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Floating Urban Development—Sustainable Growth and Affordable Housing

Gil Wang, Daniel Bar, Fransje Hooimeijer, and Sebastian Schreier

Abstract Driven by population growth and rural migration toward the cities, the demand for affordable housing continues to increase. However, due to the scarcity of urban development space—especially in coastal areas, the supply is limited. As increasing land availability is one of the most effective ways to reduce real estate costs, this interdisciplinary research explores the alternative of urban expansion toward the adjacent marine environment of coastal cities. It focuses on floating residential dwellings from both technological and urban planning perspective, aiming to include the waterfront of coastal cities as viable, sustainable, and affordable alternative for urban development. The research takes on one of the most expensive cities in the world, Tel Aviv-Yafo, as a case study for increasing the supply of affordable housing in addition to vital sustainable future growth in the adjacent marine environment.

Keywords Floating urban development · Occupant comfort · Spatial planning · Numerical modeling

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1 Introduction

“Floating modular housing communities can be a breakthrough in resilient, sustainable, and affordable living” [1]. This research continues to explore the vast potential of modular floating structure (MFS) for urban development offshore.

1.1 Motivations and Literature Review

1.1.1 The Global Context

Brought to us by the creative efforts of authors, artists, architects, and engineers, sea and ocean space utilization concepts have been around for many centuries. Magnificent utopian “tomorrow” metropolises on posters and novels on floating cities have ignited the imagination of people around the world regarding the potential of using the vast ocean space for various urban activities—including political philosophies [2]. One example is Jules Verne’s (1828–1905) novel Floating City from 1895. However, during the past 30 years this topic has also entered the academic arena, covered by various disciplines such as mathematics, engineering, and architecture [3–9].

Today, coastal areas are home to almost half of the global population [10], and the influences of land scarcity and the projected consequences of climate change are carrying a great deal of uncertainty for sustaining the quality of life—or to improve it. Massive urbanization processes and population growth are posing real challenges on the organization of the available spatial space, posing a real threat to the open spaces, nature reserves, and the quality of life [11]. In addition, the increasing global sea level rise is threatening to further reduce the currently available spatial space [12].

1.1.2 The Local Context

Tel Aviv-Yafo provides a very good case study for this research. Israel is a country with high population density, and the highest rate of population natural increase (fertility rates) in the OECD [13]. Further, according to the Central Bureau of Statistics (CBS) “Statistical Abstract of Israel 2014”, the Tel Aviv metropolitan area contains 60% of the country’s total urban development and accounts for 45% of its population. This is despite the numerous government policies encouraging people to dwell in the rural part of the country (e.g., the Ministry for the Development of the Negev and Galilee). As a result, the spatial tension between urban development, infrastructure, and green fields is imminent and affecting not only the costs of housing but mostly the quality of life. Floating urban development can alleviate some of this pressure by creating much-needed space. Located on the shores of the Eastern Mediterranean Sea, Tel Aviv-Yafo has no natural shelter or bay. Therefore, when considering the adjacent marine environment as an alternative for urban development, it basically means open-water conditions including annual waves heights up to 4 m and design wave height of 8.5 m [14]. The interaction between the floating structures and the waves presents the greatest challenge, and it is a crucial factor for both occupant comfort and structure [15].

The current interdisciplinary research combines developed engineering methodologies with urbanism to provide a holistic perspective on the spatial layout and design considerations for the city's additional floating development. The technological aspects of this research are based on physical and numerical studies currently conducted in collaboration between the Ship Hydromechanics laboratory at Delft University of Technology and Coastal and Marine Engineering Research Institute (CAMERI) at the Technion—Israel Institute of Technology [16].

1.2 Modular Floating Structures (MFS)

This study continues the line of research on modular floating structures (MFS) for urban use [11, 14, 15]. The MFS can be best described as an array of relatively small floating elements (modules), assembled into a consolidated large-scale platform designed for the various urban development requirements. The MFS concept differs from the, perhaps more common, very large floating structure (VLFS) configuration, which is a very large single floating platform [5]. In addition, the MFS is not designed for a single task such as floating airports, storage facilities, or bridges, and its modular layout allows dynamic spatial growth, compatible for urban use. Another interesting feature of the MFS relates to the hydrodynamic interaction between the modules at the various tiers, where the modules positioned directly to the propagating wave direction (first tier) can provide a sheltering effect to the other modules in the configuration. This hydrodynamic interaction could potentially increase the performance criteria of the MFS to larger waves [4] and thus its compliance with urban and residential use.

1.3 Research Question and Main Objectives

1.3.1 What is the Best Design for Floating Cities?

Given a carte blanche, what would be the spatial shape, size, and module configuration of a floating urban development? And what are the principal methodological instruments needed to define these parameters? These are naturally extremely broad propositions, which are largely dependent on the local environmental, technological, and cultural conditions. And to narrow these propositions down, the current research incorporates additional sub-questions, as means to lower the gain on the subjective noise, making this a case study based on a universal methodology and design approach. The following sub-questions are included.

What Is the Best Design for a Modular Floating Suburb off the Coast of Tel Aviv-Yafo?

This question already closes-in on the specific environmental conditions off the Israeli coastline, which includes a bathymetric profile, wave climate, wind, and current. In addition, it provides the local context in terms of expectation from the newly proposed real estate and the design of the new venue. Further we can ask.

What Should Be the Shape of the Modular Floating Suburb, and How Can Their Location, at the Various Tiers, Influence Wave Attenuation Performance?

The size of the modules should be determined with respect to the local building climate, which denotes the common dimensions of the apartments and the communal spaces in square meters. Naturally these are not constant values, and the size of the modules will be changed according to the appointed purpose (residential, commerce, recreation, etc.) and location in accordance with the zoning plan. Having said that, we still need to answer the following:

How Can This Concept Still Provide Affordable Housing?

Together with sustainability, affordability is a crucial factor to the relevancy of floating alternatives. Thus, when looking to increase the urban development space of coastal cities, we must ensure this conceptual solution also accommodates the basic demand for affordable housing. Therefore, in addition to the technological aspects (the feasibility of the structure and supporting interface), which have been the focus of most recent research in this field, it is also a question of design choices and policy.

1.4 Criteria

Performance criteria should be determined to understand what is the best configuration, i.e., the best design for a floating city. Naturally, on a single module level, the structure must follow to the relevant IMO regulations, which can be achieved in module dimensions which are conforming to industry sizes (e.g., ships, barges, and offshore structures) [11]. That said, the main challenge is to come to terms with motion criteria that are related to occupant comfort. It is expected that the residential MFS modules will be able to provide the comfort of an onshore structure during the worst storms of an annual return (Service Limit State). And will stay intact and safe during the worst storm of a 100-year return (Ultimate Limit State). Looking at the local conditions off the coast of Tel Aviv-Yafo, the significant wave height is ~ 3.5 m (wave periods of ~ 10 s) during an annual storm. Whereas the design wave height (1–100 years return) is 8.5 m with wave periods of ~ 15 s. Therefore, the suggested perception thresholds for the Service Limit State design are taken from ISO6897 and ISO10137 [17, 18], which are used to evaluate the acceleration magnitudes acceptable in residential buildings. An additional source of comfort criteria can be found in ISO2631 [19]. These are generally more permissible thresholds that are commonly used in the shipping industry and could provide a reference to extreme events leading to motion sickness.

1.4.1 Main Objectives

Based on the research question above, the main objectives are as follows:

- *Identifying and selecting relevant building typologies*
- *Defining a floating neighborhood scale*
- *Creating a parametric, code-based, and numerical simulation for various spatial architypes.*

2 Methodology

To answer the research question, the following interdisciplinary methodology was developed. It is based on both qualitative input and quantitative analysis approaches. The qualitative study will close the gap on cultural aspects and building typologies, together with policy issues—which are all related to the chosen venue. In addition to the building typologies, it also provides the dimensions of the neighborhood—or unit block. The first quantitative analysis (substructure) is done on a module level and focuses mainly on the design of the substructure (hydrostatic and structural analysis) purposed to support (whatever) superstructure is defined. The second analysis calculates the influence of the chosen spatial layout on the allowable building acceleration from occupant comfort perspectives (hydrodynamic analysis). In the current research, the focus is on the spatial layout as the qualitative input is still being gathered. Therefore, this methodology provides a detailed road map for the intended analysis but on the module level, the applied input is currently still indicative.

2.1 Building Typologies

To create a smart (sea) city, that could potentially provide affordable housing, a spatial planning approach has been created, using urban planning and urbanism strategies, to examine the interaction of the offshore development with the existing city [20–22]. To reduce building costs and increase affordability, the substructure and superstructure design as well as the design algorithm are taken into consideration.

2.1.1 Substructure Design

As already described in previous study [11], the dimensions of the substructure are crucial for reducing costs. Choosing to build the modules in the size range of conventional ships or barges allows the use of current technologies (including mooring facilities) and existing shipyards locally and abroad (decentralized fabrication). In addition, a relatively small substructure can sustain the loads as a rigid body, and it does not enter the complex hydro-elastic domain. Thus, working within the conventional parameters of the shipping industry can help to obtain structural consensus. Further, as the modules are in the size range of conventional ships and barges—conforming to current industry—their transportation becomes more feasible and economical, as they can be transported using conventional tugs.

2.1.2 Superstructure Design

The superstructure design reflects the needs and properties of the intended module, separating between commerce, leisure, offices, residential, and mixed uses. This is also where the planner could put emphasis on additional affordable housing based on size and perhaps even location. As this paper presents an early stage of the research, the various superstructures typologies are not yet included, and the MFS is based on a single type—Module9000, which is presented in the following section. Naturally the presented methodology and design approach could accommodate other building typologies, as explained in the following sections.

2.1.3 The Design Algorithm

The design methodology of the MFS modules is divided into two main phases: 1. Ultimate Limit State, and 2. Service Limit State. Figure 1 shows the design algorithm for a typical module, where in "Input 1", the user provides the design parameters for the chosen module configuration (e.g., the geometry of the module and the weight distribution) for both sub and superstructures. This input data initiates an iterative process encompassed by hydrostatic and structural analysis. If the chosen design does not successfully comply with a given set of structural or stability regulations, the substructure or superstructure dimensions should be changed. It can be done, for example, by increasing the beam of the substructure to improve stability or by reducing the number of superstructure floors to reduce the load. Once the design of the module complies with given regulations, the module can be classified as an approved offshore structure, based on the class notation it was aiming for. However, being a valid offshore structure does not necessarily make it a compatible structure for residential use. Therefore, "Input 2" includes environment conditions that assess whether this offshore structure is acceptable for residential use, mainly from occupant comfort point of view. This is done through a hydrodynamic analysis and occupant comfort regulations for residential buildings such as given in [14, 15].

The main building unit for the various MFS structures presented in this paper is Module9000, a twin hull barge with six buildings (ten floors each), as schematically shown in Fig. 2. A preliminary design of Module9000, including classification compliance, can be found in published literature [11, 14, 15, 23, 24], and the main particulars are given in Table 1.

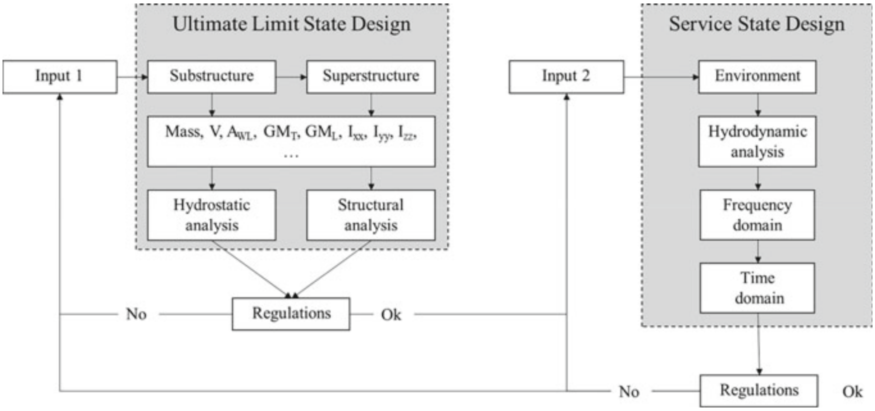


Fig. 1 Analysis algorithm for the design of MFS module [14]

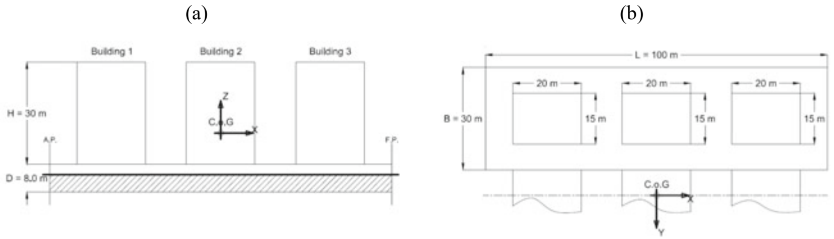


Fig. 2 Schematic model of Module 9000 with general dimensions. **a** Side view and **b** plan view showing one half of the module. The distance between hulls is 15 m

Table 1 Main particulars

Length	(L)	100.0	[m]	Displacement	(Δ)	31,365	[ton]
Beam[a]	(B_t)	75.0	[m]	Center of gravity	(KG)	16.74	[m]
Depth	(D)	8.1	[m]	Metacentric height (transverse)	(GM_T)	99.79	[m]
Design draft	(T)	5.1	[m]	Block coefficient	(Cb)	~ 1.00	[-]

[a] Total beam, two hulls with 15 m clearance between them

2.2 Neighborhood Scale

As the qualitative input is still being gathered for the current location, the chosen spatial dimension of the MFS is 750 by 750 m, corresponding to Clarence Perry's "neighborhood unit" philosophy, or the rule of the "five-minute walk", implementing some of the existing knowledge of urbanism [25]. In addition, the spacing between the models cannot be smaller from 30 m, as part of the preliminary constraints used to run the spatial layout analysis.

2.3 Spatial Layouts

Based on developments in city planning, the spatial layout of the city blocks could be arranged in a Cartesian grid or in a radial arrangement. Also, more random patterns of organically grown cities shall be investigated. The spatial arrangement of the floating city block modules has a large impact on the hydrodynamic response for each individual module as well as on the performance of the floating city as a whole. To allow for automated generation of the models for the numerical analysis, the spatial arrangement has been set up as a parametric model. This model includes the arrangement of 20 modules in a 4 × 5 rectangular grid as well as the radial configuration with an inner and outer ring, containing 7 and 13 modules, respectively. Also, more random configurations based on a 5 × 5 grid in which 20 of the 25 positions hold a module with random rotation around the vertical axis can be created. Examples of these configurations are shown in Fig. 3. Naturally other layouts could also be programed, but these three archetypes do cover large numbers of spatial options.

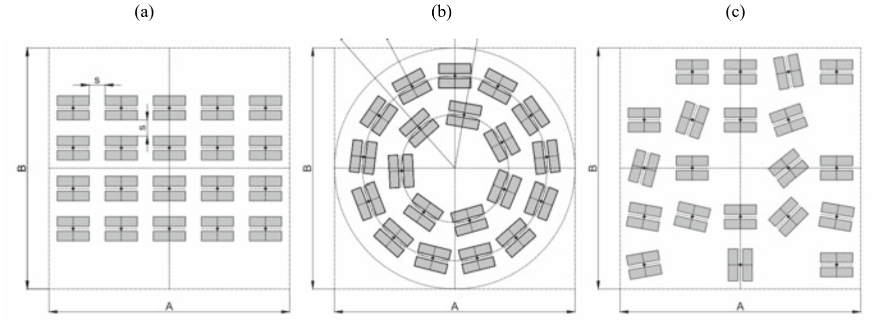


Fig. 3 Schematic MFS configurations, **a** Cartesian layout, **b** radial layout, and **c** random

3 The Analysis System: ANSYS-AQWA

This research uses the numerical platform ANSYS-AQWA to solve the diffraction problem including the structure motions and their hydrodynamic interaction. This software package is a potential flow solver that uses the boundary element method (BEM).

3.1 *First-Order Solution (Linear and Monochromatic)*

The potential function Φ can be written as given in Eq. 1, where ϕ is complex space-depended part of the potential function. In Eq. 2, the ϕ is separated into incident wave potential, diffracted wave potential, and the potential functions of the radiated waves in six degrees of freedom. Formulation of the first-order linear problem also denotes the following relations for the incident and diffraction potentials, as given in Eqs. 3 and 4. The continuity equation (Laplace) is given in Eq. 5.

$$\Phi = (X, Y, Z, t) = \mathrm{Re}\left[\phi(X, Y, Z)e^{-i\omega t}\right] \tag{1}$$

$$\phi(X, Y, Z) = (\phi_i + \phi_d) + \sum_{j=1}^{6} \phi_j x_j \tag{2}$$

$$\phi_i = \phi_0, \phi_j = \phi_j, j = 1, \ldots, 6 \tag{3}$$

$$\phi_d = \phi_j, \phi_j = \phi_j, j = 7 \tag{4}$$

$$\nabla^2 \phi_j = 0, \quad j = 1, \ldots, 7 \tag{5}$$

The solution of the first-order linear problem used by the analysis system ANSYSAQWA is written in Eq. 6. Where z is the vertical coordinate measured to the water plane; h is the water depth; g is the gravitational acceleration; k is the wave number; ω is the wave angular frequency; β is the wave direction, and a_w is the wave amplitude.

$$\phi_i = \frac{iga_w \cosh[k(h+z)]e^{i[k(x\cos\beta + y\sin\beta)]}}{\cosh(kh)} \tag{6}$$

$$\omega^2 = gk\tanh(kh) \tag{7}$$

The solution employed by ANSYS-AQWA, for the diffracted and radiated wave potentials ($\phi_i + \phi_d$), is pulsating source distribution—numerical method that is based on the Green's function. Once the velocity potentials are known the first-order pressure can be calculated as given in Eq. 8. Integrated value of the pressure along the wetted surface area of the module provides the applied fluid force on the floating structure (F_j) as given in Eqs. 9 and 10. The forces are separated into Foude–Krylov (F_{ij}), diffraction forces (F_{dj}), and radiation forces (F_{rjk}). The radiation force F_{rjk} is given in in Eq. 11, where A_{jk} is the added mass coefficient, and B_{jk} is damping coefficient.

$$P^{(1)} = -\rho\frac{\partial\Phi}{\partial t} = i\omega\rho\phi\left(\overline{X}\right)e^{-i\omega t} \tag{8}$$

$$F_j\left(\overline{X}\right) = i\omega\rho \int \phi\left(\overline{X}\right)n_j \mathrm{d}s \tag{9}$$

$$F_j = \left[\left(F_{ij} + F_{dj}\right) + \sum_{k=1}^{6} F_{rjk}x_k\right], \quad j = 1, \ldots, 6 \tag{10}$$

$$F_{rjk} = -i\omega\rho \int \left\{\mathrm{Re}\left[\phi_{rk}\left(\overline{X}\right)\right] + i\mathrm{Im}\left[\phi_{rk}\left(\overline{X}\right)\right]\right\}n_j \mathrm{d}s = \omega^2 A_{jk} + i\omega B_{jk} \tag{11}$$

3.2 Equation of Motion (EOM) and the Response Amplitude Operator (RAO)

Based on the Equation of Motion (Eq. 12) presented in, the response amplitude operator (RAO), indicated as X, can be calculated, when writing, $X = X_0e^{-i\omega t}$, and $F = F_0e^{-i\omega t}$. Where M_s is the structural mass matrix of the chosen module, M_A is hydrodynamic added mass matrix, C is the linear damping matrix (noted differently than the mathematical formulation given in Eq. 11), K is the stiffness matrix, X is the response motions, F is the external wave force as given in Eq. 13, and **H** is termed the transfer function which relates input forces to output response as written in Eq. 14

$$M_s\ddot{X} + M_A\ddot{X} + C\dot{X} + KX = F \tag{12}$$

$$\boldsymbol{H} = \left(K - [M_s + M_A]\omega^2 - iC\omega\right)^{-1} \tag{13}$$

$$X_0 = \boldsymbol{H}F_0 \tag{14}$$

4 Research Implementation

Once the modules and the neighborhood block size (A by B) are determined, the code files can be written to run the analysis in AQWA-ANSYS. As this is an analysis in the frequency domain, the results are given for all the selected frequencies (wave periods between 6 and 15 s), to meet the annual and extreme storms conditions off the Israeli coastline. The RAO output from ANSYS-AQWA can then be used to calculate the RMS accelerations (about the center of gravity or any other point on the structure). The calculated input in the analysis system is given for monochromatic waves, therefore, to generate the results in RMS, and the data must be postprocessed using the relevant wave spectrum to transform the results into irregular waves. The JONSWAP spectrum [26] provides a good representation of the statistical wave climate in the Eastern Mediterranean Sea, and it is given in Eq. 15. Both Gamma (γ), spectrum broadness parameters, and the peak periods (T_p) are typical to the wave measurements at the chosen location.

$$S(f) = \alpha\frac{Hm0^2}{T_P^4}f^{-5}\exp\left[-\frac{5}{4}(T_P f)^{-4}\right]\gamma^{\exp\left[\frac{1}{2\sigma^2}(T_P f-1)^2\right]} \tag{15}$$

Equation 16 describes the relation between the wave amplitude and acceleration in irregular waves, where ω is the wave angular frequency, and a_w is the wave amplitude. And Eq. 17 shows the motion sickness dose value (MSDVz), where $a_{z_w}(t)$ is the frequency-weighted vertical acceleration (in Heave (z)), and T is the duration of the measurements in seconds. Both the RMS acceleration and MSDV$_z$ provide values to help determine the compliance of the modules for residential use [17–19].

$$\text{Acc. RMS} = \omega^2 \cdot a \tag{16}$$

$$\text{MSDV}_z = \sqrt{\int_0^T a_{zw}^2(t)\,\mathrm{d}t} \tag{17}$$

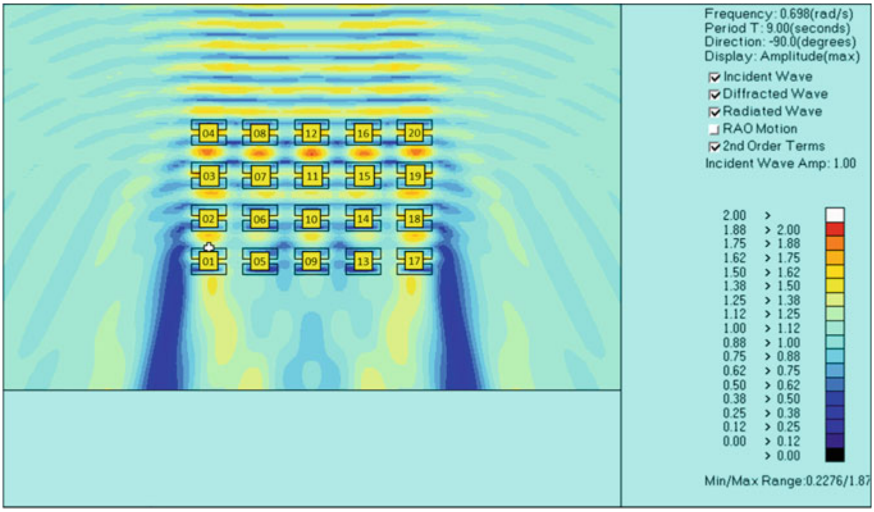
5 Preliminary Results

5.1 *Wave Diffraction Characteristics—Graphical Supervisor AQWA (GSA)*

Figures 4, 5 and 6 show the results of the hydrodynamic analysis, for one wave period ($T = 9$ s), per spatial layout. Each figure indicates the position of the modules and their identification numbers, in addition to the associated waves pattern. The amplitude scale, at the lower right corner, is equal at all three figures, and the waves are propagating from top to bottom. The incident wave amplitude is 1.0 m such that the color coding is the local wave amplitude response operator.

The second-order term given in the presented results is the second-order slowly varying wave drift. This is obtained by the solver as default and can be used to calculate the time wave drift forces in time domain. The second-order term does not interfere nor influence the results obtained in the frequency domain.

Figure 7 shows all the modules in the random layout without their identification numbers, to provide a better representation of their position and orientations. It should be noted that all the results hereafters are given to the module based on their identification numbers from #1 to #20, about their center of gravity.



Frequency: 0.698(rad/s)
Period T: 9.00(seconds)
Direction: -90.0(degrees)
Display: Amplitude(max)
☑ Incident Wave
☑ Diffracted Wave
☑ Radiated Wave
☐ RAO Motion
☑ 2nd Order Terms
Incident Wave Amp: 1.00

Min/Max Range:0.2276/1.87

Fig. 4 Representation of the MFS block using the Cartesian layout code, including the modules identification numbers

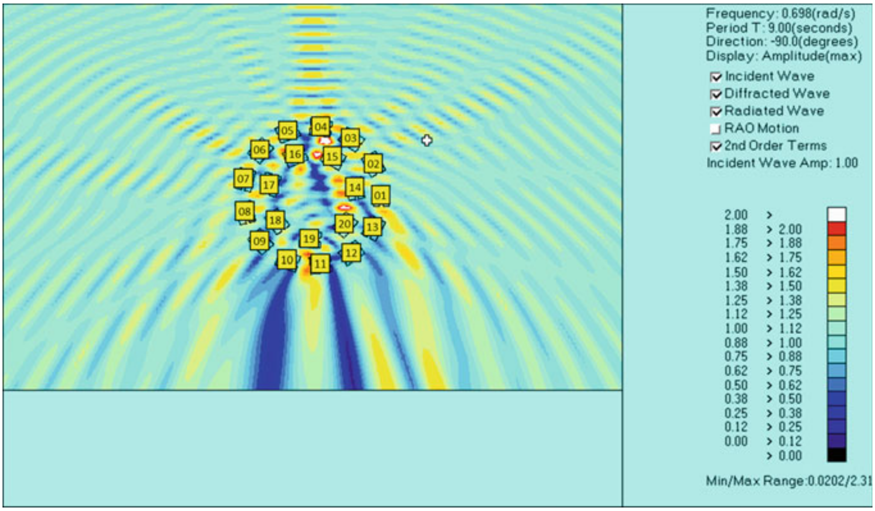


Fig. 5 Representation of the MFS block using the radial layout code, including the modules identification numbers

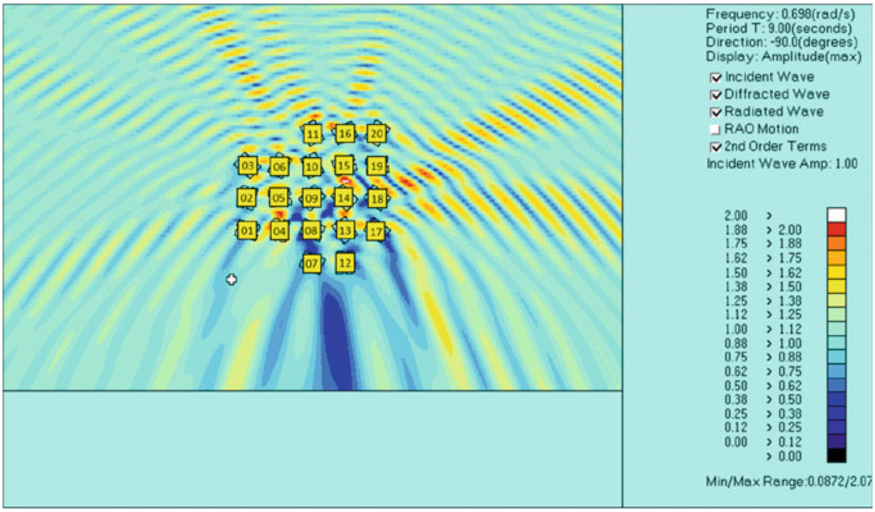
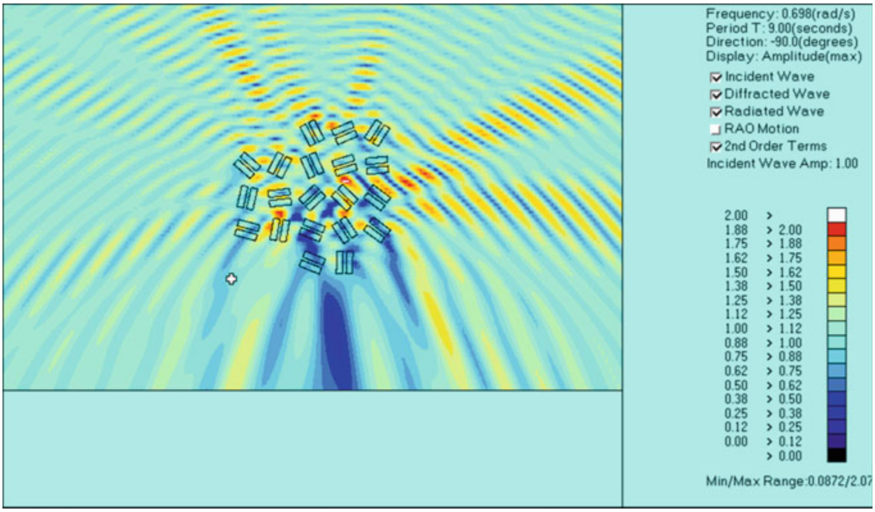


Fig. 6 Representation of the MFS block using the random layout code, including the modules identification numbers

5.2 RAO

Figures 8, 9 and 10 show the vertical RAO for each wavelength (from 6 to 15 s) for all the modules per layout.



Frequency: 0.698(rad/s)
Period T: 9.00(seconds)
Direction: -90.0(degrees)
Display: Amplitude(max)
☑ Incident Wave
☑ Diffracted Wave
☑ Radiated Wave
☐ RAO Motion
☑ 2nd Order Terms
Incident Wave Amp: 1.00

Fig. 7 Representation of the MFS block using the random layout code, showing the modules' orientations

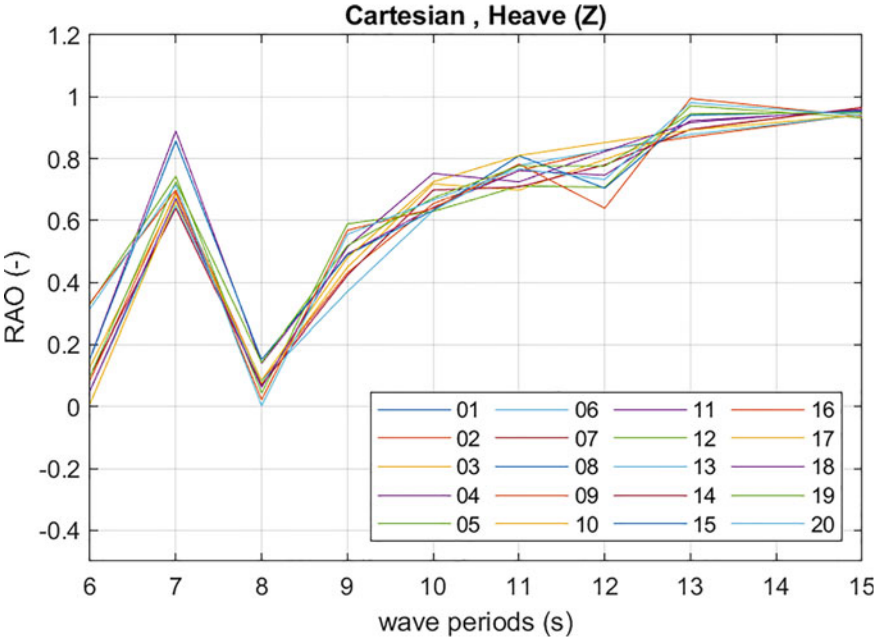


Fig. 8 Calculated RAO for all 20 modules in Cartesian layout

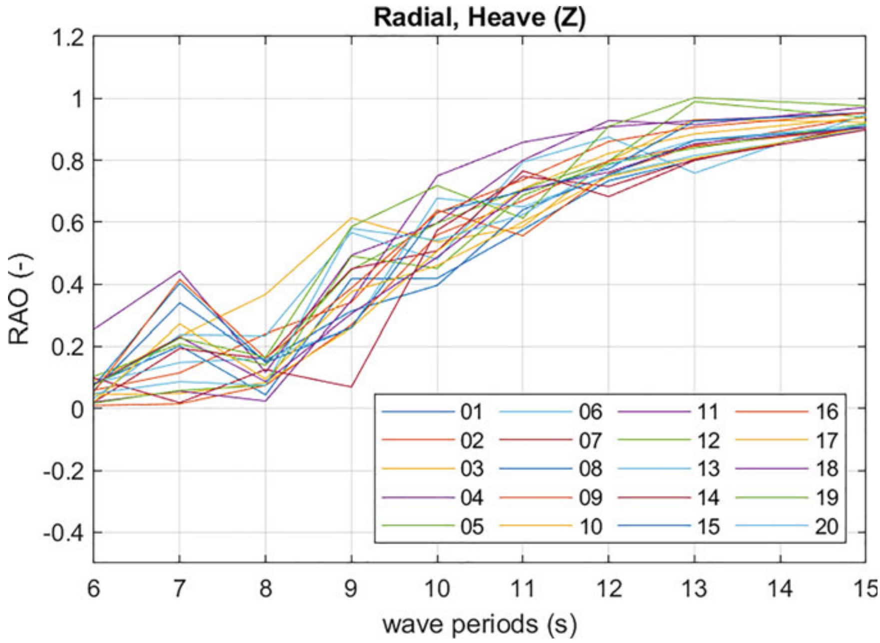


Fig. 9 Calculated RAO for all 20 modules in radial layout

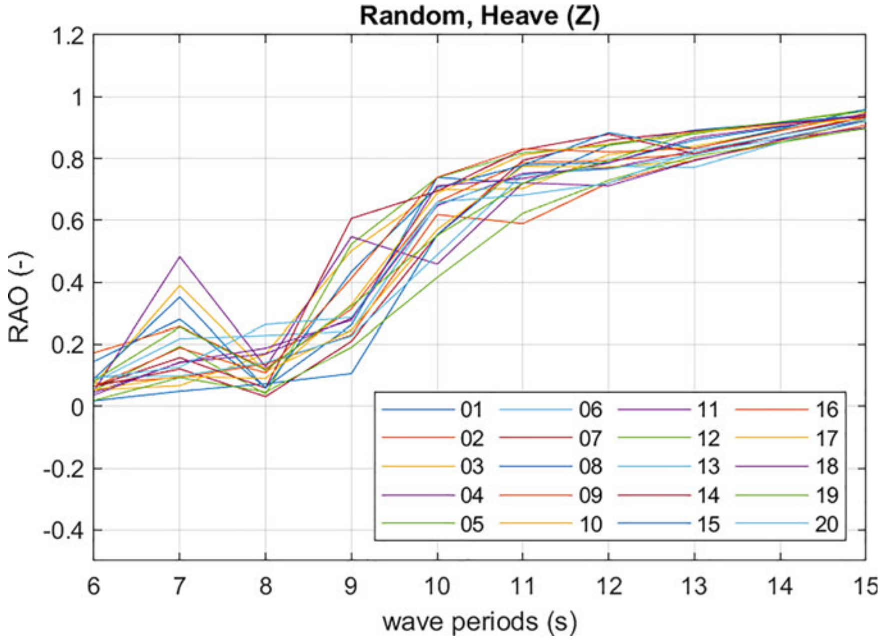


Fig. 10 Calculated RAO for all 20 modules in random layout

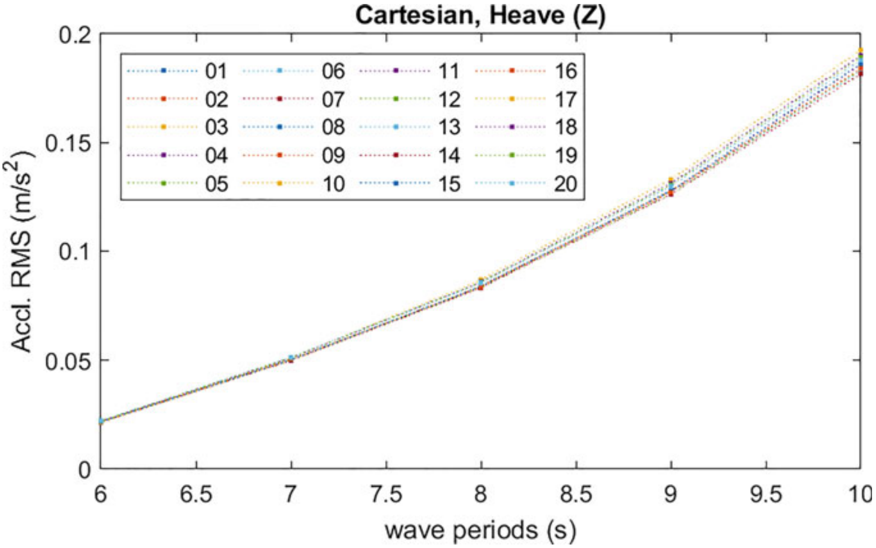


Fig. 11 Calculated accelerations for all 20 modules in Cartesian layout

In addition to the calculated RAO, Figs. 11, 12 and 13 show the associated RMS acceleration as given in Eq. 16 based on the integration of the spectral density function given in Eq. 15 [15, 27]. The results are given at wave periods up to 10 s, which is considered as Service Limit State, where occupant comfort is the main evaluation criteria. Storms greater than 10 s are considered Ultimate Limit State design, and they are evaluated mainly from structural perspective based on the calculated hydrodynamic interactions.

5.3 Summary of the Presented Results

The results presented in this section show the hydrodynamic analysis in the frequency domain for three different MFS layouts. It has been purposely chosen to present only one degree of freedom, Heave (Z), which is most critical to determine the behavior of the MFS, on a module level, from both Service and Ultimate Limit State design as shown in Fig. 1. From the vertical RAO results, we can already see the difference between the performances of the three layouts, e.g., there is a distinct peak at 7 s in the RAO for the Cartesian configuration that is not present in the other results. Further, in the Cartesian layout the result variance is relatively on a narrow band, and hence, there is not much to gain from the hydrodynamic interaction in the specified geometry (spacing) and model typology. That said, we can see that in both radial and random layouts there is slightly greater variance between the modules, which is also demonstrated in the acceleration results.

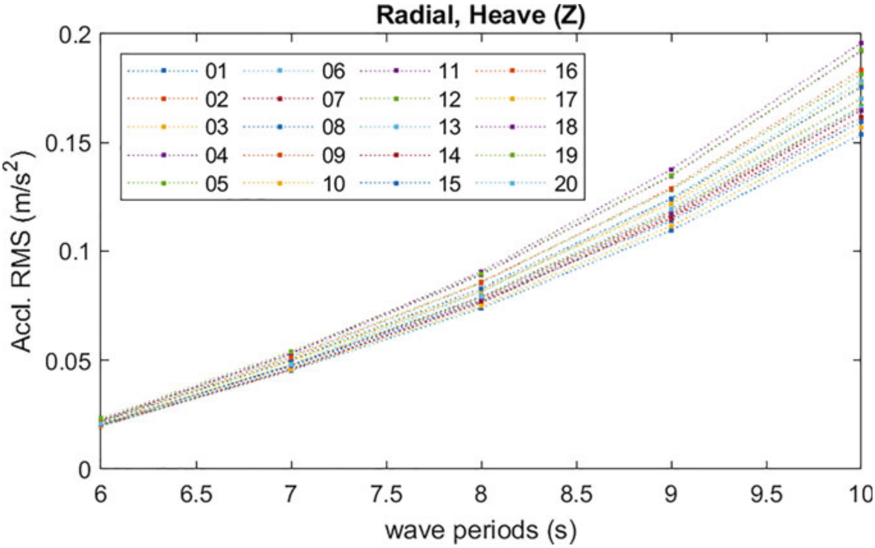


Fig. 12 Calculated accelerations for all 20 modules in radial layout

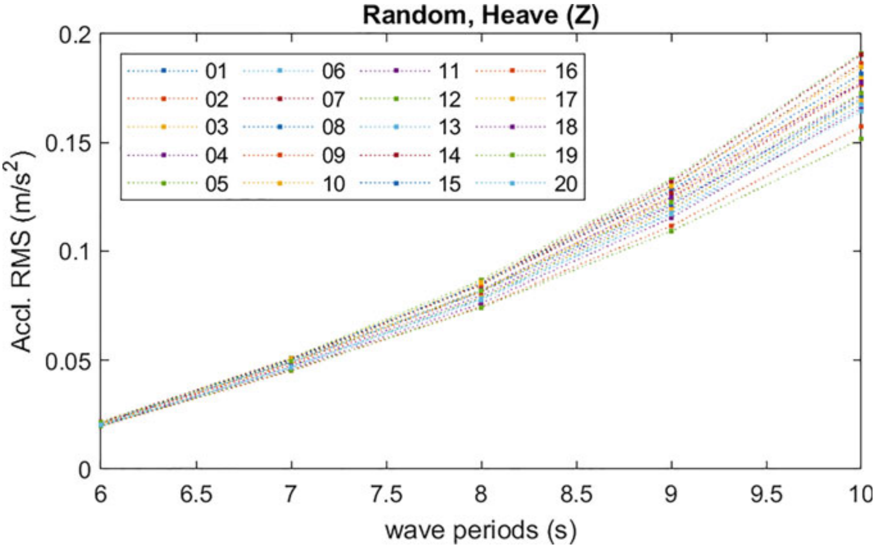


Fig. 13 Calculated accelerations for all 20 modules in random layout

Same as the RAO, the module's vertical accelerations are given about the center of gravity. The wave periods were reduced to 10 s for the appropriate Service Limit State design range, and we can see that the acceleration in all modules is lower than 0.2—the allowable margin for cruise liners [28]. However, they must be evaluated against residential criteria in order to determine their compliance for residential use.

6 Discussion

6.1 Machine Learning for Spatial Optimization

This paper demonstrated a design approach for urban development space offshore. The presented results are indicative, as the qualitative part of this research has not been concluded yet. But once the selected building typologies are decided upon, the three proposed layouts could be further optimized using machine learning. Running numerous iterations where the aim is to converge to minimum acceleration could reveal the best location and orientation of the modules, for a given neighborhood block. Using the presented analysis system and methodology, this could be achieved. That said, the automation process is particularly interesting for the random layout, as the entire design is code driven and arbitrary in nature, and consequently it is very difficult to forecast its final layout. The neighborhood unit optimization is only one layer in the complex concept of sea and ocean space utilization. Additional aspects such as infrastructures (roads, energy, water, and sewage) and access should also be examined in the context above, as they bring additional spatial input.

6.2 Design and Policy for Sustainability and Affordability

Although the focus of the current study has been on the development of a parametric, code-based, and numerical simulation for various spatial architypes, it also provides a guideline and methodology for further research input, which includes fundamental design values and urban characteristics. Again, this input could also denote the principal philosophy of affordable housing in terms of size, residential blend, and other policies to support this objective. Creating a new urban development offshore provides the unique opportunity for adopting sustainable methods, design values based on the vast experience (and mistakes) of current coastal cities, and new development. In addition, governmental and municipal policies are also examined to cultivate and activate this potential growth driver in sustainable and responsible ways.

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