing, and prioritizing the potentials and limitations of each platform shape. Finally, it offers design considerations for using such approach for floating cities and discusses how can such approach solve previous design restrictions of interlocking capabilities and challenges in maximum space utilization.

### Results and discussion on criteria

#### *Decision making criteria*

Relying on Table 2 for preferences, the pairwise for the criteria is shown in Table 5. This formed the basis for a

**Table 6** Standardized matrix for weighting each criterion

| Criterion | | C1 | C2 | C3 | C4 | Weight /100 | Average |
|---|---|---|---|---|---|---|---|
| C1 | Seakeeping | 0.545 | 0.500 | 0.500 | 0.600 | 53.6% | 0.536364 |
| C2 | Modularity | 0.136 | 0.125 | 0.125 | 0.100 | 12.2% | 0.121591 |
| C3 | Zoning and Circulation | 0.136 | 0.125 | 0.125 | 0.100 | 12.2% | 0.121591 |
| C4 | Feasibility | 0.182 | 0.250 | 0.250 | 0.200 | 22.0% | 0.220455 |

**Table 7** Sum of each criterion

| Criterion | | C1 | C2 | C3 | C4 | SUM | SUM/Weight |
|---|---|---|---|---|---|---|---|
| C1 | Seakeeping | 0.536 | 0.486 | 0.486 | 0.661 | 2.170 | 4.047 |
| C2 | Modularity | 0.134 | 0.122 | 0.122 | 0.110 | 0.488 | 4.009 |
| C3 | Zoning and Circulation | 0.134 | 0.122 | 0.122 | 0.110 | 0.488 | 4.009 |
| C4 | Feasibility | 0.179 | 0.243 | 0.243 | 0.220 | 0.886 | 4.017 |
| | λmax | | | | | | 4.021 |

**Table 8** Decision making on platforms

| | | C1 | C1 priority adjusted 0.536364 | C2 | C2 Priority Adjusted 0.121591 | C3 | C3 Priority Adjusted 0.121591 | C4 | C4 Priority Adjusted 0.220455 | Average | Average adjusted |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Triangular | 0.068673 | 0.036834 | 0.428266 | 0.052073 | 0.038041 | 0.004625 | 0.210934 | 0.046501 | 0.186479 | **0.140034** |
| 2 | Squared | 0.11001 | 0.059005 | 0.2775 | 0.033742 | 0.17248 | 0.020972 | 0.537705 | 0.11854 | **0.274424** | 0.232258 |
| 3 | Hexagonal | 0.318602 | 0.170887 | 0.183707 | 0.022337 | 0.235113 | 0.028588 | 0.142102 | 0.031327 | 0.219881 | **0.253139** |
| 4 | Octagonal | 0.184113 | 0.098752 | 0.060634 | 0.007373 | 0.17248 | 0.020972 | 0.065706 | 0.014485 | **0.120733** | 0.141581 |
| 5 | Dodecagonal | 0.318602 | 0.170887 | 0.049892 | 0.006066 | 0.381886 | 0.046434 | 0.043553 | 0.009601 | 0.198483 | 0.232988 |

numerical pair-wise comparison. When the criterion in row intersects with the same criterion in column, it gets a credit of one since there is no comparison between it with itself. While each criterion is given the weight relative when compared with other criteria as consensus is reached by the experts in the brainstorming session; thus, for weighting the criteria, arranging such judgments on every criterion in relation to other criteria is arranged and guided by Table 2 for preferences. For example, when seakeeping overtakes modularity by four to one means that experts have reached consensus that the row of seakeeping is moderately to strongly more significant to the column of modularity. Respectively, the column of seakeeping is moderately to strongly more significant to the row of modularity meaning that the row of modularity is moderately to strongly less significant to the column of seakeeping which is numerically translated into 1/4. The rest of criteria are judged and arranged similarly relying on Table 2. The significances of the criteria are demonstrated in Table 6.

To illustrate the significance of each criterion, the sum of each criterion is shown in Table 7 through multiplying each item from Table 5 with its significance from Table 6. Each platform design was assessed to outcome in Table 8. Through the significance of each criterion in Table 6, the platform performance was adjusted by the significance of each criterion to indicate the difference between the most and least performing platforms before and after being adjusted to their significances as demonstrated in bold in Table 8. As demonstrated in Table 6, seakeeping scored the highest with 53.6% followed by feasibility with 22.0% while modularity, and zoning and circulation scored the lowest at 12.2% each.

### *Discussion on criteria*

Since the core concept is to safely host dislocated people, the first criterion assessed is seakeeping. Seakeeping include formation behind breakwater, individual platform performance, platform area ratio to adjacent platform, connection to area ratio, and superstructure loads. A breakwater is always recommended feature to protect the city from any extreme climatic conditions and keep maintenance to the bare minimum. Platforms that can create ring formation behind the breakwater for calmer conditions offer higher seakeeping attributes. Apart from being VLFS, minimum number of platforms to configure ring formation is recommended. The implication of the individual performance of platform design regarding the seakeeping when not assembled within a configuration offers self-sufficient platforms. The platform design should facilitate simple and economical implementation of mooring systems to platform area ratio. Moreover, platforms should provide stability whilst requiring the least amount on connections to area ratio for least costs and minimum maintenance. Large area ratio between adjacent platforms in configuration contribute greatly to sagging and hogging in smaller platforms if left at the outside perimeter of the configuration. Superstructures loads impact the stability of the platform itself; therefore, if the platform design is based on an even number of sides, load distribution of superstructures could be directed through the axes of the platform whereas if based on an odd number then the zoning and load distribution must be carefully considered. Seakeeping is determined as the fundamental criterion against all the other criteria since it considers many factors like breakwater shape, platform relationship with adjacent platforms, possible city location on water, probable configuration, and superstructure's locations on platforms.

Modularity considers dynamic expandability of urban configurations as well as compatibility and forced design decisions. It is observed that platforms that have a number of sides that is divisible by two facilitates easier distribution for superstructures. Since each platform is costly to build; thus, being able to build on 100% of the platform is key. Regarding any configuration, it is observed that the less the shapes, the simpler the process of assembly/disassembly. If modular floating cities are configured via one regular platform shape, no forced gaps will be created. This will result in a floating city which is directed by design choices not forced outcomes. However, some platform shapes, like the octagonal and dodecagonal ones, impose forced decisions such as gaps of water surface if implemented individually which will interrupt the services and movement systems and result in more unusable area and longer circulation periods. Nevertheless, such issue could be avoided by implementing them in the required ETFPC configuration. Configurations should be able to extend beyond the breakwater in the high seas and not only in shallow waters. It is recommended to have a configuration that can be simply modified to branch out on its own while facing low sagging/hogging effects to promote higher quality of life. Modular capabilities of platform designs are important as it affects the city's growth and impacts design decisions; however, it comes secondary to more significant criteria that consider inhabitants' safety and the availability of platforms.

Zoning and circulation are impacted by a design that promote optimum usable space to ratio when/when not in configuration and promote higher circulation qualities. Platform shapes should maximize space utilization with maximum flexible zoning qualities through offering dynamic divisions through geometrically dissecting each individual platform into usable spaces as shown in Tables 1 and 10. Based on platform shape dissection, each platform offers the shortest routs for inter-platform circulation which will be beneficial in emergency situations through configurations that offer both orthogonal and ring paths within the platform and with adjacent platforms. Although zoning and circulation are important; nevertheless, they come secondary to the criteria that deal with the seakeeping and feasibility of the project.

Cost, time, and complexity for all platform design are essential for establishing a feasible project. This criterion considers efficient cost per square meter, complexity and speed of assembly and disassembly, and platform size on construction time, complexity, and mobility. Expandable floating cities directly relies on the platform shape and size which directly impacts construction time, structural complexities, and speed of mobility (Wang et al. 2008) which is critical when designed for displaced people. The affordability feature for such project heavily rely on platform design since the cost per square meter will not be economical if the platform design had steep angles in plan. In configurations with large area difference with adjacent platforms, detaching larger platforms requires disassembly with many detachments with adjacent platforms. Thus, the greater the variation of platforms sizes and the more the variety implemented in a configuration, the more complexity emerges when detaching is required. Considerations include optimum space utilization, maintenance costs, time for transport and relocation, and complexity of assembly/disassembly in emergency situations. This criterion only comes second to seakeeping as it is significant for such project to be feasible, however, it is more crucial to offer the inhabitants a smooth transition and a stable haven.

## Results and discussion on platforms

### *Decision making on platforms*

Since the result was reasonable consistency as shown in Table 5, an application of the patterns of Tables 5 and 6 for each of the five platforms regarding each of the four criteria are demonstrated in Appendix then adjusted for significance in Table 8. The consistency index and ratio are shown in Table 9. Table 8 shows the difference between before and after the results are adjusted to criteria significance. Before adjustment, the squared platform scored the highest by 27.44% while the octagonal platform scored the lowest by 12.07%. Upon adjustment, the hexagonal platform scored the highest while the triangular platform scored the lowest. This approach forms the basis for assessing any ETFPC configuration.

As shown in Table 9, the resulted consistency ratio for all criteria have been reasonable. As illustrated in Table 10, the ETFPC approach via regular and semi-regular modular floating platforms showing three stages: gradual growth from connection at one vertex; simplest ring configuration; to their adaptability to expand indefinitely based on ETFPC approach without resulting in overlapping or wasted spaces.

### *Discussion on platform performance for ETFPC*

As demonstrated in Table 11, the three regular platforms, together with the two newly introduced and assessed platforms, can be relied upon for eight semiregular as well as 20 (2-uniform) and 61 3-uniform (22 of 2-vertex and 39 of 3-vertex) demi-regular configurations based on (C&R) (Cundy and Rollett 1981) and (GJ-H) (Gomez-Jauregui et al. 2021). As demonstrated in Table 11, platform shape influence on configurations shows the diverse capabilities of the ETFPC approach. The three regular platforms can also produce many further configurations beyond the demi-regular configurations relying on k-uniform tilings since the dodecagonal platform can be substituted with either six triangles, six squares, and one hexagonal platform or twelve triangular and six squared platforms without resulting in any forced gaps as in previous literature as well as the hexagonal platform can substitute six triangles connected at one vertex in 35 configurations (seven 2-uniform, nine 3-uniform (2-vertex), and 19 3-uniform (3-vertex)).

The triangular platform shape appears not to be ideal regarding its individual performance since it is the most susceptible to sagging and hogging that is being created

**Table 9** CR and CI

| Item | All Criteria (based on Tables 5 and 6) | C1 (All Platform shapes) | C2 (All Platform shapes) | C3 (All Platform shapes) | C4 (All Platform shapes) |
|---|---|---|---|---|---|
| Count | 4.000 | 5.000 | 5.000 | 5.000 | 50.00 |
| Average λmax | 4.021 | 5.036 | 5.188 | 5.208 | 5.174 |
| CI | 0.007 | 0.009 | 0.047 | 0.052 | 0.043 |
| Constant | 0.90 | 1.12 | 1.12 | 1.12 | 1.12 |
| CR Value | 0.008 | 0.008 | 0.042 | 0.046 | 0.039 |
| Consistency | Reasonable | Reasonable | Reasonable | Reasonable | Reasonable |

**Table 10** Platform configuration analysis

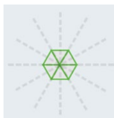
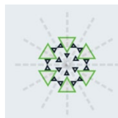
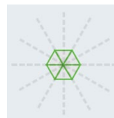
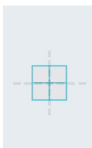
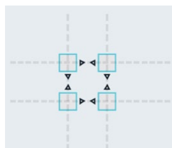
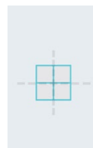
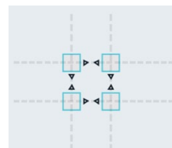
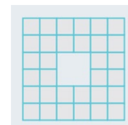
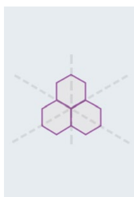
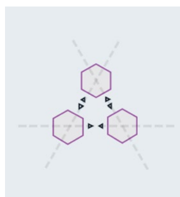
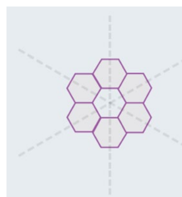
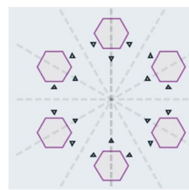
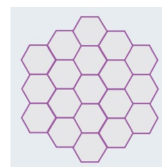
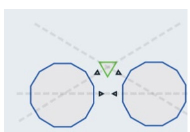
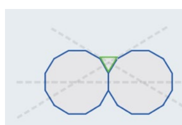
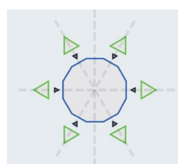
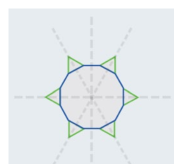
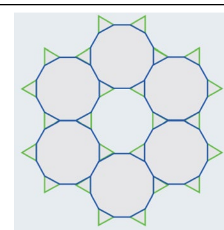
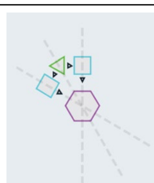
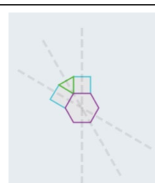
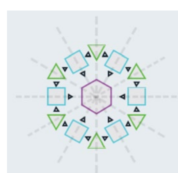
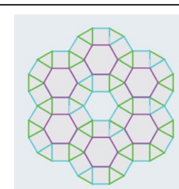
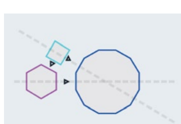
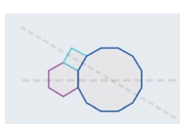
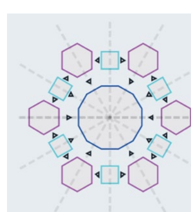
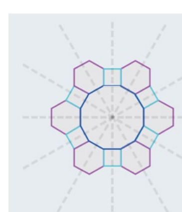
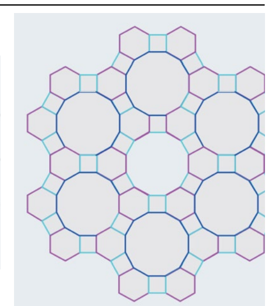
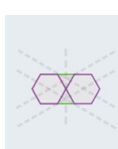
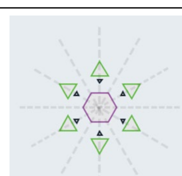
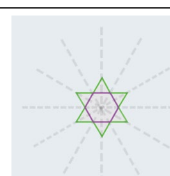
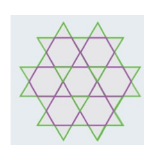
| GJ-H (Gomez-Jauregui et al. 2021) | Gradual growth from connection at one vertex | | Simplest ring configuration | | Adaptability to expand indefinitely based on ETFPC approach |
|---|---|---|---|---|---|
| 3/m30/r(h2) |  |  |  |  |  |
| 4/m45/r(h1) |  |  |  |  |  |
| 6/m30/r(h1) |  |  |  |  |  |
| 12-3/m30/r(h3) |  |  |  |  |  |
| 6-4-3/m30/r(c2) |  |  |  |  |  |
| 12-6,4/m30/r(c2) |  |  |  |  |  |
| 6-3-6/m30/r(v4) |  |  |  |  |  |

**Table 10** (continued)

| | | | | | |
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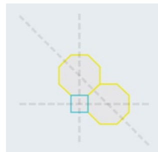
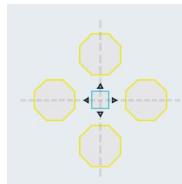
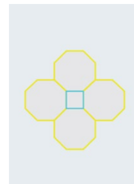
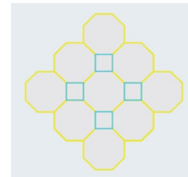
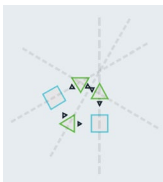
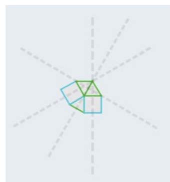
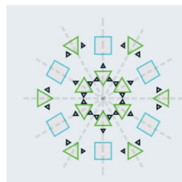
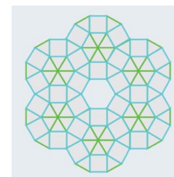
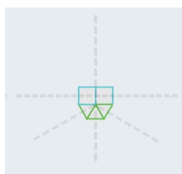
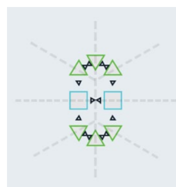
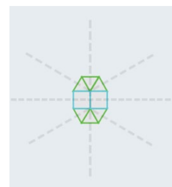
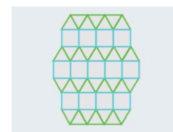
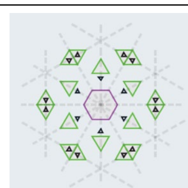
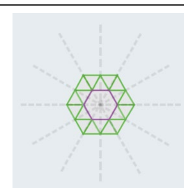
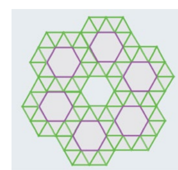
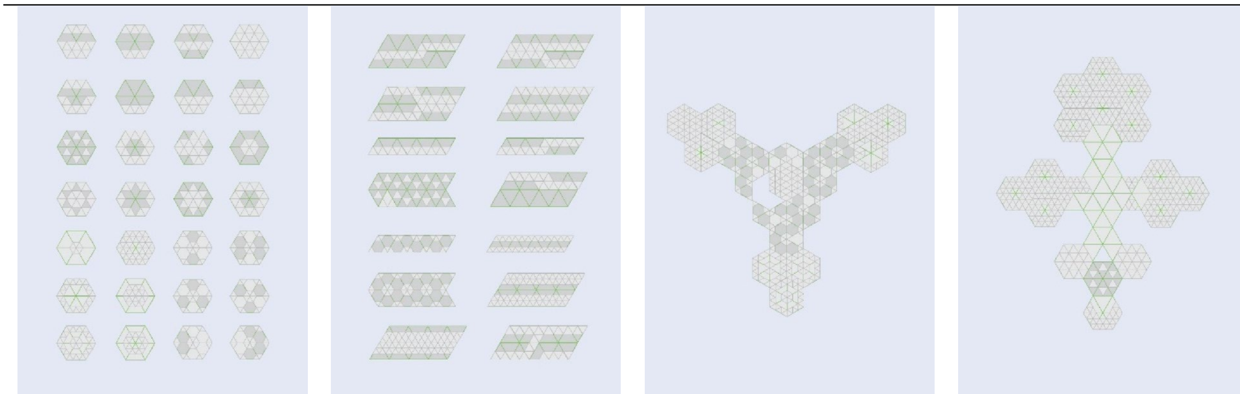
| 8-4/m90/r(h4) |  |  |  |  |  |
| 4-3-3,4/r90/r(h2) |  |  |  |  |  |
| 4-3/m90/r(h2) |  |  |  |  |  |
| 6-3-3/r60/r(h5) |  |  |  |  |  |

**Table 11** Platform shape possibilities for regular, semi-regular, and demi-regular configurations (Cundy and Rollett 1981; Gomez-Jauregui et al. 2021)

| Euclidean plane type | Platform shape | Regular Configuration | Semi-regular Configuration | Demi-regular Configuration | | | Total configurations |
|---|---|---|---|---|---|---|---|
| | | | | 2-uniform | 3-uniform | | |
| | | | | | 2 vertex types | 3 vertex types | |
| Number of configurations | | 3 | 8 | 20 | 22 | 39 | 92 |
| Number of times the platform shape is included in configuration | Triangular | 1 | 6 | 20 | 22 | 39 | 88 |
| | Squared | 1 | 5 | 15 | 15 | 29 | 65 |
| | Hexagonal | 1 | 4 | 11 | 11 | 30 | 57 |
| | Octagonal | 0 | 1 | 0 | 0 | 0 | 1 |
| | Dodecagonal | 0 | 2 | 3 | 0 | 8 | 13 |

at its edges. It also requires the most connections for its surface area. Apart from offering ring formation behind the breakwater with six platforms, it can expand diagonally and orthogonally as shown in Fig. 3. It offers high modularity since it could be configured only relying on triangular platforms as well as in other configurations with another platform designs as shown in Table 6. It does not offer any space gaps since it is a regular polygon. Its flexibility allows natural light, ventilation, and up to 300-degree views; however, this comes at a cost where such platform design approach may result in some unused spaces at the platform's corners since it offers vertices of 60-degrees. Due to its geometry, it is not ideal for orthogonal paths and the space to area ratio is the lowest among platform designs assessed. It uses the least materials among all platforms; however, outcomes in unusable space that negatively affect the cost per buildable square meter. Although being the smallest design, its shape makes it more complex and more time consuming than that of the squared platform.



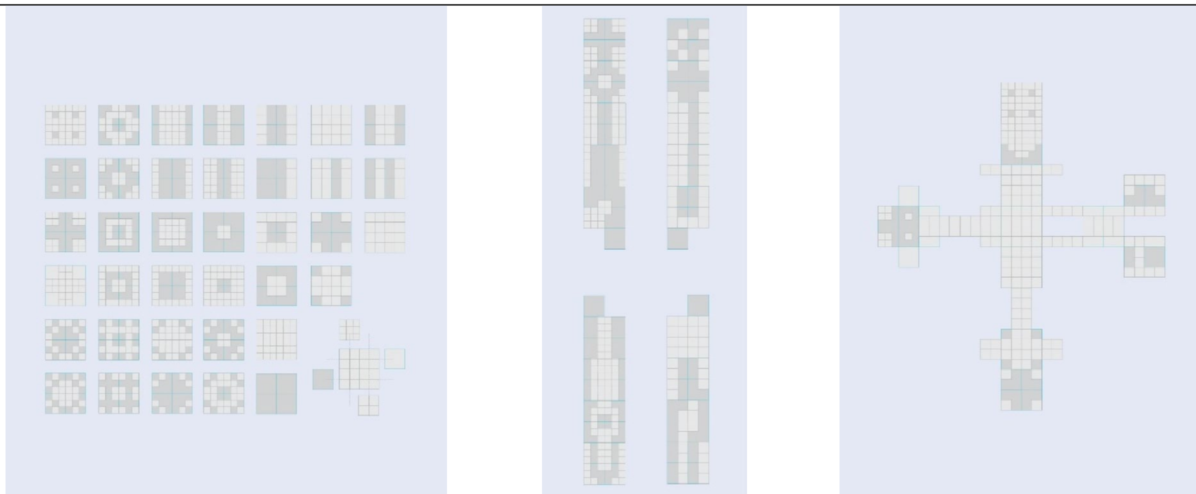
(a) Ring configuration/ expansion options with circulation and zoning possibilities (b) Linear configuration/ expansion options with circulation and zoning possibilities (c) Dynamic configuration/ expansion options with circulation and zoning possibilities (d) Orthogonal configuration/ expansion options with circulation and zoning possibilities

**Fig. 3** Modular urban configurations via triangular platforms with some zoning options based on geometric dissections

The squared platform design appears to offer moderate seakeeping characteristics providing better individual performance than that of the triangular platform in terms of susceptibility to sagging and hogging. However, the triangular platform can offer ring formations behind a breakwater unlike the squared one which could only expand orthogonally, thus mostly behind linear breakwater parallel to the shoreline. Although it does not offer the optimum number of connections to surface area, it facilitates simple assembly and disassembly. Like with triangular platforms, it delivers high modularity since it could be configured only with squared platforms as well as in other geometric configurations. Since it is a regular polygon design, it does not impose any space gaps when configured in square-based configurations. With it is 90-degrees angles, it is considered ideal for space utilization and space distribution especially when using repurposed shipping containers as superstructures. It offers the simplest and fastest structure to construct; however, it can only move orthogonally as illustrated in Fig. 4. It also offers the most economical design among the other shapes. Furthermore, it is the best platform design in terms of maintenance.

The hexagonal platform appears to offer the highest seakeeping attributes as a regular platform design. Its six-sided platform offers both ring formations and orthogonal ones. It also offers moderate number of connections to surface area. It is configured with same platform shape as well as with other designs without leaving unnecessary gaps of unused spaces. It offers good space utilization as well as the ability not only to extend orthogonally, but also in ring formations which leads to ring-road-like configuration and makes it dynamic for future expansions as demonstrated in Fig. 5. It is a simple platform shape to construct and maintain. Starting directly with a hexagonal platform will require three times less connections than of making six triangular platforms which impacts the cost, speed of construction, and carbon footprint. Thus, offering a more stable and relatively economical approach than the other regular platforms; however, it is more time consuming to construct and maintain.

The octagonal platform offers moderate seakeeping characteristics; however, it cannot be dissected into a specific geometric grid that can guide the zoning design as shown in Table 10. Moreover, it expands only orthogonally unless relied on other platform shapes. It offers moderate to low connections number to surface area ratio making it relatively better than the hexagonal platform. It offers the sense of order similar to the squared platform and the dynamism of the hexagonal shape through four axes instead of three of the hexagonal platforms which guides circulation and facilitates zoning distribution with very high expandable qualities. However, it has the lowest interlocking attributes of all platform shapes since it can only rely on the squared platform in order not to limit its circulation and zoning qualities. If used alone, leftover unused space gaps will outcome. It offers good spatial utilization with better attributes in orthogonal paths than ring ones as shown in Fig. 6. It is



(a) Ring configuration/ expansion options with circulation and zoning possibilities

(b) Linear configuration/expansion options with circulation and zoning possibilities

(c) Orthogonal configuration/ expansion options with circulation and zoning possibilities

**Fig. 4** Modular urban configurations via squared platforms with some zoning options based on geometric dissections

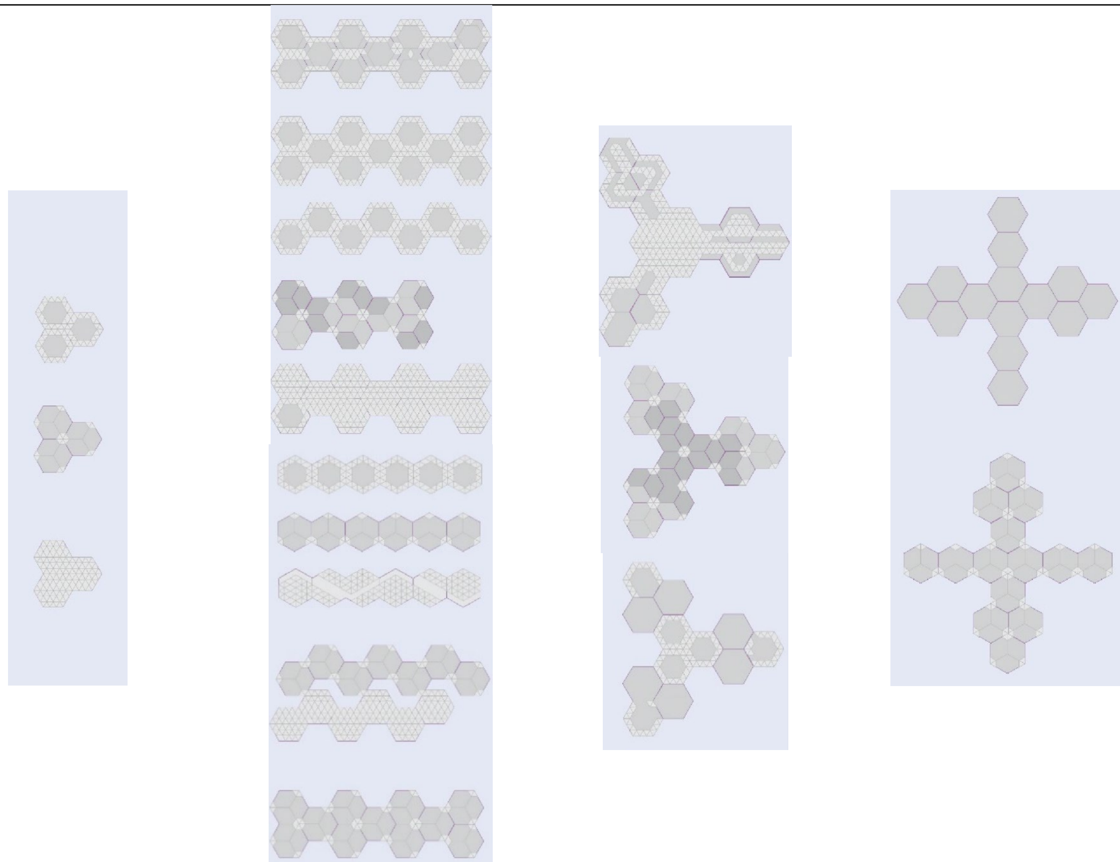
costly, time consuming, and complex to build and maintain than any of the regular platforms.

The dodecagonal platform offers high seakeeping attributes with minimal sagging and hogging; however, its shear size makes it clearly in the bracket of VLFS. It combines all the pros and cons of the triangular, squared, and hexagonal platforms in terms of platform dissection since it can be dissected using all three regular platforms. It can expand in either orthogonal or ring formation starting with all three regular platforms as illustrated in Fig. 7. In contrast to the triangular platform, it requires the least connections for its surface area among the assessed platforms. Although it is not originally considered a regular polygon; however, it shares many of the attributes of regular platform designs. Through dissecting it, six triangles, six squares, and one hexagonal platform all sharing the same edge dimension which facilitates and guides circulation and zoning distribution with very high expandable qualities as shown in Table 10. However, in dodecagonal-only configurations, leftover unused space gaps will outcome; however, less gaps to usable area ratio when compared to the octagonal platform. It offers high qualities of space to area ratio while being able to extend in ring or linear formations. Although it shares many of the attributes of the regular platform designs, it is the most complex, expensive, and time-consuming platform to construct and maintain.

## A new approach: design considerations for the ETFPC approach

Relying on these five shapes, unlimited number of configurations could be executed especially through mixing multiple configurations together suiting specific contexts as demonstrated Figs. 8 and 9. Gradual expansion from connection at one vertex to smallest circular configuration to ETFPC approach via regular and semi-regular configurations showing their adaptability to expand and join other regular configurations flexibly as demonstrated in Figs. 8 and 9 respectively. Thus, relying on such notations and mixing them together due to their geometric abilities, architects and planners are guided on configuration selection through where and how much a specific platform is repeated for a specified area of water surface.

Since the platform acts as the foundations for the superstructures. Therefore, the zoning for the platforms directly relies on the structural design of the platform for a better seakeeping approach. Although the structure for each platform design differs, it could be led by dissecting the platform shape into various geometric divisions which will accordingly influence superstructures designs. The key for a successful spatial layout is the usage of standardized modular platforms to offer both high stability and zoning qualities. Therefore, dissecting such platforms into smaller geometric divisions via middle vertex dissection, 2 middle vertex dissections, or original vertex dissection as shown in Table 1 is the approach to assess



(a) Ring configuration/ expansion with circulation and zoning possibilities

(b) Linear configuration/ expansion options with circulation and zoning possibilities

(c) Dynamic configuration/ expansion options with circulation and zoning possibilities

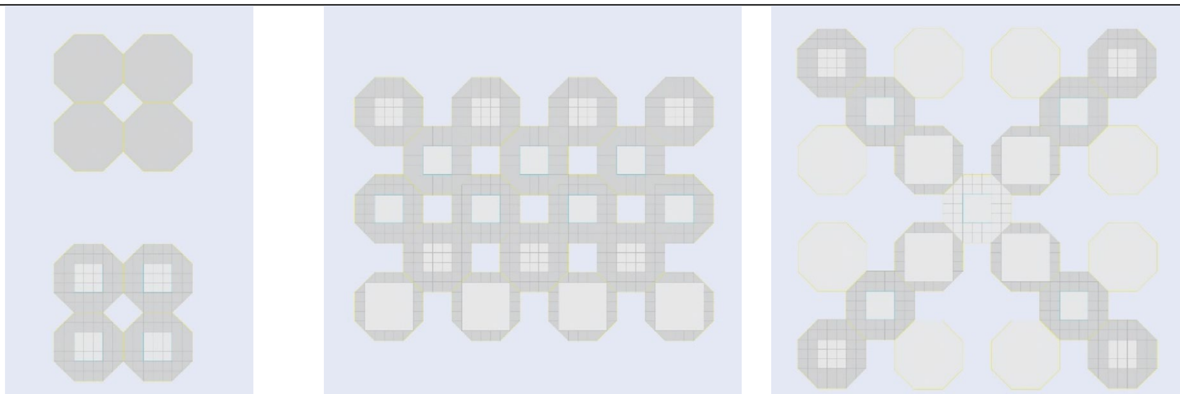
(d) Orthogonal configuration/ expansion options with circulation and zoning possibilities

**Fig. 5** Modular urban configurations via hexagonal platforms with some zoning options based on geometric dissections

the performance of platform shapes. Platform shapes doesn't only influence the structure and as a result influences the intra-platform zoning, but also impacts the inter-platform zoning of adjacent platforms and the configuration itself as a result.

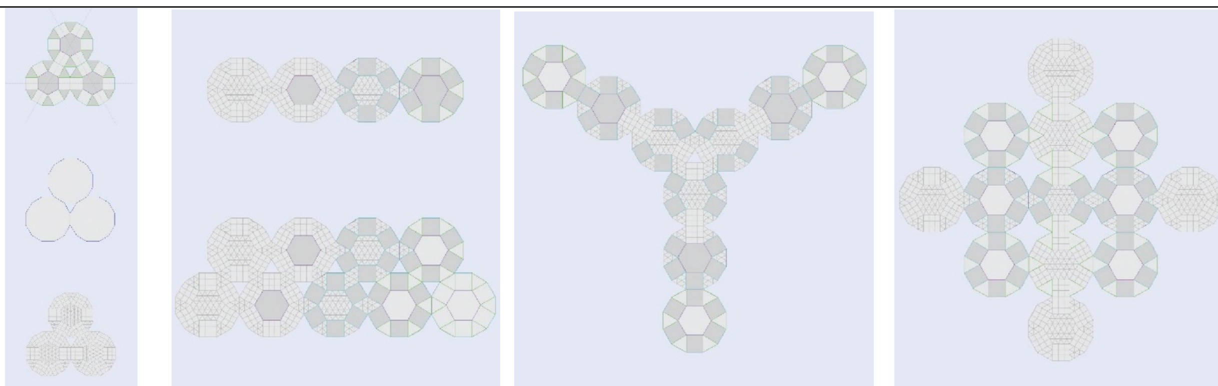
The formation approach for such standardized modular floating city is divided into two approaches, the clustered approach, and the stretched approach. The clustered approach occurs as a ring or circular configuration which promotes seakeeping and circulation. Ring configurations based on only one platform design allows similar predictable performance; however, adding breakwaters positively attribute to the floating city's stability, safety, and decreases maintenance. Such feature allows starting in protected waters, then locating to open seas behind a breakwater. This approach also allows the city to get shielded within a breakwater especially in open waters for protection from extreme climatic conditions and keeping maintenance to the minimum. The stretched approach on the other hand occurs in a linear formation parallel to coastlines. This could be useful especially in the initial stages of the city for keeping the floating settlement near coastlines in calmer conditions if mainland services are required.

As the mooring systems fix the platforms to the seabed to avoid individual platforms from drifting and reduce sagging and hogging, the interconnected platforms also stabilize the floating city together via their connection with one another to form a floating city; thus, requiring fewer mooring systems which will as a result minimize the maintenance needs, frequency, and costs. Consequently, the less the sides of the platform shape, the more it will be prone to sagging and hogging (Ko 2015). Moreover, the more the edges the platform has, the less



(a) Ring configuration/ expansion options with circulation and zoning possibilities
(b) Linear configuration/ expansion options with circulation and zoning possibilities
(c) Dynamic and orthogonal configuration/ expansion options with circulation and zoning possibilities

**Fig. 6** Modular urban configurations via octagonal platforms with some zoning options based on geometric dissections



(a) Ring configur ation/ex pansion options
(b) Linear configuration/ expansion options with circulation and zoning possibilities
(c) Dynamic configuration/ expansion options with circulation and zoning possibilities
(d) Orthogonal configuration/ expansion options with circulation and zoning possibilities

**Fig. 7** Modular urban configurations via dodecagonal platforms with some zoning options based on geometric dissections

connections to area ratio is required. Although connecting a smaller modular floating platform shape with a large one is a possible strategy; however, any low sagging and hogging that the VLFS will experience, will outcome in high sagging and hogging to the modular platforms (Ko 2015). Moreover, such platforms would be rather unstable due to both high eccentric forces and loads from VLFS (Ko 2015). Thus, a balance between the areas of adjacent platforms in any configuration is recommended.

Large floating structures pose various engineering challenges. For example, they are described by their hydroelastic behavior to the final sea site (Suzuki et al. 2006). Furthermore, because of their extraordinary lengths, such structures are designed with anticipation to diverse possible failures because of the challenges that the ocean environment impose on the structure (Suzuki et al. 2006). Thus, relatively smaller floating platforms than VLFS are recommended which in the case of this research, 30m

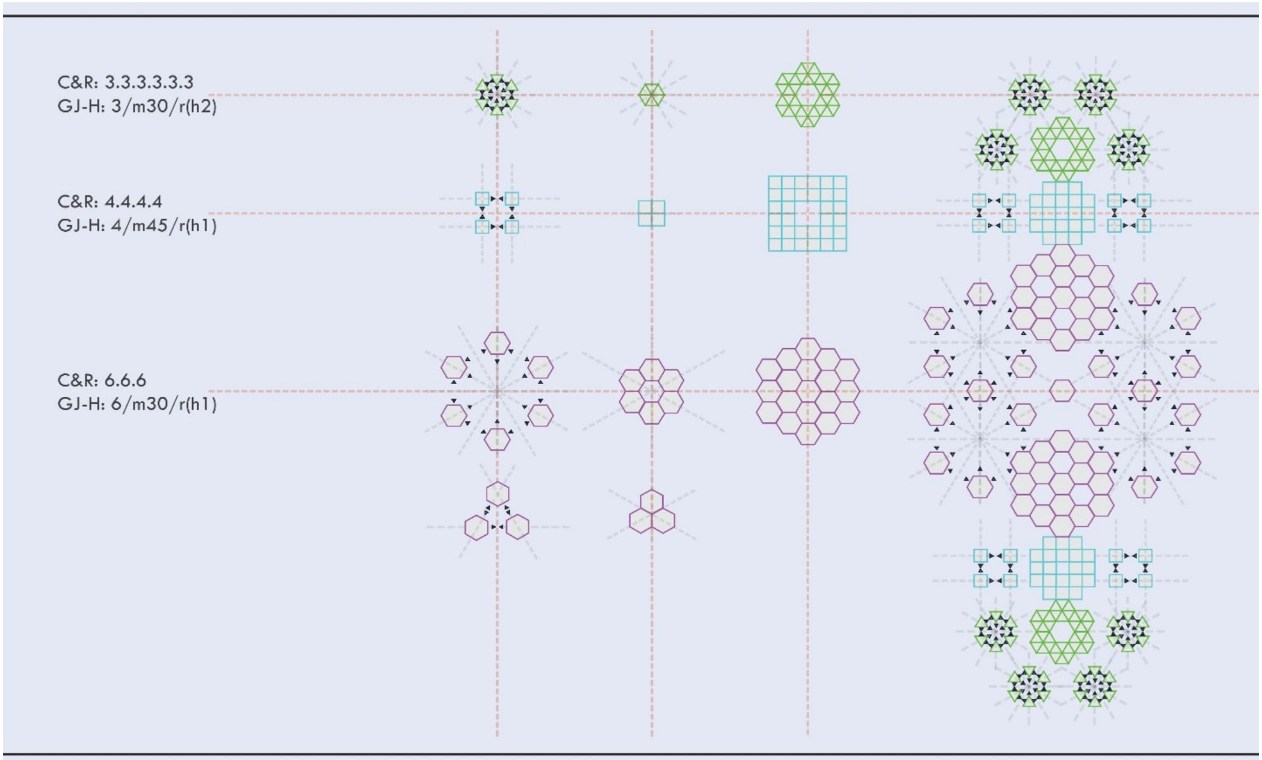



**Fig. 8** Gradual expansion of regular configurations based on ETFPC approach

per edge is recommended for its dissection abilities of 30×1 to 15×2 to 10×3 to 5×6. Moreover, the symmetric design of any given platform design plays a huge role in the stability of the platform itself. A platform design which is based on an even number of sides may distribute the loads through the platform's axes while a platform design which is based on an odd number of sides require cautious considerations for load distribution. Hence, higher seakeeping abilities regarding the load distribution could be approached.

Unlike VLFS, to facilitate fabrication, speed, and the overall structural strength of the floating platform, smaller floating structures should abide to length and width restrictions. Unlike smaller floating platforms, VLFS must be constructed on sea site since towing the structure to the required location will be a challenge. Only semisubmersible vessels can transport VLFS and only VLFS can handle severe wave conditions of open seas. The size of the semisubmersible vessels will mainly depend on the floating platform dimensions. In terms of the structural strength of the platforms, the longer the span, the greater bending moments the structure will be subjected to (Ko 2015). In concrete floating platforms, the rigidity could be enhanced via adding further reinforcement; however, such addition increases the overall weight of structure which outcomes in greater draught and would possibly lead to the inability to even float (Ko 2015). In order to create large floating cities, configurations of smaller floating platforms attached to one another since creating one huge floating platform would not be practical.

To create an interlocking floating city which is capable of being stable and produce dynamic configurations that are capable of future expansions with logical circulation, the choice for platform shapes should be carefully studied as it directly affects possible configurations for the floating city. This strategic development regarding the city's expansion can pave the way to transform such settlement from a temporary one into a more complete and a permanent one. Apart from regular configurations, other platform shapes will rely on regular platform shapes for interlocking. Therefore, at least two shapes are required in order not to leave leftover unused space gaps since they don't provide the same interlocking qualities of regular polygon-based platforms as shown in Table 10. In this case, the expandability strategy must rely on a dynamic modular approach. A platform design that would not outcome in forced gaps when implemented on water surfaces facilitates on foot circulation which is crucial. The idea is not to cover the water surface since this would negatively affect marine life; however, adding and removing platforms in configuration should be based on

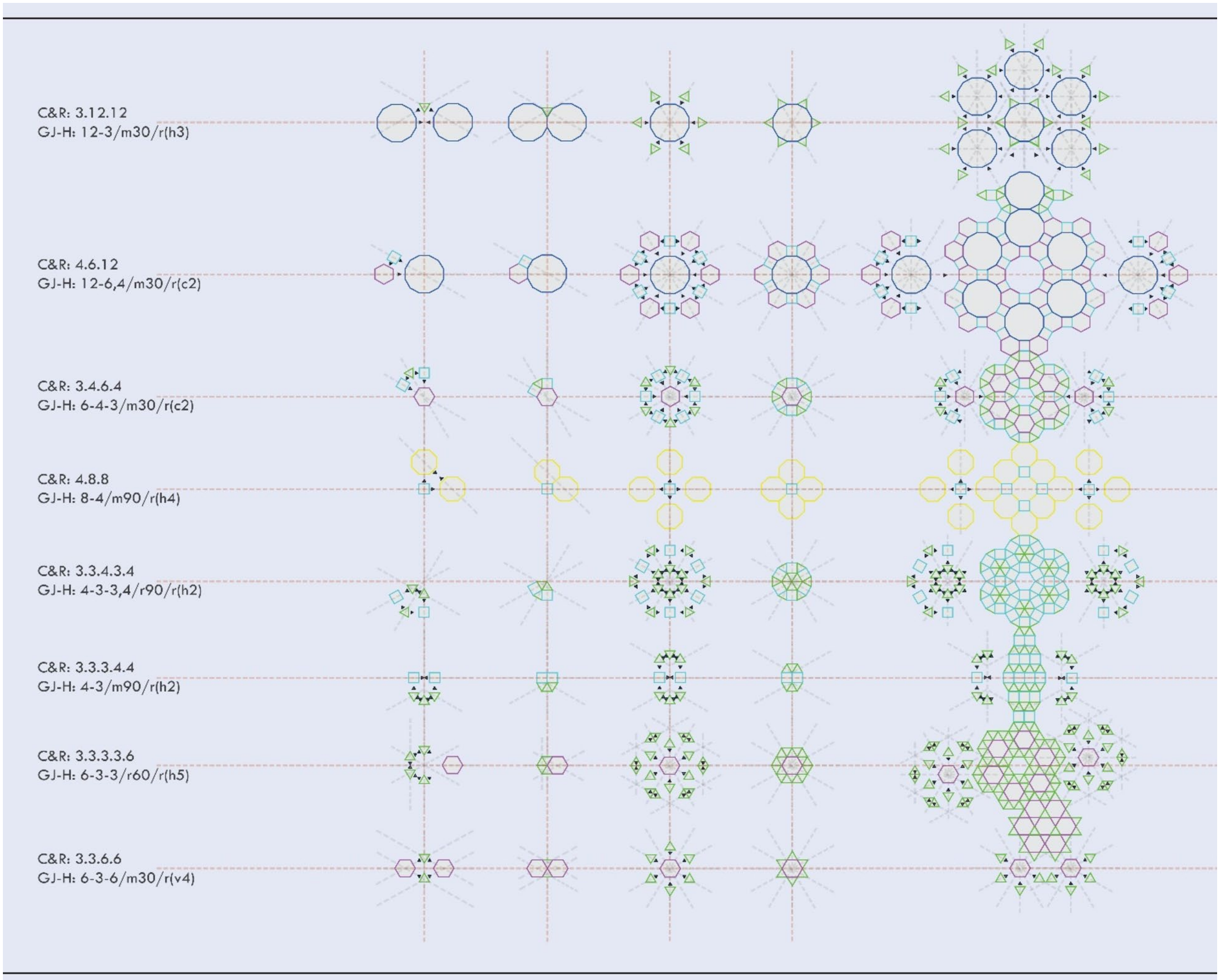



**Fig. 9** Gradual expansion of semi-regular configurations based on ETFPC approach

design decisions not unchangeable imposed outcomes. Furthermore, if a floating city is configured using only one platform design that would create forced gaps, the circulation and sense of direction with adjacent platforms will be limited. A linear configuration results in long circulation paths which will result in higher demand on certain platforms while lower on others. This will result in low on foot circulation and more reliance on vehicular transportation which would possibly lead to traffic congestion due to limited platform area. Therefore, configurations based on platform shapes which promote circulation paths of both circular and orthogonal movement systems would be highly beneficial.

The individual performance for each platform design should maximize usable space to platform area ratio. Platform that can be individually divided geometrically via middle vertex dissection, 2 middle vertex dissections, or original vertex dissection for usable space is of great importance for the viability of the project. This could be achieved via polygons that offer usable angles at their vertices to host repurposed shipping containers as superstructures within their boundaries. Although this issue could be solved through configuring the right polygons together to avoid gaps then adding superstructures that span more than one platform; however, such overlay will create disassembly challenges and result in illogical zoning and circulation from platform shapes underneath. Moreover, it will result in unstable overhung superstructures if disassembly is required for any reason. Therefore, how platforms function individually and how they behave after connecting them to the adjacent platforms is of great importance for a fully functional city.

The implication of the platform design on the cost will be directed towards the end-users. Since the cost per square meter will not be economical if the platform design promotes unused space, the viability for such project relies on platform designs that maximizes space usage. Moreover, platform design implication on the speed of the construction is crucial since time is crucial especially when the intention is to host displaced people. The less the number of connections to area ratio, the simpler and faster the process of assembly and disassembly of platforms, the less the cost required for connections and maintenance. Furthermore, platform shape dictates the simplicity or complexity of construction since this impacts the cost for construction and maintenance. Not only the design of the platform affects the cost, speed, and complexity of the platform, but the size as well. Platform size impacts construction time, transportation time to site, and only semisubmersible vessels can transport large ones. Placement of a platform within a configuration directly relates to the time and complexity for the assembly and disassembly process which is crucial in emergency situations. In some configurations, detaching smaller platforms would be impossible without detaching other adjacent platforms. Thus, when configuring a modular floating city via multiple platform shapes or integrating nonregular configurations or different configurations together, more complexity emerges in the assembly or disassembly processes.

## Conclusions, implications, and future research

Previous research on modular floating platforms resulted in configurations with many critical design restrictions mainly regarding interlocking capabilities and space utilization. Therefore, a comprehensive exploration for solutions regarding such restrictions systematically was found as crucial. This paper systematically attains its objective to solve previous functional and design challenges with modular floating planning design via a proposed dynamic approach based on Euclidean tilings as a strategy to offer numerous configurations based on regular (see Fig. 8), semi-regular (see Fig. 9), and demi-regular tessellations by means of AHP method. This paper focused on adaptable and expandable configurations as a whole and not just modular platform shapes. Since the ETFPC approach mainly relies on more than one platform shape for configuration, this research was not limited in offering the optimum platform, but to rank platform shapes while stating exactly how and when can they contribute to their configurations as each site requires different configuration(s). A low score for any platform does not mean to avoid using it since all platforms have their own pros over the others; thus, logical implementation is key. Moreover, any configuration on any particular site relies on how much each platform shape is repeated to know if it is a viable configuration.

Both quantitative and qualitative data methods were implemented. Initially, conducting a comprehensive literature review to derive the assessment criteria then consensus is reached by experts in the brainstorming method in the GDM to rank criteria and platforms via the AHP method to reach the research objectives. Although such method could be time-consuming especially when many main and sub criteria are included; however, such method offers a comprehensive mathematical analysis of the challenge presented in a hierarchical way while involving experts ensures attaining the goal objectively. According to (Stoltmann 2016), one can determine the purpose for using the AHP method with the suitable choice of experts included, careful undertaking of mathematical calculations and critical analysis of outcomes.

In terms of criteria significance, seakeeping scored the highest by 53.6%, followed by feasibility by 22%, while modularity as well as zoning and circulation scored the lowest at 12.2% each. Regarding platform ranking, prior to adjustment, the squared platform scored the highest by 27.44%, followed by hexagonal with 21.98%, dodecagonal with 19.84%, triangular with 18.64%, while the octagonal platform scored the lowest by 12.07%. Upon weight adjustment, the hexagonal platform scored the highest with 25.31%. followed by the dodecagonal with 23.29%, squared with 23.22%, octagonal with 14.15%, while the triangular platform scored the lowest with 14%. Relying on time for a city to grow and expand systematically, this paper explored such approach through the pros and cons for five platform designs through four criteria for creating an adaptable floating city.

As stated in the literature, previous research mainly relied on regular platform shapes resulting in three configurations, the ETFPC approach can still rely on two or three of these regular platforms in addition to the octagonal and dodecagonal to result in three regular, eight semi-regular, as well as 20 (2-uniform) and 61 3-uniform (22 of 2-vertex and 39 of 3-vertex) demi-regular configurations besides possibly an unlimited number of configurations based in k-uniform tilings. From the platforms in regular, semiregular, demi-regular configurations, the triangular can be in 88, squared in 65, and hexagonal in 57 while only one configuration required the octagonal and 13 configurations require the dodecagonal platform which can be substituted with either six triangles, six squares, and one hexagonal platform or twelve triangular and six squared platforms concluding that regular platforms are more efficient than irregular ones for their opportunities in floating city configurations based on the ETFPC approach without resulting in any forced gaps as in previous literature. Although the triangular platforms are concluded to be the most versatile since it can substitute the hexagonal shape with six triangular platforms; however, it creates the most wasted space due to its angles and requires the most connections whereas the hexagonal platform can substitute six triangles connected at one vertex with much less building materials, with one third less connections, and much more usable space for superstructures in 35 configurations, making it the overall most significant platform concluded. As illustrated in Figs. 8 and 9, via connecting multiple configurations together to flexibly suit specific contexts, an unlimited number of configurations relying on such five shapes could be achieved.

#### Implications and future research

The proposed ETFPC approach systematically solves the restrictions in previous literature regarding floating city design in terms of interlocking capabilities and space utilization where they relied on either one repeated regular shape or a combination of regular/irregular shapes resulting in configurations with limited design capabilities and/or gaps between platforms to an unlimited number of configurations using the ETFPC approach. Where previous research concluded that hexagonal configurations as the optimum configurations; however, the ETFPC approach offers various configurations using the hexagonal platform together with other platforms to practically exploit other platforms' attributes to suit any particular site. Moreover, previous research attempted to create configurations via hexagonal and squared platforms together resulting in dynamic configurations but with imposed gaps; however, this approach systematically offers configurations that are not limited by imposed space gaps giving architects, urban designers, and urban planners the entire freedom to make design decisions. Thus, this approach utilizes five platform shapes through introducing the octagonal and dodecagonal platforms to regular platforms. Assessment relied on their geometric attributes and similarities with VLFS properties and with other shapes to assess such shapes that were not sufficiently addressed in previous research which relied on shapes that created forced gaps between platforms if not relying on same regular shaped platforms which consequently created their own challenges. Since no research on modular floating city planning has been based on Euclidean tilings; thus, an original approach to cope with SLR is proposed with design considerations to guide architects and urban planners to efficiently select the optimum floating city configuration or mixture of configurations.

The concluded potentials and limitations of each platform practically guides which platforms are more significant for any configuration for any particular site. A configuration can employ a mixture between high performing platforms with low performing ones if the latter is used relatively less in comparison with other platforms in the configuration. Platform selection could either be due to a specific purpose for a specific site or dictated by different platform attributes. Therefore, this paper does not suggest one perfect configuration but a flexible and adjustable system that acts as an ever-growing organism to suit the needs of any particular site. As such approach is designed to fit to any context, any proposed floating city can practically apply such ETFPC approach with different criteria following this model to check its potentials where only future advancements in materials and technology may impact the choice of configuration selected; thus, future research on the real applicability of the findings of this research is recommended.

Since SLR a complex phenomenon, this paper attempts to add to the literature via proposing an approach from an urban planning standpoint to offer modular and expandable floating cities while giving unlimited design possibilities to flexibly suit any site; however, this paper did not touch specific material aspects of floating platforms or the legal aspect of floating platforms regarding any sovereign territory but focused on producing an adaptable and expandable approach for unlimited dynamic configurations.

For further research, since projects of such scale are multifaced even at a local stage; therefore, for attainable practical policies and strategies for any country, various case studies on the ETFPC approach should take place for further understanding on such a new approach. Thus, to test and visualize options, parameters will depend on platform shapes that configure the floating settlement and depending on the city's location whether coast-by or in high seas, a specific floating city configuration or a mixture between configurations can be suggested. Thus, the results of this paper can be replicated using the ETFPC approach regarding specific contexts using an initial fixed water surface area and fixing platform edge dimension to guide the configuration selection process when comparing the performance between regular, semi-regular, and demi-regular configurations.

## Appendix A

See Tables 12, 13, 14

**Table 12** Pairwise comparison matrix for the criteria

| Criterion | Shape | Triangular | Squared | Hexagonal | Octagonal | Dodecagonal |
|---|---|---|---|---|---|---|
| Seakeeping | Triangular | 1.000 | 0.500 | 0.250 | 0.333 | 0.250 |
| | Squared | 2.000 | 1.000 | 0.333 | 0.500 | 0.333 |
| | Hexagonal | 4.000 | 3.000 | 1.000 | 2.000 | 1.000 |
| | Octagonal | 3.000 | 2.000 | 0.500 | 1.000 | 0.500 |
| | Dodecagonal | 4.000 | 3.000 | 1.000 | 2.000 | 1.000 |
| | Sum | 14.000 | 9.500 | 3.083 | 5.833 | 3.083 |
| | CR = 0.008 | | | | | |
| Modularity | Triangular | 1.000 | 2.000 | 3.000 | 7.000 | 6.000 |
| | Squared | 0.500 | 1.000 | 2.000 | 6.000 | 5.000 |
| | Hexagonal | 0.333 | 0.500 | 1.000 | 5.000 | 4.000 |
| | Octagonal | 0.143 | 0.167 | 0.200 | 1.000 | 2.000 |
| | Dodecagonal | 0.167 | 0.200 | 0.250 | 0.500 | 1.000 |
| | Sum | 2.143 | 3.867 | 6.450 | 19.500 | 18.000 |
| | CR = 0.042 | | | | | |
| Zoning and Circulation | Triangular | 1.000 | 0.167 | 0.200 | 0.167 | 0.143 |
| | Squared | 6.000 | 1.000 | 0.500 | 1.000 | 0.500 |
| | Hexagonal | 5.000 | 2.000 | 1.000 | 2.000 | 0.333 |
| | Octagonal | 6.000 | 1.000 | 0.500 | 1.000 | 0.500 |
| | Dodecagonal | 7.000 | 2.000 | 3.000 | 2.000 | 1.000 |
| | Sum | 25.000 | 6.167 | 5.200 | 6.167 | 2.476 |
| | CR = 0.046 | | | | | |
| Feasibility | Triangular | 1.000 | 0.250 | 2.000 | 4.000 | 5.000 |
| | Squared | 4.000 | 1.000 | 5.000 | 7.000 | 8.000 |
| | Hexagonal | 0.500 | 0.200 | 1.000 | 3.000 | 4.000 |
| | Octagonal | 0.250 | 0.143 | 0.333 | 1.000 | 2.000 |
| | Dodecagonal | 0.200 | 0.125 | 0.250 | 0.500 | 1.000 |
| | Sum | 5.950 | 1.718 | 8.583 | 15.500 | 20.000 |
| | CR = 0.039 | | | | | |

**Table 13** Standardized matrix for weighting each criterion

| Criterion | Platform | Triangular | Squared | Hexagonal | Octagonal | Dodecagonal | Weight /100 | Average |
|---|---|---|---|---|---|---|---|---|
| Seakeeping | Triangular | 0.071 | 0.053 | 0.081 | 0.057 | 0.081 | 6.9% | 0.068673 |
| | Squared | 0.143 | 0.105 | 0.108 | 0.086 | 0.108 | 11.0% | 0.11001 |
| | Hexagonal | 0.286 | 0.316 | 0.324 | 0.343 | 0.324 | 31.9% | 0.318602 |
| | Octagonal | 0.214 | 0.211 | 0.162 | 0.171 | 0.162 | 18.4% | 0.184113 |
| | Dodecagonal | 0.286 | 0.316 | 0.324 | 0.343 | 0.324 | 31.9% | 0.318602 |
| Modularity | Triangular | 0.467 | 0.517 | 0.465 | 0.359 | 0.333 | 42.8% | 0.428266 |
| | Squared | 0.233 | 0.259 | 0.310 | 0.308 | 0.278 | 27.8% | 0.2775 |
| | Hexagonal | 0.156 | 0.129 | 0.155 | 0.256 | 0.222 | 18.4% | 0.183707 |
| | Octagonal | 0.067 | 0.043 | 0.031 | 0.051 | 0.111 | 6.1% | 0.060634 |
| | Dodecagonal | 0.078 | 0.052 | 0.039 | 0.026 | 0.056 | 5.0% | 0.049892 |
| Zoning and Circulation | Triangular | 0.040 | 0.027 | 0.038 | 0.027 | 0.058 | 3.8% | 0.038041 |
| | Squared | 0.240 | 0.162 | 0.096 | 0.162 | 0.202 | 17.2% | 0.17248 |
| | Hexagonal | 0.200 | 0.324 | 0.192 | 0.324 | 0.135 | 23.5% | 0.235113 |
| | Octagonal | 0.240 | 0.162 | 0.096 | 0.162 | 0.202 | 17.2% | 0.17248 |
| | Dodecagonal | 0.280 | 0.324 | 0.577 | 0.324 | 0.404 | 38.2% | 0.381886 |
| Feasibility | Triangular | 0.168 | 0.146 | 0.233 | 0.258 | 0.250 | 21.1% | 0.210934 |
| | Squared | 0.672 | 0.582 | 0.583 | 0.452 | 0.400 | 53.8% | 0.537705 |
| | Hexagonal | 0.084 | 0.116 | 0.117 | 0.194 | 0.200 | 14.2% | 0.142102 |
| | Octagonal | 0.042 | 0.083 | 0.039 | 0.065 | 0.100 | 6.6% | 0.065706 |
| | Dodecagonal | 0.034 | 0.073 | 0.029 | 0.032 | 0.050 | 4.4% | 0.043553 |

**Table 14** CI and CR

| Criterion | Platform | Triangular | Squared | Hexagonal | Octagonal | Dodecagonal | SUM | SUM/Weight |
|---|---|---|---|---|---|---|---|---|
| Seakeeping | Triangular | 0.069 | 0.055 | 0.080 | 0.061 | 0.080 | 0.344 | 5.014 |
| | Squared | 0.137 | 0.110 | 0.106 | 0.092 | 0.106 | 0.552 | 5.016 |
| | Hexagonal | 0.275 | 0.330 | 0.319 | 0.368 | 0.319 | 1.610 | 5.054 |
| | Octagonal | 0.206 | 0.220 | 0.159 | 0.184 | 0.159 | 0.929 | 5.044 |
| | Dodecagonal | 0.275 | 0.330 | 0.319 | 0.368 | 0.319 | 1.610 | 5.054 |
| | $\Lambda max = 5.036$ | | | | | | | |
| Modularity | Triangular | 0.428 | 0.555 | 0.551 | 0.424 | 0.299 | 2.258 | 5.273 |
| | Squared | 0.214 | 0.278 | 0.367 | 0.364 | 0.249 | 1.472 | 5.306 |
| | Hexagonal | 0.143 | 0.139 | 0.184 | 0.303 | 0.200 | 0.968 | 5.269 |
| | Octagonal | 0.061 | 0.046 | 0.037 | 0.061 | 0.100 | 0.305 | 5.023 |
| | Dodecagonal | 0.071 | 0.056 | 0.046 | 0.030 | 0.050 | 0.253 | 5.071 |
| | $\Lambda max = 5.188$ | | | | | | | |
| Zoning and Circulation | Triangular | 0.038 | 0.029 | 0.047 | 0.029 | 0.055 | 0.197 | 5.182 |
| | Squared | 0.228 | 0.172 | 0.118 | 0.172 | 0.191 | 0.882 | 5.112 |
| | Hexagonal | 0.190 | 0.345 | 0.235 | 0.345 | 0.127 | 1.243 | 5.285 |
| | Octagonal | 0.228 | 0.172 | 0.118 | 0.172 | 0.191 | 0.882 | 5.112 |
| | Dodecagonal | 0.266 | 0.345 | 0.705 | 0.345 | 0.382 | 2.043 | 5.351 |
| | $\Lambda max = 5.208$ | | | | | | | |
| Feasibility | Triangular | 0.211 | 0.134 | 0.284 | 0.263 | 0.218 | 1.110 | 5.263 |
| | Squared | 0.844 | 0.538 | 0.711 | 0.460 | 0.348 | 2.900 | 5.394 |
| | Hexagonal | 0.105 | 0.108 | 0.142 | 0.197 | 0.174 | 0.726 | 5.112 |
| | Octagonal | 0.053 | 0.077 | 0.047 | 0.066 | 0.087 | 0.330 | 5.018 |
| | Dodecagonal | 0.042 | 0.067 | 0.036 | 0.033 | 0.044 | 0.221 | 5.082 |
| | $\Lambda max = 5.174$ | | | | | | | |

**Acknowledgements**
Not applicable.

**Author contributions**
The author confirms sole responsibility for the following: study conception and design, illustrations, analysis and interpretation of results, and manuscript preparation.

**Funding**
Not applicable.

**Availability of data and materials**
Not applicable.

## Declarations

**Competing interests**
Not applicable.

Received: 30 March 2023 Accepted: 28 February 2024
Published online: 13 March 2024

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## Publisher's Note