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A VALUE-BASED MULTI-CRITERIA DECISION-MAKING APPROACH TOWARDS FLOATING HOUSE DEVELOPMENT: A CASE STUDY IN HONG KONG

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Abstract. This study aims at investigating the cost-effectiveness of developing a new type of house, the floating house, as a solution to land scarcity in metropolitan coastal cities. Under value management framework, the "function analysis system technique" diagram was established to identify the functions of land-based and floating houses. Participants with different backgrounds shared their views through the two designed questionnaires, assisting in determining the cost allocation and functional performance levels of the houses. Fuzzy set theory was utilized to convert the collected professional knowledge and public opinions into numerical measurements. The obtained function values disclosed that, despite weaknesses in the conventional living and structural issues, the floating house still shows competitiveness and opportunities in customer attraction, environmental sustainability, and encouraging local tourism. This paper offers the evidence and reference to both practitioners and governments seeking for a better value of the money they invest in future floating house projects.

Keywords: value for money, FAST diagram, fuzzy set theory, global warming, sea level rise, construction cost.

Introduction

Featured with favorable natural environment, such as flat plains and convenient transportation, coastal areas (within 100 km of the coast) have attracted a large portion of the world's population (around 1.2 billion) (Small & Nicholls, 2003). With a population density of 3 times greater than the global average, these regions also experience faster urbanization than inlands. Consequently, many coastal areas are now suffering from intense land use and expensive land price. Moreover, the global warming is exposing more coastal lands to the rising sea level and intensified coastal flooding (Church et al., 2013). Land reclamation is a common method to create land from the sea, and it has been widely adopted by countries with long coastal lines, such as China and Netherlands (Wee, 2017). However, such approach will inevitably change the seabed topography and release large amounts of contaminants into the ocean, causing serious environmental impacts (OSPAR, 2008). The development of floating houses, on the other hand, might offer an alternative solution to the housing problems in densely populated coastal cities.

Floating houses, as the name implies, are houses built on light-weight foundations floating over the waters. Unlike the traditional houseboats, the modern floating houses (Kaushik, 2015; Thomson, 2019) are designed for high quality living without means of self-propulsion. They are usually attached to a dock and connected to sewer as part of urban planning, and can be financially categorized as immovable properties (ArchDaily, 2011; Mutia, 2013). Constructed on artificial floating platforms, the floating houses utilizes the water space in a more environmentally friendly way, offering coastal cities a new option other than land reclamation. For instance, the Baca Architects came up with the idea of deploying floating houses across waterways as a solution to the housing crisis in London (Mairs, 2015), while in IJburg, Netherland, a large floating neighborhood containing 75 floating houses (with the

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final plan of 165 in total) has already been constructed (Kaushik, 2015; Witsen, 2012). Apart from residential use, floating houses have also been developed for commercial and tourism use, such as the floating exhibition venue in Seoul, South Korea (Lee, 2020) and tourism rental housing in Tennessee, U.S. (Tennessee Valley Authority [TVA], 2015).

1. The cost-effectiveness of floating houses

Current existing floating houses vary widely in their styles, designs, and market orientations, with highly volatile costs. They could be designed for low quality living for landless people with a total cost of merely several hundred U.S. dollars (Ishaque et al., 2014), or pricey standalone entertaining offshore living such as Arkup's ultra-luxury floating house which costs over 10,000 U.S. dollars per square meter (Williams, 2019). Only a few of them are designed as an alternative to traditional residential houses with comparable living quality. The IJburg floating house project is considered a success for its high-quality living, mass production, and regulated design and utility system (Mutia, 2013). This floating community is integrated in urban development, with an intermediate cost of around 1,800 US$/m^2 (Interesting Engineering, 2016). Recent research has further explored the potentials of floating houses in relieving housing shortage or global climate crisis. These studies have discussed the opportunities and challenges of floating houses based on practical experience (Lin et al., 2019; Moon, 2015; Penning-Rowsell, 2020; Storbjörk & Hjerpe, 2022) and reviewed associated construction technologies such as the building stability and mooring system (El-Shihy & Ezquiaga, 2019; Endangsih & Ikaputra, 2020). In addition, floating houses have also been investigated in its sustainability and energy efficiency (Moon, 2014; Habibi, 2015), along with its capability of adapting to floods (Kusliansjah & Suriansyah, 2013; Strangfeld & Stopp, 2014). Despite these studies, the discussion and quantitative financial analysis regarding whether such investment in floating houses is cost-effective has remained scarce in the literature. On the other hand, while there are a few exceptions such as the ultra-luxurious product in Dubai (Weller, 2017), existing floating houses are mostly designed to stay in rivers or lakes, where the water condition is usually calm. When they are introduced to rougher coastal waters, their cost-effectiveness might be further affected due to safety and comfort concerns, and associated research is also limited, if not none, in the literature.

In this study, the floating house is investigated in its cost-effectiveness, or more specifically, whether this new housing product offers reasonable value on investment, by measuring the benefits people could receive with the price they pay, as an alternative to traditional land-based houses. To understand the cost, benefit, and value of floating house projects, a structured managerial approach – the value management (VM) process – is applied. By generally defining the value as the ratio between benefit and required cost, VM focuses on increasing or maximizing this "value for money" (Churcher, 2017). The VM theory originated from the U.S. manufacturing industries in the 1940s and extended to construction design in the 1960s (Kelly et al., 2015). During its development, the focus of VM shifted from production to design phase of products, using estimated costs (Crum, 1971; Society of Japanese Value Engineers [SJVE], 1971). Furthermore, its scope extended to the design of new products, which has provoked large interest of the construction industry, with associated research persisting till today (Kelly et al., 2015; Rohaninejad & Bagherpour, 2013; Thneibat & Al-Shattarat, 2021; Yu et al., 2018). Being an innovative housing product in coastal cities, the floating house lacks practical experience and market strategy. The application of VM before its implementation will supposedly reveal its strengths and weaknesses, contributing to the value optimization.

Overall speaking, this research aims to tackle three unaddressed questions:

1. How a cost-effectiveness analysis of the floating house can be made?
2. How does the rougher sea state affect this cost-effectiveness?
3. What are the major strengths and weaknesses of floating houses from the financial management standpoint, as compared with the land-based houses?

In the following Section 2, a typical metropolitan coastal city – Hong Kong is chosen as the study area, with a preliminary survey carried out, exploring citizen's acceptability of this new type of house. In Section 3, the entire VM approach of identifying building functions, estimating construction costs, and designing questionnaire surveys for determination of function costs and performances is explained in detail. During this process, the Fuzzy Set Theory (FST) (Zadeh, 1965) is adopted to handle people's qualitative judgements on function costs and performances more effectively. Section 4 presents the results of allocated costs, performances, and true values of building functions. Based on the obtained function values, the strengths and weaknesses of floating houses are discussed, with practical recommendations provided accordingly in Section 5. Lastly, the limitations and conclusions are given. By applying the fuzzy-based VM approach, this study fills up the gaps in the literature: (i) evaluating the cost-effectiveness of the floating house in terms of its true values when deployed in different coastal environments; and (ii) disclosing the advantages and disadvantages of the floating houses, in turn, providing the foundation for evaluating the feasibility of future floating house/community projects.

2. The study area and citizen's perspectives

In this study, Hong Kong (HK) is selected as the target coastal city to systematically examine the cost-effectiveness of implementing the floating houses as an effective means to alleviate the housing shortage and sea level rise (SLR) problems. Owing to the geographical constraint – about

60% of the HK city is covered by mountainous terrains (Hong Kong Special Administrative Region Government, Civil Engineering and Development Department [HKSAR CEDD], 2016) – the urban population density in HK has reached 26,100/km^2, ranking No. 6 of the world's built-up urban areas (Cox, 2019). The shortage in usable land has brought HK residents a small living space (with an average floor space per dwelling of 45 m^2), which is about half and a quarter as compared to those of the UK and the US (with 85 m^2 and 174 m^2, respectively) (Jayantha & Hui, 2010). Moreover, the high and soaring housing price makes HK the world's least affordable housing market for 9 years in a row (Cox & Pavletich, 2019). It is also believed that the poor housing condition and overcrowded streets in HK have greatly raised the tension between the locals and the immigrants/tourists from mainland China (Siu, 2019; Xinhua, 2019). Moreover, the global warming is making the situation worse. The HK Observatory estimated that the global mean SLR by the end of the 21st century (Hong Kong Observatory [HKO], 2020) would be between 0.73 m and 1.28 m, while the National Oceanic and Atmospheric Administration in the U.S. [NOAA] suggested a worst-case scenario of 2.5 m (Sweet et al., 2017) among others. In response to this, authors conducted a preliminary study to investigate the impact of future mean SLR and subsequent storm surges on HK's coastal line under NOAA's worst-case scenario. It is estimated that under this scenario, the 100-year return period extreme high-water event could result in a temporary SLR of 2.91 m (above the current mean sea level) in HK by 2050 and 4.78 m by 2100. Figure 1 shows the corresponding submerged and inaccessible areas at northern HK Island under different SLR scenarios predicted using Google Earth. The result indicates that the central business districts in HK may suffer heavy losses if the temporary SLR is over 3 m. The demographic conditions, geographical constraints, and future threats have put HK in a dire need of a sustainable housing solution.

To explore citizens' perspectives and the potential market of floating houses in HK, our research team carried out a pilot survey involving 245 people (Chung, 2015), with around 70% of the participants holding at least an undergraduate degree. The vast majority (92%) showed their acceptance of living in a floating house if it provides the same quality and service levels as a traditional land-based house does. In addition, when given a hypothetical price that the floating house is 10% cheaper, 84% of people expressed their interests in the floating houses. The survey also confirmed that over 80% of the participants take the price as their greatest concern when seeking for a home. Consequently, in this study, we estimate the construction cost of a prototype floating house and explore its cost-effectiveness using the value management (VM) process, so as to assess whether the floating house can be a viable solution to coastal land scarcity.

As HK is a place that frequently exposed to typhoons which induce large offshore waves in summer, the safety and comfort issues must be inspected. Compared to ordinary floating houses designed for calm waters, floating houses in rougher coastal waters require additional costs on different structural configurations and wave attenuation devices, which could affect the cost-effectiveness. In this study, two different scenarios of floating house development are considered, including: (1) ordinary floating houses located at protected waters such as the harbor areas and gulfs, (2) strengthened structures with the protection of breakwaters in offshore waters.

3. Assessment of the values of house functions

To reveal the true values of floating houses, the function-oriented approach – value management (VM) process is adopted. With principles that functions are what make products or services to work or sell (SAVE, 1998) and that "buy function, don't buy product" (Cartlidge, 2006), VM theory aims to achieve an optimum balance between the

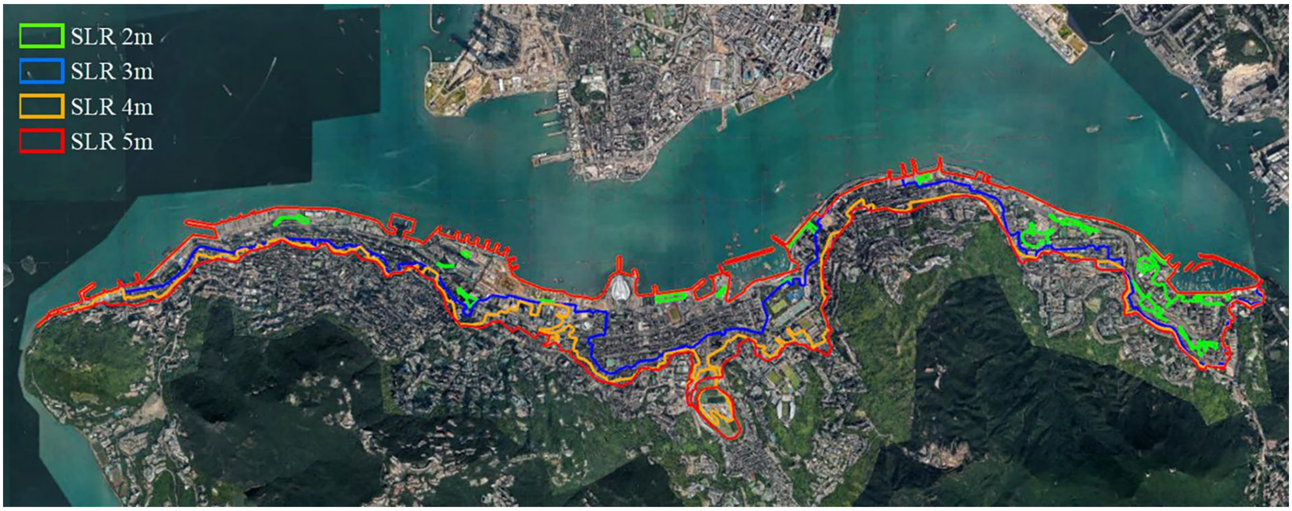

Figure 1. Flood maps of northern HK Island under the SLR scenarios varying from 2 m to 5 m

functions provided by the product, the performance levels of the functions, and the corresponding costs (Mubarak, 2015). Following a widely accepted expression "Value = Function/Cost" (Kaufman, 1998), the best value of a function can be achieved by striving for a maximum quality or performance with the lowest cost, or by providing additional auxiliary functions without an increase in the cost (Norton & McElligott, 1995; Rangelova & Traykova, 2014). VM is particularly favored at the early stage of a project, as an earlier application period allows greater opportunities of enhancing the value (Ellis et al., 2005; Lee et al., 2015). With these features, VM has been adopted in new product development which lacks market experience (Gerhardt, 2006; Ibusuki & Kaminski, 2007; Rich et al., 2000). In this study, both the traditional house and its alternative, the floating house are designed for a series of functions that contribute to accommodating residents; the latter is likely to allocate part of the total cost to enhance some functions that differ from the former, such as those dealing with SLR. The main concern of this research is therefore to determine, through VM process, whether it is worthy of spending money on those particular functions and whether the values of the fundamental residential functions still maintain in the acceptable ranges.

This section presents the complete VM approach of quantifying the values of floating houses and traditional houses. In the following subsections, the building functions of the two types of houses are first identified through the Function Analysis System Technique (FAST). Next, the construction cost of the floating house is estimated, implying the total cost spent on functions that the house provides. Then, two questionnaire surveys are designed and conducted, to determine the costs allocated to functions, and performances of functions, respectively. To handle the vagueness of participants' qualitative judgements, the fuzzy set theory is applied to improve the conventional VM process.

3.1. Functions of houses

Function identification and analysis are vital in VM practice, as the value of a product can be assessed only when its functions are fully comprehended. To link all the functions of a system, the Function Analysis System Technique (FAST) diagram is used. FAST diagram is a graphical representation of the functions of a product and has become the foundation of function analysis since its introduction (Borza, 2011; Bytheway, 1965). The FAST diagram usually is organized in such a logical relationship that following the path from the higher order functions to the lower order functions (i.e., from left to right on the diagram), it demonstrates the "How" relationship, while the "Why" relationship holds true for the opposite direction of the path (Wojciechowski, 1978). In other words, when higher order functions describe what is being accomplished, the lower order functions define the approaches to accomplish it. In this study, the FAST diagram was structured from the customer's perspective instead of the designer's (i.e., the so-called customer FAST diagram (Snodgrass & Fowler, 1972; Thiry, 2013)). That is to say, the basic functions (which demonstrate the purpose of the existence of the houses) are placed at the top of diagram, whereas the supporting functions (which are created to make the houses more acceptable and desired) are located at the lower portion. A group of construction professionals were invited to identify the functions of traditional land-based and floating houses in a FAST diagram, as shown in Figure 2.

The Basic Functions were determined from the original intention of introducing the floating houses in densely populated coastal cities, that is, "Increase Capacity", "Extend City" and "Release Overcrowding", all of which contribute to the ultimate target function – "Improve Life". Among these three basic, higher order functions, "Extend City" can further be achieved through the lower order subfunction, "Form Site-platforms", either on the sea or on the land. Similarly, "Release Overcrowding" can be realized by creating land, so as to reduce the population density. As for the supporting functions, they are determined from the viewpoint of customers, which usually include: attract user, assure convenience, assure dependability, and, satisfy user (Woodhead & Downs, 2001). Three similar expressions "Attract Customers", "Ensure Convenience" and "Ensure Dependability", are thus selected as the higher order supporting functions in the FAST diagram. A lower order function, "Connect Utilities", was designed to accomplish the dependability issue. The fourth supporting function, satisfy user, was replaced by a more specific function, "Ensure Adaptability", which is composed of four lower order functions concerning with humidity, steadiness, weight, and lifespan subjects. These supporting functions focus on enhancing the product's nature, namely, creating a safe and comfortable environment for people to live. In addition, two extra supporting functions are introduced into the FAST diagram to emphasize on the main differences

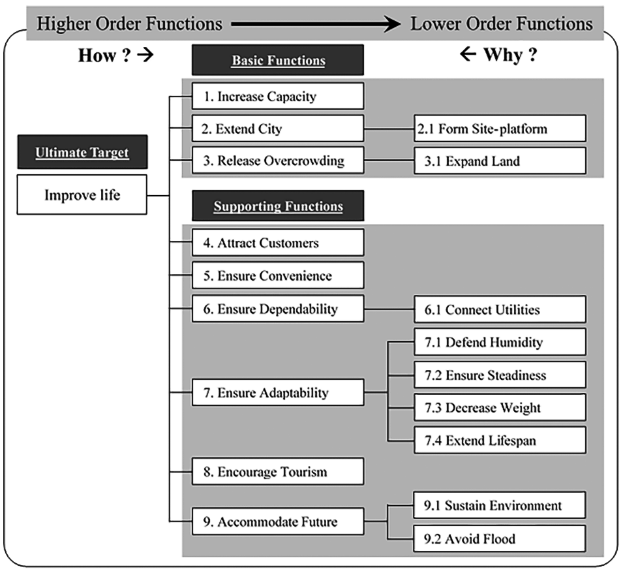

Figure 2. The FAST diagram showing the basic and supporting functions of housing projects

between the floating houses and the traditional houses. The function, "Encourage Tourism", demonstrates the ability of the housing project to attract visitors (by developing recreational zones or holiday houses) that benefits the local tourism industry. Another extra function, "Accommodate Future", on the other hand focuses on some issues that people in coastal cities may need to face in the future such as environmental sustainability, along with the potential flood problems caused jointly by the SLR and the more frequently seen extreme weather.

3.2. Function cost analysis

After determining all functions in the FAST diagram, the following steps were undertaken: (1) allocate construction costs to the functions, (2) evaluate the performance level of each function, and (3) compute the value index of the functions. When distributing the cost to each function, it should be noticed that different building components might emphasize on particular functions. It is therefore reasonable to divide the entire house into several primary building elements such that the cost of each building element can be more precisely allocated to associated functions. Afterwards, the function cost should be adjusted based on the performance level of the function, in order to make a fair comparison on the value of spent money. According to a widely accepted classification of building elements, a house can be decomposed into substructure, floor, roof, staircase, external walls, internal walls, finishes, and external works (Hong Kong Special Administrative Region Government, Architectural Services Department [HKSAR ASD], 2001). These components are straightforward and self-explanatory for the land-based houses. As for the floating houses, the substructure is normally a floating platform (see Figure 3a), and the external works (see Figure 3b) contain three major components, including: the anchoring facilities (i.e. the mooring anchors used to fix the floating house in place, preventing it from drifting away with waves), the bridges and docks (including all the passageways, jetties, and breakwaters of floating communities), and the grinding-pumping system for drainage (i.e. a macerating-pumping machine in which the contents collected from toilets or sinks are grinded up into a slurry and pumped through pipes to the city's sewer system) (Sniesen, 2008). As it is unlikely for an individual to be familiar with all components or functions of a product, a multidisciplinary team approach was considered in questionnaire survey when allocating the costs to the functions and later on determining the performance levels of functions (SAVE, 2007). The "Cost to Function Worksheet" (see Appendix, Table A.1) was used to facilitate allocating the costs to each building element (Younker, 2003; SAVE, 1998).

3.3. Construction cost estimation and breakdown

At present, there is no floating houses in HK. Therefore, an existing floating house project located in Lake Huron, Canada (Meade, 2012) was used as the prototype (see Figure 3a) in this study to establish the construction cost data. This floating house is initially designed for the calm waters without exposure to the rough sea state. It is a two-story villa for a single family, with a total construction floor area (CFA) of 1500 square feet (≈140 m^2). Since its floor area is around three times the size of the current average floor space per dwelling in HK (i.e., 45 m^2), its floor plan was slightly revised to hold two families accommodating up to eight people. The dimension of each floor is 5.5 m × 12.7 m and the story height is 3 m. The substructure is a floating platform made of steel pontoons, while a wooden frame superstructure was adopted for the purpose of reducing the self-weight. Following the estimation procedure for wood frame structures suggested by Dagostino and Feigenbaum (2015), the construction cost of the floating house was estimated and broken down to the element level, as summarized in Table 1.

When deployed at the sea, the offshore waves may pose a threat to the residents concerning the safety and comfort issues. To examine the structural performance of the floating house at extreme sea states, we built a finite element

a) Superstructure and floating platform b) External works

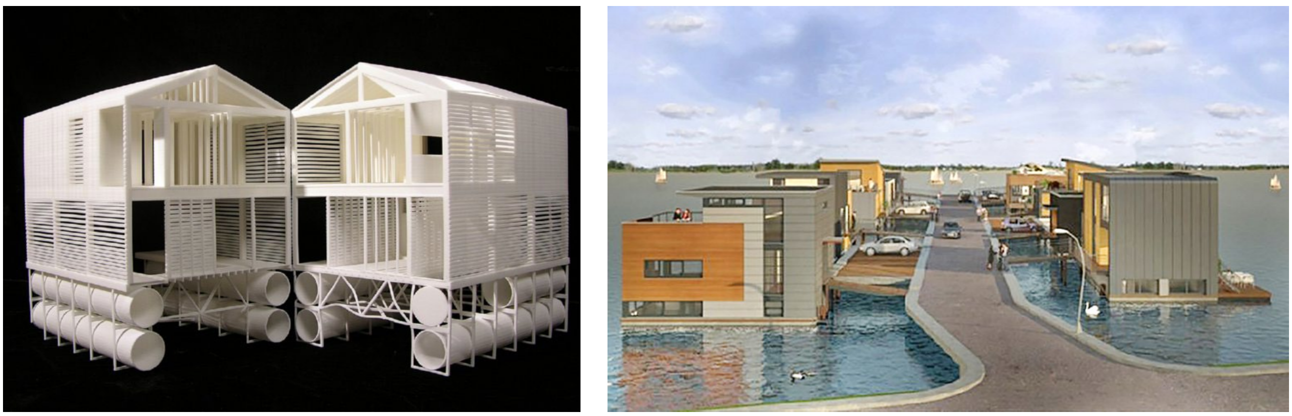

Figure 3. a – Structural system of the prototype floating house (Meade, 2012); b – external works (Michuki, 2014) of a floating community

Table 1. Elemental cost of ordinary and strengthened floating houses

	Building elements		Ordinary floating house (140 m^2)		Strengthened floating house with breakwaters (140 m^2)	
			Elemental cost (US$)	Unit cost (US$/m^2, CFA)	Elemental Cost (US$)	Unit cost (US$/m^2, CFA)
A	Foundation / floating platform		47,084	336.31	47,084	336.31
B1	Floor		23,320	166.57	25,420	181.57
B2	Roof		19,016	135.83	22,937	163.83
B3	Staircase		4,500	32.14	4,500	32.14
B4	External wall		17,288	123.49	22,916	163.69
B5	Internal wall		11,725	83.75	11,725	83.75
C	Finishes		65,000	464.29	65,000	464.29
D1	External works / drainage	Anchoring facilities	40,800	291.43	40,800	291.43
D2		Bridge and dock	54,306	387.90	101,984	728.46
D3		Grinding-pumping system for drainage	3,000	21.43	3,000	21.43
SUM			**286,040**	**2,043**	**345,366**	**2,467**

(FE) model in the commercial FE program, Abaqus/Explicit (Dassault Systèmes, 2014). Real wave fields were numerically reproduced based on local wind and wave data in both offshore and protected nearshore waters (HKSAR CEDD, 2019). The safety issue was then examined through the story drift, while the comfort performance is quantified using the "1-hour motion sickness incidence (MSI)" (International Organization for Standardization [ISO], 1997) which indicates the percentage of people who may acquire sea sickness symptom after staying in the house at rough sea state for one hour. The results showed that the performance of floating houses is highly dependent on the site selection. The prototype floating house performs well in protected nearshore waters, with 0.35% maximum story drift and 1.23% MSI in a 100-year wind wave event. However, when deployed in offshore waters, the resultant story drift is over 5%, significantly exceeding the limitations dictated in the common seismic and wind codes (American Institute of Steel Construction [AISC], 2003; American Society of Civil Engineers [ASCE], 2002; Searer & Freeman, 2004). It verified the worries regarding the safety issue. A strengthened superstructure and breakwaters were thus employed and tested in the FE model to mitigate the excessive vibration of the floating house. With the enhancements, the story drift was found to be brought down to 0.1%, with a 6.33% MSI. Consequently, in this study we will examine the cost-effectiveness of both the ordinary and the strengthened floating houses. The scale of the community and external works is assumed to be close to that of the IJburg project (Kaushik, 2015). The construction cost is estimated accordingly, and the resultant cost breakdown is listed in Table 1.

As the floating house usually possesses a beautiful sea view and its floor plan layout is more spacious than an average land-based house in HK, it is assumed that the potential customers of the floating houses are people with relatively high income. Therefore, a high-quality 3-story residential building at Yuen Long, N. T. (with a total CFA of 250 m^2) was taken as the land-based counterpart (see Table 2 for detailed cost breakdown), which can accommodate three families with up to 12 people. Building components like furniture and building services inside the houses were assumed to be identical in the two types of houses and thus were excluded from the cost comparison. The cost for acquiring the ownership of land or sea was excluded, too.

3.4. Importance levels of building elements and performance levels of building functions

In order to objectively allocate the elemental costs to building functions, and assess the function performances for both types of houses, two questionnaire surveys were carried out respectively. Owing to the requirement for professional knowledge, questionnaires in the first survey were distributed among professionals with the expertise in the construction-related industries, including engineers, architects, quantity surveyors, and other professions, such as the project managers, academics, etc. These construction professionals were consulted to determine the *importance* level of building elements with respect to each function for both types of houses.

As various types of houses may offer the building functions at different quality levels, the second survey was performed to assess the *performance* level of building functions in the two types of houses. Unlike the first survey, the second one is more general, and people of different backgrounds can possess their own distinct opinions. Therefore, four groups of people classified as the customers (i.e., house buyers), construction professionals, tourism clerks and policy developers in the government were invited. The data collected from the four groups were analyzed separately to investigate how people with different standpoints would show their particular emphasis and how this would affect the function values.

Table 2. Elemental cost of a high-end traditional land-based house

	Building elements	Land-based house (reinforced concrete structure) (250 m^2)	
		Elemental cost (US$)	Unit cost (US$/$m^2$, CFA)
A	Foundation / floating platform	44,748	178.99
B1	Floor	19,491	77.96
B2	Roof	23,568	94.27
B3	Staircase	7,985	31.94
B4	External wall	165,522	662.09
B5	Internal wall	23,652	94.61
C	Finishes	179,979	719.92
D1	External works / drainage	70,968	283.87
SUM		**535,913**	**2,144**

Table 3. The occupational background and experience of participants in the first survey

Work Background			Work Experience		
	Number	Per-centage		Number	Per-centage
Engineer	25	36%	< 5 years	29	41%
Quantity surveyor	17	24%	5~10 years	23	33%
Architect	12	17%	10~15 years	10	14%
Others	16	23%	15~20 years	2	3%
			>20 years	6	9%

Finally, 70 valid questionnaires were collected in the first survey, with more than half of the participants having work experience of over five years, as summarized in Table 3. In the second survey, 120 valid questionnaires were collected in total, with 30 replies from each group. Referring to a recent VM related questionnaire survey which involves 195 valid responses (Mohamad Ramly et al., 2015), the sample size of 190 in total is considered sufficient to give an objective evaluation on function cost and function performance.

3.5. Data processing with fuzzy sets

When allocating the construction costs to functions using the conventional "Cost to Function Worksheet", people usually assign exact costs from building elements by measuring their contributions to different functions (SAVE, 1998). This process is often time consuming as the complexity and required workload largely increase with the quantity of involved building elements and functions, while the vagueness feature of human's subjective measurements is not well addressed. In this study, a more effective way is adopted by introducing the fuzzy set theory (FST). As the cost allocated from a building element to a certain function is directly correlated with its importance in achieving that function, participants only need to rate the importance levels of the building elements to different functions in the modified worksheet. Then, these collected qualitative linguistic variables (namely, "Importance Levels of Building Elements" in the first survey and "Performance Levels of Building Functions" in the second survey) are converted to numerical values for computation through FST. Being capable of dealing with the inherent vagueness and imprecision nature of human thought process (Zadeh, 1965, 1988), FST has been applied to performance evaluation in VM process in recent research (Chen & Su, 2017). Following the "seven plus or minus two" standard (Miller, 1956), the two questionnaire surveys in the present study provided five values to qualitatively evaluate the importance and performance levels: "Very Low", "Low", "Medium", "High", and "Very High". When mapping these linguistic values (e.g., "Low", "High") to the numerical base values, triangular fuzzy numbers were adopted. The fuzzy number refers to a collection of possible values instead of an exact number, so as to capture the ambiguity that exists in human's perceptions. The distribution of the possible values is described by a weighting function (between 0 and 1) known as the membership function (Chan, 2017). In this study, the triangular fuzzy numbers (TFNs) were adopted for its wide application, intuitive representation, and efficient computation. The mathematical expression of such a TFN is (L, M, N); its membership function $\mu_A(x)$ is graphically presented in Figure 4 (Left). The complete fuzzy set adopted in this study is shown in Figure 4 (Right) and Table 4.

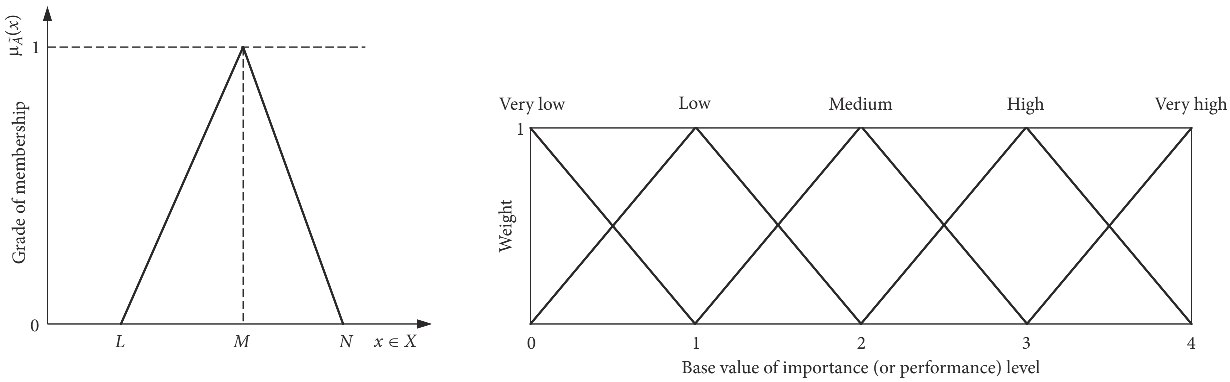

Figure 4. Membership function of a triangular fuzzy number (Left); and fuzzy sets adopted in this study (Right)

Table 4. Mapping from linguistic values to triangular fuzzy numbers

Level of Importance (or Performance)	TFNs: $E_k = (L_k, M_k, N_k)$
Very Low	(0, 0, 1)
Low	(0, 1, 2)
Medium	(1, 2, 3)
High	(2, 3, 4)
Very High	(3, 4, 4)

To integrate all the fuzzy values evaluated by the participants, the mean value can be computed following the principals of TFN calculation algorithm (Tsaur et al., 1997). The addition operation between two TFNs, $\mu_{A1}(x)=(L_1,M_1,N_1)$ and $\mu_{A2}(x)=(L_2,M_2,N_2)$, is given in Eqn (1). If the importance level for building element i against function j evaluated by participant k is denoted as E_{ij}^k, then the mean value representing the integrated judgments of all participants (with the total number of m) can be computed using Eqn (2) and expressed in the TFN format as in Eqn (3) (Buckley, 1985).

$$(L_1,M_1,N_1)\oplus(L_2,M_2,N_2)= (L_1+L_2,M_1+M_2,N_1+N_2); \quad (1)$$

$$E_{ij}=(1/m)\cdot\left[\left(E_{ij}^{1}\right)\oplus\left(E_{ij}^{2}\right)\oplus,\cdots,\oplus\left(E_{ij}^{m}\right)\right]; \quad (2)$$

$$E_{ij}=\left(LE_{ij},ME_{ij},NE_{ij}\right), \quad (3a)$$

$$\text{where } LE_{ij}=\left(\sum_{k=1}^{m}LE_{ij}{}^{k}\right)/m; \quad (3b)$$

$$ME_{ij}=\left(\sum_{k=1}^{m}ME_{ij}{}^{k}\right)/m; \quad (3c)$$

$$NE_{ij}=\left(\sum_{k=1}^{m}NE_{ij}{}^{k}\right)/m, \quad (3d)$$

where E_{ij} denotes the aggregated results of all the respondents' responses, while LE_{ij}, ME_{ij}, and NE_{ij} denote respectively the lower bound of appraisal, the most likely value of appraisal, and the upper bound of appraisal.

After obtaining the integrated fuzzy value, the centroid method (Chiou et al., 2005; Zhao & Govind, 1991) was employed to compute the final defuzzified numerical measurement indicating the level of importance or performance, as given in Eqn (4). Afterwards, the percentage of the cost of a building element that should be allocated to various functions was computed following Eqn (5) (note that the defuzzied values of the importance and performance levels are evaluated separately but using the same approach).

$$\alpha_{ij}=\frac{LE_{ij}+ME_{ij}+NE_{ij}}{3}; \quad (4)$$

$$P_{ij}=\frac{\alpha_{ij}}{\sum\alpha_{ij}}\times 100, \quad (5)$$

where α_{ij} represents the defuzzied value related to the importance/performance of relative element, while P_{ij} denotes the allocation percentage of elemental costs.

4. Results

Following the FST method, the importance levels of building elements with respect to various building functions are defuzzified to numerical measurements (see Appendix). Based on it, the percentages of elemental costs that should be allocated to each function can be computed. The overall function cost then is obtainable by adding up the costs contributed by all building elements for that function. Similarly, the function performance can be quantified through the same FST approach. Under VM framework, function costs and function performances yield true function values.

4.1. Function costs

By summing up the contributions from each building element, the overall function costs have been calculated and presented in Table 5. Overall speaking, the construction cost per unit floor area of an ordinary floating house is about 5% cheaper than that of the land-based house. On the contrary, a strengthened floating house with breakwaters is 15% more expensive.

4.2. Function performances

Through the same FST method, the linguistic evaluations (e.g., "Very High", "Low") of performance levels of various functions for the two types of houses were converted into numerical measurements, as listed in Table 6.

4.3. Function values

According to Table 5 and Table 6, the function costs and performance levels of the same set of functions could be quite different between the two types of houses. In order to make a fair comparison, the VM theory is applied here to reveal the true value for the money spent on the functions. The "Value" (= "Function" / "Cost") of each function in the two types of houses, classified based on the standpoints of the four groups of respondents, can be computed through dividing the measurement of function performance by the cost allocated to that function. The comparison of function values between the two types of houses are as shown in Figure 5.

5. Discussion

Based on the obtained function values, a comparison between the floating house and traditional land-based house is drawn in this section, in terms of both basic and supporting functions, disclosing the advantages and disadvantages of floating houses. With the purpose of achieving greater values, practical recommendations are given on developing future coastal floating house projects.

Table 5. Overall function cost allocations for both types of houses

	Function	Land-based house (US$/m^2, CFA)	Ordinary floating house (US$/m^2, CFA)	Strengthened floating house (US$/m^2, CFA)
1	Increase Capacity	139.49	154.00	187.88
2	Form Site-platform	112.63	135.83	165.60
3	Expand Land	105.18	122.88	153.00
4	Attract Customers	218.66	187.30	226.47
5	Ensure Convenience	153.73	167.38	209.80
6	Connect Utilities	148.58	144.79	180.84
7	Defend Humidity	212.44	157.51	181.25
8	Ensure Steadiness	174.86	173.00	208.13
9	Decrease Weight	165.49	148.77	174.53
10	Extend Lifespan	203.40	184.36	213.34
11	Encourage Tourism	187.17	173.97	215.40
12	Sustain Environment	180.76	147.17	173.49
13	Avoid Flood	141.25	146.18	177.17
SUM		**2144**	**2043**	**2467**

Table 6. Performance levels of various building functions for both types of houses

	Construction Professionals		Customers		Tourism Clerks		Policy Developers	
House Type	land-based	floating	land-based	floating	land-based	floating	land-based	floating
Increase Capacity	2.944	1.967	3.178	1.344	2.389	1.856	3.111	1.000
Form Site-platform	2.278	2.567	2.233	1.922	1.778	2.056	2.522	1.633
Expand Land	1.822	2.511	1.900	2.267	1.100	2.178	2.033	1.622
Attract Customers	2.378	2.378	2.322	2.444	1.900	1.867	2.344	2.222
Ensure Convenience	3.056	1.578	3.022	1.400	2.411	1.422	2.756	1.467
Connect Utilities	3.089	1.867	3.056	1.500	2.667	1.656	3.133	1.400
Defend Humidity	2.833	1.111	2.733	0.900	2.456	0.944	2.789	0.989
Ensure Steadiness	3.144	1.378	3.344	1.211	2.933	1.522	3.311	0.922
Decrease Weight	1.233	2.900	0.967	2.911	1.511	2.856	1.156	3.044
Extend Lifespan	2.778	1.800	3.078	1.322	2.267	1.222	2.956	1.189
Encourage Tourism	1.411	3.133	1.056	3.122	1.533	2.644	1.156	2.944
Sustain Environment	1.833	2.622	1.800	2.011	1.456	2.100	1.967	2.311
Avoid Flood	2.689	1.756	2.089	1.833	2.367	1.522	2.444	1.444

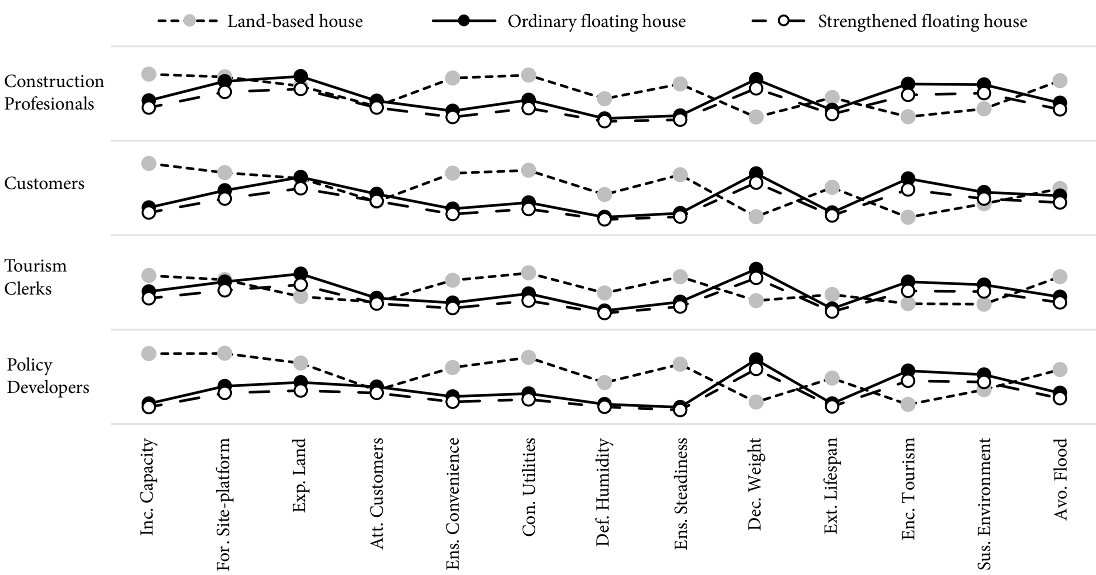

Figure 5. Comparison of function values between two types of houses from different standpoints

5.1. Values of the basic functions

It can be concluded from the computed function values (see Figure 5) that the traditional land-based houses still possess advantages over the floating houses, regardless ordinary or strengthened, in most of the functions. The basic function, "Increase Capacity", represents the ability to accommodate residents. Due to the stability issue on water, floating houses are usually low-rise. Therefore, the capacity of floating houses (over per unit area of sea) is indeed lower than that of the traditional residential buildings (on per unit area of land). However, in HK this disadvantage may be offset by the vast sea area available along its coastlines, as opposed to the limited supply of constructible land remaining in HK.

The second basic function, "Extend City" – "Form Site-platform", aims at extending the urban area toward either the mountainous inland or the sea area. No matter it is on the land or over the sea, there are some engineering problems to face/resolve. For traditional houses, the main difficulties lie in performing the site formation, which may require to deal with the slopes and/or soil liquefaction problems. As for the floating houses, the major challenge is creating stable platforms on water. The VM results indicate that the cost needed to turn the originally uninhabitable ocean into residential use is higher than that required for altering the landscapes on land.

For the third basic function (i.e., "Release Overcrowding" – "Expand Land"), it seems debatable whether the land-based or the floating houses possess a greater value for money. The Tourism Clerks group gave a higher value to the floating houses whereas the Policy Developers group voiced otherwise. As for the Construction Professionals and the Customers groups, their favor shifted from the floating houses to the land-based houses as the former will inevitably incur extra cost when deployed in offshore waters.

5.2. Values of the supporting functions dealing with conventional housing issues

As mentioned in Section 3.1, conventionally the higher-order supporting functions of a house include "Attract Customers", "Ensure Convenience", "Ensure Dependability", and "Ensure Adaptability". According to the VM analysis results (see Figure 5), the value for the money invested in the "Attract Customers" function of the land-based house basically ties with that of the floating house. This indicated that the two different types of houses have their own attractions to the customers, despite that the land-based houses actually possess higher values for money in more house functions. For the other conventional supporting functions mentioned above, they are associated with the living issues (such as the convenience, utilities, and comfort) and the structural issues. The values for money of the floating houses are lower than those of the land-based houses in all of the living-related functions, implying the primary disadvantages of the floating houses.

The two supporting functions related to the structural issues (namely, "Decrease Weight" and "Extend Lifespan") are predominately affected by the construction materials. Due to the dire need of decreasing the self-weight, the superstructures of floating houses usually are made of lightweight materials such as wood. It is predictable that the floating house will possess a much higher value of decreasing weight, as it is not a required function for the traditional houses. Nevertheless, the high function value implies that the invested money to achieve this specific function is effectively spent. Furthermore, due to the nature of wooden material, along with the high humidity and corrosion in the sea environment, the floating houses may have a shorter lifespan, resulting in a lower value for money in "Extend Lifespan" when compared with the land-based RC structures. This may not really be a disadvantage though, since in reality the RC buildings are often demolished prior to the expiration of their lifespan due to urban rezoning.

5.3. Values of the extra supporting functions introducing new opportunities

Aside from the conventional supporting functions as discussed in Section 5.2, the floating houses may bring about some extra values. By offering the chance for people to live over the sea encompassed by the beautiful ocean view, the floating house can provide a novel experience to its customers and consequently can create an opportunity of attracting visitors. It is therefore not surprising that the floating house received a much higher value than the traditional house in the function of "Encourage Tourism". According to Figure 5, this function is the major strength of the floating house and will possibly yield an effective way to boost tourism, and thus, benefit the local economy.

The remaining two supporting functions are associated with the future issues: the environmental sustainability and climate change. The construction sector accounts for a large portion of total greenhouse gas emission and energy consumption, which might further double or even triple by the mid-century (Lucon et al., 2014). A vital factor that determines whether a building is able to "Sustain Environment" or not is the construction material. According to the life cycle assessment, woods from sustainably managed forests have significantly less life cycle environmental impacts than concrete and steel (Sathre & González-García, 2014). Our VM analysis result verifies that the wooden floating house has the potential to play a role in developing a sustainable built environment.

For the function, "Avoid Flood", all four groups thought that the floating house has a lower performance (and thus a lower value), presumably because the participants were comparing the life on floating houses with their present living experience in HK, without much of the thought about the future SLR. In our opinion, floating houses are nearly immune to floods caused by heavy rainfall and only need a minor increase in the cost of external works (i.e., anchoring facilities) to adapt to the future sea level change.

The land-based houses, on the other hand, are fixed on ground once the construction is completed, and hence, are unable to deal with the flood problem themselves. For this reason, we still believe that in the long run when the sea level does rise to an extent that threats the low elevated coastal areas, the value of floating houses in fighting the flood will be clearly revealed.

5.4. Practical recommendations

The floating house has raised people's interest by bringing a new waterfront living style, while its cost-effectiveness as an alternative to the land-based house has never been thoroughly investigated. Taking HK as a typical case of metropolitan coastal cities, the present study answers some common questions regarding the idea of deploying the floating houses in the coastal environment, with several major findings:

1. If looking at the construction cost data alone, one may be misled that an ordinary floating house is about 5% cheaper than the land-based house while a strengthened floating house with breakwaters is 15% more expensive. Through the VM process, the true values of different types of houses can be revealed.
2. Owing to the technical challenges to ensure the safety and comfort of people living over the sea, it is more costly transforming the uninhabitable ocean into residential use than preparing the land for construction. That being said, to achieve the same level of living quality (e.g., comfort, convenience, and so forth) as in the land-based house, the required investment in the floating house is higher.
3. Despite of the many weaknesses when compared against the land-based house, the floating house still presents its attraction to customers and competitiveness in reliving the overcrowded urban atmosphere in more eco-friendly way, and in the meantime, benefiting the local tourism industry.

Based on the generated function values, we provide the following recommendations for practitioners and governments to establish planning and development strategies of future floating house projects in metropolitan coastal cities:

1. It is always the first choice to launch the floating house projects at the harbor areas or gulfs where the waters are relatively calm. Compared to rough waters, a better performance in functions like "Form Site-platform" and "Ensure Steadiness", along with a saved cost on wave attenuation devices and superstructure strengthening (about 20% for the prototype floating house considered in this study) lead to higher values of floating houses in calm waters.
2. Following up point 1, larger scale projects are preferred, as a lower distributed cost for the external works means higher function values, especially for those functions to which external works contribute most (see the importance levels in Table A.2 of Appendix), including basic functions of "Increase Capacity" and "Form Site-platform", as well as supporting functions like "Ensure Convenience" and "Connect Utilities"
3. The major weaknesses of the floating house lie in those supporting functions concerning with the living and structural issues, majorly due to limited function performances. The government should extensively investigate these issues and tailor-make the building code accordingly before allowing this kind of housing product to be deployed in offshore waters. Proper promotions are required to help citizens better understand and become more confident in the floating house, achieving more reliable functional evaluations (e.g., Avoid Flood).
4. The major strength of the floating house is its ability to boost tourism. Therefore, it is suggested to include a floating recreational zone or some holiday rental houses for visitors, even though the floating house project may be initiated primarily for the residential purpose.
5. It is worth mentioning that in this study the cost for acquiring the ownership of land or sea was excluded. In those cities where the land price contributes to a significant portion of the total project cost, the floating house might be an advantageous housing option for it may then display greater values in more functions. With the above in mind, the consideration of pecuniary and legal matters associated with land/sea ownership need to be taken into account in the future studies/projects.
6. The service experience of modern floating houses gained in practice is not yet sufficient to allow for a more comprehensive cost-effectiveness analysis over the life cycle, which include future performance variation, maintenance cycle and cost, etc. It is thus highly recommended to raise some pilot projects to gain practical experience and feedbacks about this new lifestyle on water, so as to improve the value analysis in the future.

6. Limitations

The participants of the two VM questionnaire surveys carried out in this study were the HK residents mostly. Although HK is a highly internationalized city, the survey results may still be affected by the Eastern values and/or cultural background. Furthermore, the construction costs were estimated based on the HK local market that is greatly supported by the non-expensive materials and labors from China. The local sea states at HK will also considerably affect the extra cost required to strengthen the floating house. Consequently, the quantitative results produced in this study may not represent the situations in those cities/regions whose social, economic, and/or ocean current conditions diverge significantly from those of HK. Nonetheless, the proposed fuzzy-based VM approach in this study can be applied globally to inspect the cost-effectiveness of floating houses in other coastal areas, by inputting local construction and survey data when necessary.

Conclusions

Sea level rise in the foreseeable future due to global warming may pose great threats to the lives and properties of people living in the low-elevated coastal areas. As compared to land reclamation, the floating house is a more environmentally friendly method to increase land supply for residential or commercial use. Although there are a few pioneering projects completed around the world, the cost-effectiveness of the floating house as a long-term solution to the land scarcity problem in overcrowded coastal areas have never been systematically examined before. Taking HK as an example of metropolitan coastal cities, this study applied a fuzzy-based VM approach to identify building functions and evaluate true values of the floating house. Despite the lower values in conventional house functions, the floating house shows potentials in releasing overcrowding and attracting customers. It also brings opportunities of encouraging local tourism and achieving environmental sustainability by demonstrating higher values in related functions. The generated value curves and proposed practical recommendations in this study will aid investors and governments in establishing future strategies of launching this new housing product in coastal cities, on the basis of a comprehensive understanding of its strengths and weaknesses against land-based houses.

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Author contributions

Xinhao Wang, Shi-Yu Xu, Mei-Yung Leung and Qi Liang conceived the study and were responsible for the design and development of the whole methodology. Xinhao Wang, Shi-Yu Xu and Mei-Yung Leung were responsible for data collection through questionnaire surveys. Xinhao Wang and Qi Liang were responsible for data analysis using fuzzy set theory. Xinhao Wang and Shi-Yu Xu were responsible for data interpretation. Xinhao Wang wrote the first draft of the article; Shi-Yu Xu revised and finalized the manuscript.

Disclosure statement

Xinhao Wang, Shi-Yu Xu, Mei-Yung Leung, and Qi Liang declare that they have no competing financial, professional, or personal interests from other parties.

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APPENDIX

Defuzzified numerical measurements of importance levels of building elements with respect to associated building functions

Table A.1. Importance levels of each building element against relevant functions for traditional land-based houses (RC structure)

Building Elements	Basic Functions			Supporting Functions									
	Increase Capacity	Form Site-platform	Expand Land	Attract Customers	Ensure Convenience	Connect Utilities	Defend Humidity	Ensure Steadiness	Decrease Weight	Extend Lifespan	Encourage Tourism	Sustain Environment	Avoid Flood
Foundation	2.822	2.981	2.357	0.765	1.169	1.671	1.808	3.066	1.822	2.634	0.756	1.681	2.085
Floor	2.944	1.977	2.197	2.061	2.188	2.202	1.986	2.441	2.507	2.455	1.366	1.484	1.507
Roof	1.535	1.103	1.117	2.009	1.427	1.413	2.390	1.972	2.141	2.460	1.714	1.878	1.315
Staircase	1.873	0.981	1.033	2.075	3.197	2.136	0.925	1.643	1.413	1.714	1.578	1.211	1.174
External walls	2.038	1.380	1.343	2.441	1.643	1.747	3.000	2.596	2.315	2.610	2.249	2.127	1.977
Internal walls	1.784	1.009	0.930	2.169	2.155	1.840	2.014	1.972	2.188	1.986	1.413	1.474	1.085
Finishes	0.883	0.747	0.685	2.756	1.545	1.310	2.418	1.371	1.634	2.132	2.301	2.005	1.197
External works	1.254	1.404	1.362	2.765	2.221	2.211	1.568	1.470	1.103	1.709	2.437	2.394	1.812

Table A.2. Importance levels of each building element against relevant functions for floating houses (wooden structure)

Building Elements	Basic Functions			Supporting Functions									
	Increase Capacity	Form Site-platform	Expand Land	Attract Customers	Ensure Convenience	Connect Utilities	Defend Humidity	Ensure Steadiness	Decrease Weight	Extend Lifespan	Encourage Tourism	Sustain Environment	Avoid Flood
Fdn-Floating platform	3.070	2.958	2.653	2.056	2.000	1.944	2.272	2.967	2.174	2.728	2.183	2.089	2.761
Floor	2.925	2.009	2.085	1.972	2.085	2.070	2.028	2.305	2.540	2.258	1.502	1.634	1.596
Roof	1.559	1.239	1.141	2.254	1.620	1.310	2.390	1.873	2.178	2.268	2.005	1.981	1.568
Staircase	1.465	1.089	0.991	1.634	2.639	1.732	1.066	1.624	1.446	1.526	1.338	1.329	1.225
External walls	2.089	1.427	1.286	2.578	1.643	1.714	3.033	2.385	2.498	2.498	2.465	2.225	1.995
Internal walls	1.732	1.005	0.817	1.962	1.869	1.531	2.019	1.906	2.296	1.897	1.559	1.718	1.169
Finishes	0.873	0.822	0.667	2.634	1.578	1.150	2.272	1.296	1.728	2.488	2.362	1.864	1.216
Anchoring facilities	2.005	2.080	1.648	1.878	2.155	2.066	1.225	2.817	1.258	2.160	1.479	1.559	2.075
Bridge & dock	2.282	2.094	2.146	2.639	3.080	2.573	1.282	2.347	1.512	1.784	2.887	1.653	2.113
Grinding-pumping system for drainage	1.624	1.343	1.127	1.751	2.338	2.211	1.587	1.479	1.132	2.225	1.371	2.347	2.132