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Research Article

Influence of connector forces on the expansion configuration of a hexagonal modular floating structure

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ABSTRACT

The preliminary design of a hexagonal modular floating structure (HMFS) system includes two configurations: U-shaped and V-shaped, which link seven hexagonal modules that create a network of connectors. The connector force is a crucial consideration in the layout of the connector network, as it must sustain the forces generated by wave motion due to its influence on the stability and safety of the modular floating structure. This paper presents the development of the HMFS connector network and the estimation of the connector horizontal force influence by two types of configurations. The design concepts of these configurations for HMFS configurations are proposed where analysis was implemented for regular wave in various directions of 0°, 30°, 45°, 60°, 85°, and 90°. The impact of these various wave directions and the HMFS configurations on the connector force is analysed accordingly. According to this research finding, the connector force in U-shaped configuration is higher than the load in V-shaped of HMFS configuration. The connector force of the V-shaped configuration is arranged in hexagonal vertices (VV-shaped) facing wave direction receive a higher connector force than hexagonal parallel sides (VP-shaped) facing wave directions. The determination of horizontal connector load of hexagonal modules with varying configurations enabled the designer to estimate the horizontal connector load for various conceptual designs of hexagonal shapes, such as dock ships, yacht terminal and floating cities.

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1. Introduction

The development and exploitation of the ocean have become significantly more diverse due to the growing human demand and advancements in ocean engineering technology (Song et al. 2023; Park et al. 2023). The design of ocean structure has evolved from traditional ships to complex interconnected platforms for various functions (Song et al. 2023), such as space resources (Wong et al. 2013), ocean energy utilization, etc. A single floating structure with large sizes of floating structure could cause massive loads in structures; thus, the types of modular floating structure are preferred which has advantages for constructure, transportation and deployment (Watanabe et al. 2004). The structure is fabricated in modularized and the modules are assembled with connectors at the operation location owning to the large size of floating structure. Very large floating structures (VLFS) for the purpose of floating islands have been grouped into two: semi-submersible suitable use in open oceans and pontoon types suitable for mild seas (Park et al. 2023). Furthermore, the location of the central module, tail module and outer module in deciding the arrangement of the multi-floating structure gives effect to the motion characteristic of floating islands (Park et al. 2023).

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1.1. Conceptual design of modular floating structure

Six sides of a hexagonal regular polygon give advantages to the researcher in expanding their decision making to arrange the modular floating structure with their creativity and purpose of the floating structure. Xiaozhou et al. (2024) conducted the experiment to investigate the hydrodynamic performance of the double module hexagonal floating structure in a linear arrangement. Three hexagonal modular floating structures arranged in linear and L-shaped arrangements by Ikegami et al. (2007). Vincenzo (2023) studied the behaviour of three hexagonal platforms that were arranged in linear arrangement on the surge, heave and pitch degrees of freedom through simulation for regular and irregular waves. Li et al. (2023) modified the design layout by proposing four hexagonal modules, one in the middle module and another module arranged in an L-shaped attachment to the middle module. Li et al. (2022) also studied the linear arrangement linked to a five modules hexagonal shape floating structure. Li et al. (2024) conducted the experiment to investigate the hydrodynamic performance of five hexagonal floating structures in linear arrangement. Hamamoto and Fujita (2016) investigated the hydrodynamic motion of seven hexagonal modular floating structures introduced in two types of arrangements: are in centralized shaped and stretched shaped as shown in Fig.1.

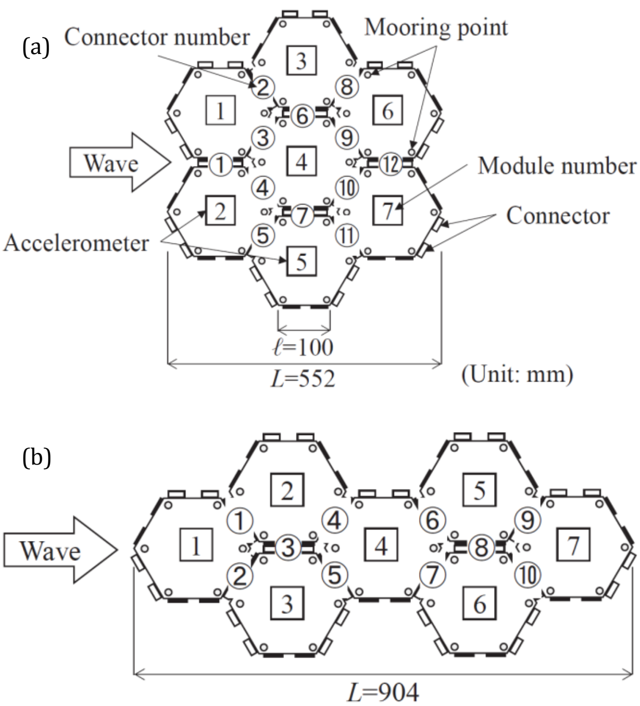

Fig. 1. Two arrangements of hexagonal modular floating structure proposed by Hamamoto and Fujita (2016): (a) Centralized shape; (b) Stretched shape.

Nowadays, the exploration of hexagonal modular floating structures into the development of floating cities gives expansion an additional higher number of modular floating structures rather than a small number floating within two to seven modules linked together. Wong et al. (2013) proposed three arrangement hexagonal modular floating structure comprising 493 modules, 352 modules in one circular pattern to build a man-made island on water bodies for recreational activities and amenities for the public, and a sanctuary for plants, birds and other wildlife for Punggol floating wetlands. Moreover, Lister and Muk-Pavic (2015) described a sustainable artificial island designed for Republic of Kiribati's inhabitants and explore the layout of hexagonal modular floating arranged U-shaped and centralized arrangements. Stanković et al. (2021) proposed the modular floating structure arranged in regular tessellation in triangular, square and hexagonal shapes for Kiribati Island. Jiang et al. (2021a) investigated the hydrodynamic analysis of a hexagonal modular floating structure in a linear tandem arrangement with a size of 251.9×66 m and 137.4×132 m looking as one square shape.

1.2. Internal connector force analysis

The connector system suffers force and bending moment from the adjacent module which is the commonly most fragile component of the whole structure, thus, the interaction between the connector and modules should be studied due to the loading characteristic of the is also key part for the very large multi-floating structure (Li et al. 2022). Dai et al. (2021) compared connection loads of difference design options of the multi-floating floating structure such rectangular, square and hexagon, then the small different in terms of shear force and twisting between rectangular and hexagonal but still the connection bending moment for hexagonal is lower 27% than rectangular. Li et al. (2022) investigated the connector forces which include horizontal force, vertical force, shear force and pitch bending moment at wave directions of 0°, 30°, 60° for five hexagonal modules linked in a linear arrangement. Li et al. (2023) investigated the connector forces includes horizontal force, vertical force, shear force and pitch bending moment at wave directions of 0°, 30°, 60° and 90° for five hexagonal modules linked in the center and an L-shaped concept arrangement. Ikegami et al. (2007) stated the connecting horizontal force in the L-shape arrangement become larger in the longer wave period range as a complex behaviour pattern in L-shaped may occur due to each floating body facing the different direction of incident waves. Xiaozhou et al. (2024) investigated how the relative pitch motion of the two modules affects the connector loads the most such as using a larger cable stiffness, which will reduce the pitch motion, but increase the connector loads.

Jiang et al. (2021b) mentioned that the internal forces generated in the connector significantly affected the structural integrity during wave action. However, only a few of studies have performed numerical evaluations of these internal forces, encompassing module arrangements, shallow water effects and incident wave periods. The trend of the connector load depending on the shape of the floating structure. The horizontal connector force trend of five square modular floating structures, as presented by Riggs et al. (1998), indicated a gradually increase in horizontal connector force from 0° wave direction to 75° wave directions, a sharply decline at 80° wave directions, with the peak horizontal connector force occurring at 85° wave directions. The trend of horizontal connector force has also been similar to the rectangular modular floating structure that has been proposed by Ding et al. (2020), wherein the highest horizontal connector force at 85° wave directions linked three rectangular modular floating structures. Meanwhile, Otto et al. (2019), Hongtao et al. (2020), and Azlan et al. (2024) identified that the higher horizontal connector force for the hexagonal modular floating structure occurs at 0° wave direction. Otto et al. (2019) built the combination of triangular module that has 60° connector directions that create a big hexagonal module, then he asserted that to avoid a typical in-line environment with less than 30° spreading into wind, waves and current as it will give the higher connection loads. Azlan et al. (2024) studied five modules of HMFS together in a linear arrangement and discovered that 0° wave direction gives higher connector force and gradually reduces the horizontal connector force as the wave direction increases.

The objective of this research is to determine the impacts of different wave directions on the maximum horizontal connection load, while varying the HMFS arrangements. The hexagonal shape of the modular floating structure facilitates diverse designs, as its six sides can be arranged without gaps. Therefore, the suitable arrangement should been design in the conceptual design of modular floating structure, taking into account the effects of connector load.

2. Materials and Method

2.1. Conceptual design of hexagonal modular floating structure *(HMFS) system*

The idea configuration of the HMFS system was identified by a literature review. The idea from Stanković et al. (2021) and Lister and Muk-Pavic (2015) was adopted and three configurations of the HMFS system were proposed in this research: such as U-shaped and V-shaped, while V-shaped is divided into two configurations that take into account the sides hexagonal (VP-shaped) and vertices hexagonal (VV-shaped) shown in Fig. 2. These three concepts of HMFS system arrangement are exposed to the conceptual design of floating structures. The VP-shaped arrangement of floating cities proposed by from Stanković et al. (2021) illustrates the layout has been adopted to express communication, especially in terms of transportation between the central module and side circular modules. Meanwhile, the primary functions in floating cities, including governance area, commercial area and hospitality area and water transportation are organized in the U-shaped arrangement of floating cities, ensuring that all facilities are centrally located close to one another. Lister and Muk-Pavic (2015) proposed the residential area presented in the VV-shaped arrangement of floating cities.

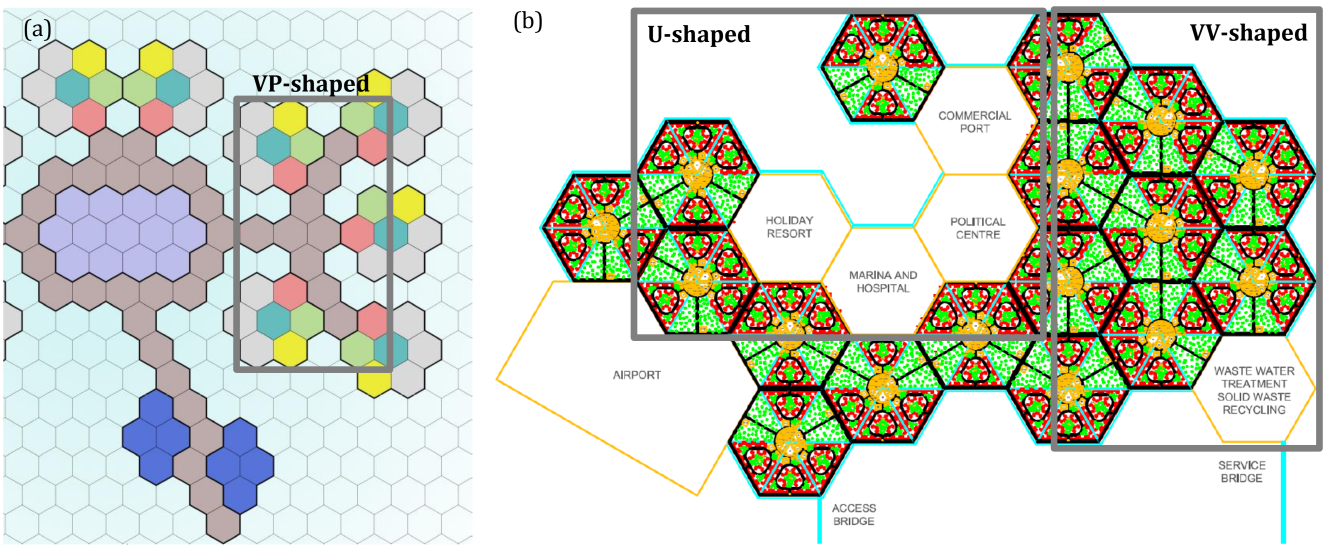

Fig. 2. The idea of HMFS system arrangement for (a) VP –shaped by Stanković et al. (2021); and (b) U- and VV-shaped configurations by Lister and Muk-Pavic (2015).

There are seven hexagonal modules (M1-M7) linked with a ball connector for each configuration of HMFS system as shown in Fig. 3. The main module is the M1 module, which acts as the pivot point of a symmetrical module layout. The overall configuration starts with M1 as the middle, the top continues sequentially with M2, M4 and M6, while the bottom is arranged with M3, M5 and M7. The numbering of connectors also follows the same ideology by continuing sequentially as top (C1, C3, C5) and bottom (C2, C4, C6) as numbering of hexagonal modules. The U-shaped arrangement presents the central module as M1 as the inner module, while the top modules and bottom module are arranged in linear arrangements and early modules face wave force. The VP-shaped presented the module M1 as the center and early facing the wave force, while both top and bottom modules are arranged in staggered arrangements. The parallel side of the hexagon is facing the 0° wave direction for both the U-shaped and V-shaped of HMFS arrangements. The VV-shaped also arranged the modules M1 as the central, meanwhile implement combination of a linear layout for bottom modules and a staggered layout for top modules. The vertices sides of the hexagon are arranged facing the 0° wave direction.

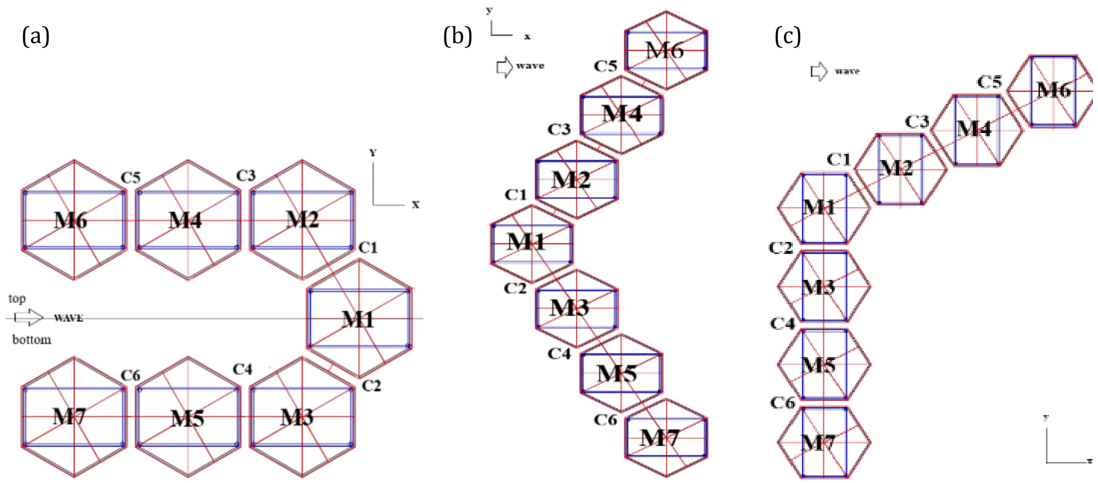

Fig. 3. Three configurations of hexagonal modular floating structure (HMFS): (a) U-shaped; (b) V-shaped, parallel sides facing wave (VP); (c) V-shaped, vertices facing wave (VV).

The detailed design of all components for HMFS, included the hexagonal floating structure, connector and mooring was adopted by Li et al. (2023). Each hexagonal floating structure is linked with a ball connector and moored with four tension legs to the seabed. The fenders have also been installed at the bottom edge of adjacent modules to avoid a possible collision. The details of the HMFS system are shown in Table 1.

Table 1. Details about the HMFS system.

Details	Value	Unit
Side length, height	20, 12	m
Water depth, draft	80, 10	m
Mass	6000	t
$I_{xx} = I_{yy}$	9.6 x10^8	m^4
Tension – leg dimension	*D*=1.2; *T*=0.04; *L*=70	m
Steel tension leg	2.1 x 10^{11}	N/m^2
Stiffness of fenders	1.0 x 10^7	N/m
Adjacent distance	3	m
Ball connector linear rotational dampers	4 x 10^9	Nms/rad
Ball connector linear rotational springs	0	Nms/rad

2.2. Simulation

The maximum horizontal force of each configuration was investigated under a regular sea condition (T=8s, H=2m) with different incident wave direction such as 0°, 30°, 45°, 60°, 85°, 90°). The motion responses of each hexagonal and the maximum horizontal force under different wave direction was simulated using ANSYS. The governing equation of HMFS system in ANSYS (2013) is:

$$M_i\ddot{X}_i + C_i\dot{X}_i + K_i(X_i) = F_{i,wave} + F_{i,con} + F_{i,TLP} + F_{i,Fender} \quad (1)$$

where M_i, C_i and K_i are the mass matrix, radiation damping (with certain artificial damping usually applied to compensate for viscous fluid effects) and the hydrostatic restoring matrix, respectively. Xi (6-DOF) denotes the generalized displacement vector of the i-th module. $F_{i,\mathrm{wave}}$, $F_{i,\mathrm{Con}}$, $F_{i,\mathrm{TLP}}$ and $F_{i,\mathrm{Fender}}$ denote the matrix of the generalized wave force, the connector force, the tension matrix of tension legs and the impact force matrix of fender, respectively. The connector force between adjacent modules can be expressed as:

$$F_{i,con} = \sum_{j=1}^{7} (\varphi_{ij}\, K_{cij}\, \delta(X_i, X_j)) \quad (2)$$

where φ_{ij} denotes a topology matrix. The value of φ_{ij} is 1 when the i-th module is connected to the j-th module, otherwise the value of φ_{ij} is 0. K_{cij} and $\delta(X_i,X_j)$ denote the connection stiffness matrix and the relative motion matrix between the i-th module and the j-th module, respectively. The total tension-leg force of the i-th module can be expressed as:

$$F_{i,TLP} = \sum_{j=1}^{4} E_i\, A_i \varepsilon_{ij} \quad (3)$$

where E_i denotes the elastic modulus. A_i denotes the sectional area of the tension leg of the i-th module. ε_{ij} denotes the strain of the j-th tension leg of the i-th module.

The possible bottom fender impact force $F_{i,\text{fender}}$ can be expressed as:

$$F_{i,fender} = \begin{cases} K_{fij} \cdot \ \delta x, \text{if } \delta x(X_i, X_i) < -3 \text{ m (contact)} \\ 0 \qquad \text{if } \delta\, x(X_i, X_i) < -3 \text{ m (contact)} \end{cases} \qquad (4)$$

where K_{fij} (1x10^7 N/m) is the bottom fender linear stiffness coefficient between the i-th module and the adjacent j-th module. $\delta x(X_i,X_j)$ is the relative bottom surge motion between the i-th module and the adjacent j-th module. If the negative relative bottom surge motion $\delta x(X_i,X_j)$ is smaller than the module gap (3m), the two adjacent modules will impacts on the bottom. Then, the contact force at the bottom fenders will be monitored.

3. Results and Discussion

There are seven hexagonal modules (M1-M7) linked with a ball connector for the HMFS system, which can create more configurations because the hexagon having six sides. The VP configuration involves connecting a series of HMFS in a vertical, staggered configuration, whereas the VV configuration is more closely resembles an L-shaped configuration. Nowadays, all these configurations are applied in various functions of floating structures, for instance, breakwater, floating solar farm, floating city and etc. Moreover, designers can create many other configurations with hexagonal floating structures, for example in floating city planning, the U-shaped combined with the V-shaped placed the danger function like a power system located further than residential, and the U-shaped used for trade shipping business. This paper only presents linear arrangement but expands in the layout of U-shaped and V-shaped due to limitations in simulation.

Other than linear arrangement, currently some researchers have done the hydrodynamic analysis for centered arrangement that linked seven modules of HMFS by Hamamoto and Fujita (2016). Park et al. (2023) also focus on hydrodynamic analysis of floating structures with expansion of the central module that create a circular hexagonal modular floating structure. Then, Dai et al. (2021) also studied hydrodynamic analysis of floating structure but expansion of HMFS in terms of tandem arrangement that expansion by side by side. Wong et al. (2013) have done simulation that in a centralized arrangement linked many hexagonal modular given a result one maximum shear force that assuming all the connector forces has the same connector force. Besides, nowadays, many research only gives attention to the dynamic analysis for HMFS because it is a new area discovered. The analysis of connector force for each connector of multi-floating should be studied because connectors are also key parts for the stability and safety of modular floating structures.

This paper presents the maximum horizontal connector force in different arrangements which comprises seven modules of HMFS, including U-shaped, VP-shaped and VV-shaped. This is because, Lan et al. (2004) stated that the longitudinal forces are in general substantially larger than the transverse and vertical forces; therefore, the focus is on these forces. The maximum connector horizontal force for each connector is identified to study the higher and lower force at which location of connector influences by the arrangement of HMFS system. The trend of horizontal connector force also studied in each arrangement maybe can be used in early approximation of horizontal connector force for expansion of the module after additional 4$^{\text{th}}$ module and higher at the top and bottom as symmetrical module is taken into account.

3.1. U-shaped configuration of HMFS arrangement

The maximum horizontal connector force of each connector for U-shaped configuration at various wave directions is shown in Fig. 4. At 0°, 30° and 45° of the wave directions, the higher horizontal connector force is at connector C3 and the lower at connector C1. The connector C2 has the higher horizontal connector force is at 60°, 85° and 90° of the wave directions. The connector C5 has the lowest horizontal connector force at 85° and 90° of wave directions. Overall value of horizontal connector force for U-shaped, the higher value is 5.23 MN on connecters C3 and C4 and the lower value is 0.32 MN at C1, meanwhile both value at 0° wave direction. Moreover, many connectors have a higher horizontal connector force value at the 0° wave direction, such as C1, C3, C4 and C6 and a lower horizontal connector force at the 90° wave directions on connectors C4, C5 and C6.

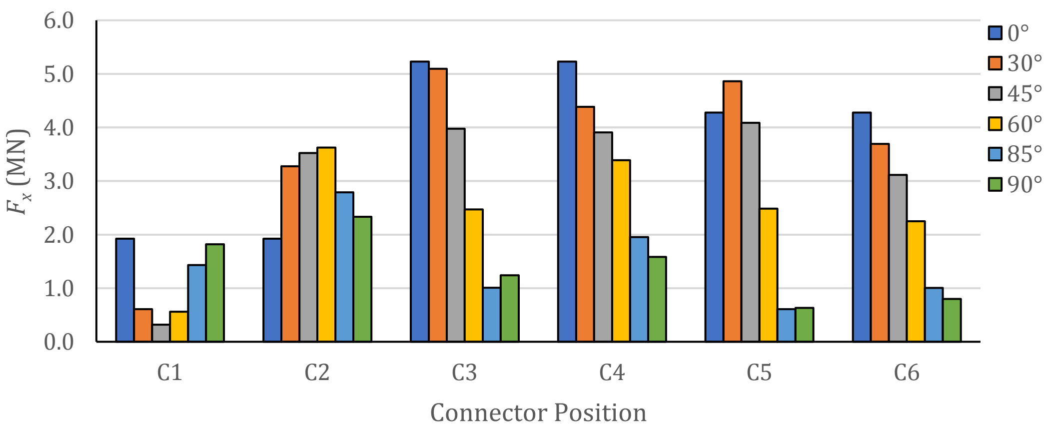

Fig. 4. Maximum horizontal connector force of each connector for U-shaped configuration at various wave directions.

There are two trend horizontal connector force for U-shaped configurations, firstly, at 0° wave direction, the horizontal connector force value at the top connector (C1, C3, C5) is similar to the bottom connector (C2, C4, C6). Initially, connectors C1, C3 and C5 at the top modules (M2, M4 and M6) is have similar value with connector C2, C4 and C6 at the bottom modules (M3, M5 and M7) at 0° wave direction, respectively. This is the connector at the top modules and bottom modules facing the wave direction 0°in same time as shown in Table 2 exhibit the similar value. The same applies by Li et al. (2023) that demonstrated the same horizontal connector load between two connectors facing the incident wave in the same time.

Table 2. Sequential orientation of the connector influenced by wave forces, highlighting the changing angle of the connector relative to the wave direction in in in 7U-shaped arrangement.

Wave direction	Sequential connector facing wave force	Angle connector facing wave force					
		C1 (DC\)	C2 (VC/)	C3 (P-)	C4 (P-)	C5 (P-)	C6 (P-)
0°	C5=C6, C3=C4, C1=C2	120°	60°	0°	0°	0°	0°
30°	C6, C4=C5, C2=C3, C1	90°	30°	-30°	-30°	-30°	-30°
45°	C6, C4, C5, C2, C3, C1	75°	15°	-45°	-45°	-45°	-45°
60°	C6, C4, C2, C5, C3=C1	60°	0°	-60°	-60°	-60°	-60°
85°	C6=C4, C2, C1, C3=C5	35°	-25°	-85°	-85°	-85°	-85°
90°	C6=C4, C2, C1, C3=C5	30°	-30°	-90°	-90°	-90°	-90°

Secondly trend, the if the top connector is higher value of horizontal connector force, the bottom will have a lower value, and vice versa for wave directions of 30°, 45°, 60°, 85° and 90°.The second trend is also given, in wave directions of 30° and 45°, the higher horizontal connector force at the top and the middle of the connector (C3) and followed by the first module facing wave (C5) while the lower of horizontal connector force is at the last module facing wave (C1). In addition, 60°, 85° and 90° of wave directions are opposite with 30° and 45°, the higher horizontal connector force at the bottom and the last module (C2) while follow by the middle module (C4). Other than that, the angle connector for C3, C4, C5 and C6 are the same angles due to the same connector orientation shown in Table 2, for example, wave direction of 30°, the parallel connector orientation of connector is C3, C4, C5 and C6 is -30°. However, the higher horizontal connector force is in connector C3, followed by connector C5, C4 and lastly C6. This finding is consistent with the findings of Liu et al. (2022), who demonstrate twelve square modules arranged in a linearly and side-by-side exhibit a higher horizontal connector load at inner modules compared to outer modules. They assert that this occurs due to the connector loads being influenced by load differences among adjacent modules, which caused by environmental conditions and other modules. Consequently, the connector loads can be effectively reduced by appropriately balancing the loads on adjacent modules.

3.2. VP-shaped configuration of HMFS arrangement

The maximum horizontal connector force of each connector for VP-shaped configuration at various wave directions is shown in Fig. 5. At 45°, 60°, 85° and 90° of the wave directions, the higher horizontal connector force is connector C5, while at 0° and 30°, the higher is at connector C3. The lower horizontal connector force on C4 at wave directions of 45° and 60° while on C3 at wave directions of 85° and 90°. Overall, the highest horizontal connector force is 4 MN on C3 and C4 at 0° of wave direction and the lowest is 0.35 MN at 30° of wave direction. Additionally, the higher horizontal connector force at 0° wave direction such as connectors of C2, C3, C4 and C6. The higher horizontal connector force of C1 is 30° wave directions at the center module while 60° of wave directions at connector C5. The lower of the connector is mostly at 30° of the wave directions on connectors C2, C4 and C6 at the bottom module (M3, M5, and M7).

There are three trends of higher horizontal connector force: Firstly, mostly higher horizontal connector force at the top connector arrangement module (C1, C3, C5) which has 0°, 30°, 45° and 60° of wave directions. The angles of connector facing the incident wave decreases on connectors C1, C3 and C5, which is below 30°, as indicated in Table 3. Besides, the findings of horizontal connector load indicates that for a linear arrangement, an increase in wave direction correspond to a decrease in horizontal connector loads. Thus, the top connectors of C1, C3 and C5 expressed lower connector angles facing wave force compared to connector C2, C4 and C6. It is similar to the findings of Song et al. (2023) and Wu et al. (2016) that the longitudinal load connecting two and three rectangular modules, respectively, experience an increase in wave direction given the decrease in longitudinal load.

Secondly, the 0° and 30° wave directions give a higher horizontal connector force on connector C3 which is the top middle module. However, in 45°, 60°, 85° and 90° the of wave direction on C5 at M6 are the outer module and end of top arrangement. Thirdly, in 85° and 90° wave direction the higher is C5 at the top module arrangement however the bottom connector (C2) is the second higher horizontal connector force. This is because the outer modules of the MFS, whether positioned at the front or rear, experience a higher horizontal connector load compared to the inner modules. The findings are similar to

Zhang et al. (2023) indicating that the connector in the middle module, assigned as connector C2 experiences lower loads compared to connectors C1 and C3, which are located in the outer modules linked three rectangular modules. Li et al. (2022) and Ren et al. (2021) also experienced the higher horizontal connection loads at the connector of outer modules, including initial modules and last modules, in comparison to middle modules for hexagonal and square for modular floating structures, respectively.

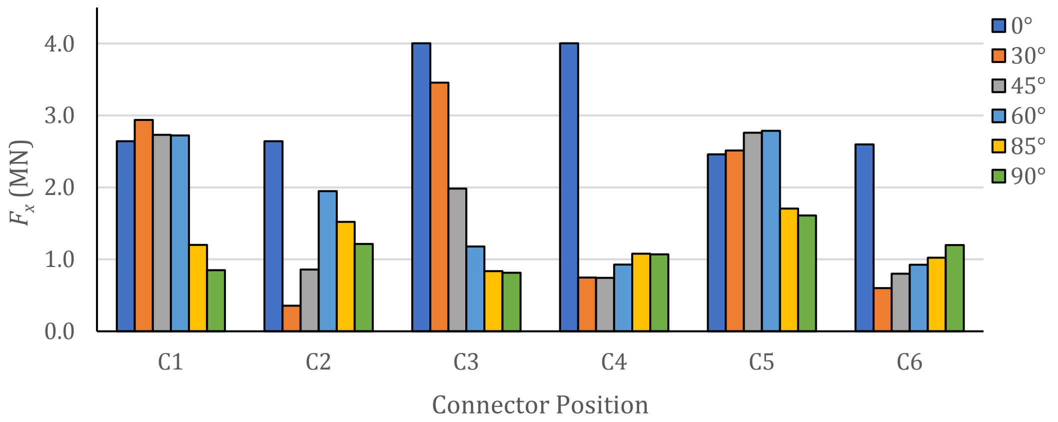

Fig. 5. Maximum horizontal connector force of each connector for VP-shaped configuration at various wave directions.

Table 3. Sequential orientation of the connector influenced by wave forces, highlighting the changing angle of the connector relative to the wave direction in 7VP-shaped arrangement.

Wave direction	Sequential connector facing wave force	Angle connector facing wave force					
		C1 (VC/)	C2 (DC\)	C3 (VC/)	C4 (DC\)	C5 (VC/)	C6 (DC\)
0°	C1=C2, C3=C4, C5=C6	60°	120°	60°	120°	60°	120°
30°	C2=C4=C6, C1, C3, C5	30°	90°	30°	90°	30°	90°
45°	C6, C4, C2, C1, C3, C5	15°	75°	15°	75°	15°	75°
60°	C6, C4, C2, C1, C3, C5	0°	60°	0°	60°	0°	60°
85°	C6, C4, C2, C1, C3, C5	-25°	35°	-25°	35°	-25°	35°
90°	C6, C4, C2, C1, C3, C5	-30°	30°	-30°	30°	-30°	30°

3.3. VV-shaped configuration of HMFS arrangement

Fig. 6 shows the maximum horizontal force of each connector for a VV-shaped configuration at various wave directions. At 0°, 85° and 90° of the wave directions, the higher horizontal connector force is at connector C3 while at 30°, 45° and 60° of the wave directions, the higher horizontal connector force is at connector C5. Connector C4 receives the majority of the lower horizontal connector force value. Overall value of horizontal connector force for VV-shaped, the higher value is 4.77 MN on connecter C3 at 0° wave direction and the lower value is 0.14 MN at C6 at 90° wave direction. In addition, many connectors have a higher F_x value at the 30° wave direction, such as C1, C2, C5 and C6 as the connectors attached at the center module (M1) and outer module facing the wave (M6, M7). The lower F_x force at the 90° wave directions on connectors C4, C5 and C6 because HMFS linked M1, M3, M5 and M7 illustrates as linear arrangement. The lower connector F_x forces at C1, C3 and C5 are 30°, 60°, and 90°. Due to linear arrangement at the bottom (M3, M5 and M7), the connector F_x force at C2, C4 and C6 is lower and higher horizontal connector force at C1, C3 and C5 for the top symmetrical loop arrangement module (M2, M4 and M6).

The higher horizontal connector force at the top arrangement has two trends: at the outer module (C5) for wave directions of 30°,45° and 60°, while 0°, 85° and 90° of wave directions at the connector on the middle module (C3). The lower horizontal connector force at the bottom arrangement also has two trends: at outer module (C6) for wave directions 45°, 60°, 85°, and 90° while 0° and 30° of wave directions are at the middle module (C4). The connector of C1, C3 and C5 shown the angle connector facing wave force shifting to below 30° incident waves for wave direction 0°, 30°, and 45° shown in Table 4. In contrast, the connector of C2, C4 and C6 is facing wave directions 0°, 30°, and 45° shifting to above 30° incident waves, as indicated in Table 4. This finding confirmed by Otto et al. (2019), indicating the hexagonal modular floating structures should avoid the environmental condition below 30° as given the higher connector loads and also compared with the square modular floating structures.

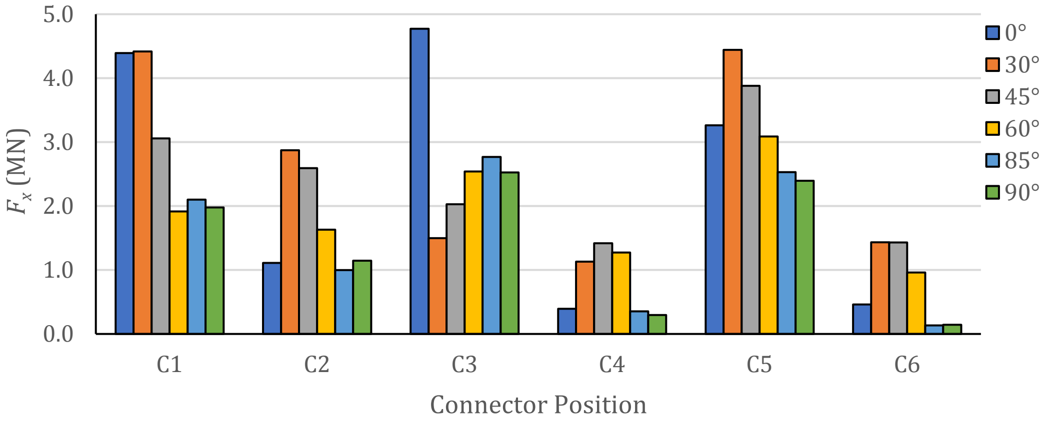

Fig. 6. Maximum horizontal connector force of each connector for VV-shaped configuration at various wave directions.

Table 4. Sequential orientation of the connector influenced by wave forces, highlighting the changing angle of the connector relative to the wave direction in in 7VV-shaped arrangement.

Wave direction	Sequential connector facing wave force	Angle connector facing wave force					
		C1 (VC/)	C2 (P|)	C3 (VC/)	C4 (P|)	C5 (VC/)	C6 (P|)
0°	C2=C4=C6, C1, C3, C5	30°	90°	30°	90°	30°	90°
30°	C6, C4, C2, C1, C3, C5	0°	60°	0°	60°	0°	60°
45°	C6, C4, C2, C1, C3, C5	-15°	45°	-15°	45°	-15°	45°
60°	C6, C4, C2, C1, C3, C5	-30°	30°	-30°	30°	-300	30°
85°	C6, C4, C2, C1, C3, C5	-55°	5°	-55°	5°	-55°	5°
90°	C6, C4, C2, C1, C3, C5	-60°	0°	-60°	0°	-60°	0°

However, in wave direction of 85° and 90°, the angle connectors facing the wave force 0˚ and close to 60˚ encounter the higher horizontal connector load. The findings of Li et al. (2022) different from these research findings as the higher horizontal connector loads in linear arrangements is 60°, followed by 0° and 30° linked five hexagonal modular floating structures. They stated that an incidence wave direction of 60^0 results in higher connector load due to a less significant shielding effect among modules. Additionally, Li et al. (2023) studied four hexagonal modular floating structures linked in L-shaped oblique arranged in one central module, mention that the yaw, sway and heave all tends to be higher with the incident wave direction of 0° or 60°. In their findings, they also indicate the higher horizontal connector load towards 0° and 60° compared to 30° and 90°. Thus, hexagonal shape should consider that the wave direction of 0° and 60° will be experience the higher horizontal connector loads.

3.4. Design recommendations for real-world implementations

In the real world, a hexagonal module positioned with its vertex side facing the incident wave was installed at Hakata Bay, Japan, in 2011 to evaluate its performance as floating offshore wind turbine (Watanabe et al. 2017). The hexagonal modular floating structure also has been installed in Punggol Eco Town in Singapore, serving as a sustainable waterfront community for tropical regions (Wong et al. 2013). In addition, Paul Ridden (2018) reported that twenty-eight hexagonal module floating structures made by recycled plastic was assembled at Rotterdam harbor, Netherlands, with the vertex side oriented towards incident wave on July 2018. The hexagonal modules served as the floating park that the hexagonal module being planted with greenery, benches for visitors and habitat for micro and macro fauna, such as snail, beetles, fish and birds. Furthermore, the small hexagonal modular floating structure has also functioned as a floating dock. The HMFS has also been installed in the Republic of Djibouti, Africa, operating as a fish farm (Piccolotti and Lovatelli 2013). Currently, China has installed a huge hexagonal module with 434 photovoltaic panels (CGTN 2024), functioning as wave-resistant floating photovoltaic platform located in waters near the southern part of Shandong, China. They indicated that a module has been installed to the testing process, with additional modules to be added later, resembling a giant honeycomb to provide optimal stability. Meanwhile, the HMFS function as floating cities is still in conceptual designs. The conceptual design of floating cities is presented by Lister and Muk-Pavic (2015), Stanković et al. (2021), and Shihy (2024).

This research studied two types of HMFS arrangement: linear arrangement and staggered arrangement. In the context of linear arrangements, the parallel sides of hexagon can be aligned in a straight line, as illustrated in linear arrangement; however, the vertex sides cannot arrange in a straight line. Furthermore, the linear arrangement can create two arrangements: firstly, the parallel side of hexagon facing the incident wave, as illustrated in linear arrangement and second, the vertex side facing the incident wave, represented as one apart in VV-shaped arrangements. This research identifies the connector that aligns with the incident wave as a parallel connector in horizontal direction (P-) exhibiting the highest horizontal connector loads in linear arrangements, especially in 0° wave direction. In contrast to the parallel connector in the vertical direction (P|), the lowest horizontal connector loads are indicated in the findings of VV-shaped arrangement. Besides, the shifting of the angles connector facing the incident wave in the parallel connector in vertical direction (P|) has 0° wave direction did not demonstrate a higher horizontal connector load in certain arrangements. Therefore, the vertex side facing incident wave applied the parallel connector in vertical direction is a good selection for linear arrangements. The linear arrangement is commonly used in breakwater, floating dock and renewable floating system, such as solar panels and wind turbines.

The vertex side facing the incident wave has also been recommended in designing the HMFS arrangements, which adopted the arrangement of side-by-side and circular configuration. The hexagonal side facing the incident wave influenced the number and layout of HMFS arrangements. As the finding discovers that two connectors, such as horizontal direction (P-) and vertical angles exhibit the higher horizontal connector loads. Likewise, the symmetrical conceptual design of MFS, creates the parallel side facing incident waves only can be arranged in seven modules: one in the central, three modules acting as arm, that three modules positioned top and two module bottoms, as illustrated in U-shaped (7U) utilized three directions of connector: horizontal connectors in horizontal direction (P-), vertical angles and diagonal angles. The VP-shaped arrangement connecting all seven modules utilizes two directions of connector: vertical angles and diagonal angles. Meanwhile, the VV-shaped utilized two directions of connector: vertical connectors in horizontal direction (P|), and vertical angles. However, only the vertical angles indicate the higher horizontal connector loads.

4. Conclusions

The present work proposes a HMFS connected to seven modules with a ball connector. The multi-floating structure hydrodynamics interaction effect and connector coupling effect were considered. The effect of wave direction and location of connector on the different arrangements of HMFS was investigated. The conclusion has been summarised as follows:

- The 0° wave direction gives a higher horizontal connector force for the HMFS system in all arrangements, for instance, U-shaped, VP-shaped and VV-shaped arrangement of HMFS.
- The U-shaped arrangement has the higher horizontal force of connector among three arrangements. U-shaped arrangement also has symmetrical F_x force value, the top connector and the bottom connector have the same connector force within the same location connector symmetrically.
- The parallel side hexagonal facing wave continues or changing the other sides will still get the VP-shaped layout however, in the VV-shaped arrangement the vertices facing wave given more to the L-shaped layout.
- The horizontal force at VV-shaped is higher horizontal force compared to VP-shaped as the difference between the vertices and sides facing wave direction 0°.
- The designer should choose the best arrangement for the hexagonal shape of the modular floating structure because each arrangement has its own suitable function. Then, next decision knowing the maximum horizontal connector force pattern in chosen the best arrangement due connector is also crucial for safety and stability for modular floating structure.

The determination of horizontal load in various HMFS arrangements allows early estimation of the connector load according to its HMFS functionality and HMFS layout. The identification of the higher horizontal connector load in various wave directions enables the connector and VLFS designer to focus to the 0° and 60° of wave directions when pursuing the conceptual design of the VLFS in hexagonal shape. As Otto et al. (2019) mention that designer should avoid the conceptual design of HMFS arrangement in wave direction below 30° as generated the higher horizontal connector load. Other that than, the comparison of horizontal connector load in various wave directions allowing identifying the impact of the changing angle of the connector relative to the wave direction in in HMFS arrangement.

For future recommendation, the simulation performed in this research is a limited selected case on 8s at a short-wave period at all seven arrangements. Thus, the simulation work should be extended for more wave period including short wave periods of 4s-8s and longer wave periods of 10s to 20s to enhance the safety connector and take into account that it effected the stability of HMFS. Other than that, the simulation performed in this research is limited to the determination of horizontal connector load increasing in seven numbers of modules, as the MFS has a higher number of modules, especially in the conceptual design of the floating city. Thus, the horizontal connector load should be extended further up to 20 modules as the limitation number of modules created in ANSYS software, then will confident in the early approximation of horizontal connector load.

References

ANSYS (2013). Aqwa Theory Manual, Release 15.0. ANSYS Inc., Canonsburg, PA.

Azlan NHA, Shaharuddin NMR, Ali A (2024). Influence of connector forces on the expansion configuration of a hexagonal modular floating structure. *5th International Conference on Advanced Engineering Technologies,* Bayburt, Türkiye, 1211–1217.

CGTN (2024). China's Wave-Resistant Floating Photovoltaic Platform to Enter Experimental Phase [Broadcast]. https://english.www.gov.cn/english.www.gov.cn/news/202410/03/content_WS66fe35cec6d0868f4e8eb7ff.html [accessed 05-12-2024].

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Data Availability

The datasets created and/or analyzed during the current study are not publicly available, but are available from the corresponding author upon reasonable request.

Dai J, Hellan Ø, Want A, Ang KK (2021). Modular multi-purpose floating structures for space creation. *Lecture Notes in Civil Engineering,* 158, 257–271.

Ding J, Wu YS, Zhou Y, Ma XZ, Ling HJ, Xie Z (2020). Investigation of connector loads of a 3-Module VLFS using experimental and numerical methods. *Ocean Engineering*, 195(10), 106684.

Hamamoto T, Fujita, KI (2016). Water tank experiment of shape-variable floating structures. *Journal of Structural and Construction Engineering*, 81(724), 1039–1049.

Hongtao Y, Gang C, Wei Z, Yan Y, Yuhan W, Chao W (2020). Design for flexible connector of multi-floating structure. *Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering.*

Ikegami K, Matsuura M, Wada Y, Zhang G (2007). Response characteristics of a multi-connected floating body system in waves. *Proceedings of the 26th International Conference on Offshore Mechanics and Arctic Engineering,* 1–10.

Jiang D, Tan KH, Dai J, Ang KK, Nguyen HP (2021a). Behavior of concrete modular multi-purpose floating structures, *Ocean Engineering*, 229, 108971.

Jiang D, Tan KH, Dai J, Ang KK, Nguyen HP (2021b). Research and development in connector systems for very large floating structures. *Ocean Engineering,* 229, 108971.

Lan Y, Run PL, Zhi S (2004). A numerical and experimental study on dynamic responses of MOB connectors. *Proceedings of the 14th International Offshore and Polar Engineering Conference*, 636–643.

Li Y, Ren N, Li X, Ou J (2022). Hydrodynamic Analysis of a Novel Modular Floating Structure System Integrated with Floating Artificial Reefs and Wave Energy Converters. *Journal of Marine Science and Engineering*, 10(8), 1091.

Li Y, Li X, Ren N, Ou J (2023). Hydrodynamic responses of a novel modular floating structure system with multi-direction expansion. *Journal of Offshore Mechanics and Arctic Engineering*, 145(3), 1-25.

Li Y, Ren N, Cai W, Liu Y, Ou J (2024). Experimental and numerical study on dynamic responses of a TLP-Type 2 modular floating structure system. *Ocean Engineering*, 313(3), 119427.

Lister N, Muk-Pavic E (2015). Sustainable artificial island concept for the Republic of Kiribati. *Ocean Engineering*, 98, 78–87.

Liu YQ, Ren N, Ou, J (2022). Investigation on Effects of mooring line fractures and connector failures for a hybrid modular floating structure system. *China Ocean Engineering*, 36(6), 880–893.

Otto W J, Waals O J, Bunnik THJ, Cresp J (2019). Optimization of wave induced motions and forces on a floating island. *Proceedings of the 29th International Ocean and Polar Engineering Conference*.

Park HJ, Kim JS, Nam BW (2023). Numerical analysis for motion response of modular floating island in waves. *Journal of Ocean Engineering and Technology*, 37(1), 8-19.

Paul R (2018). Floating park built using recycled waste plastic opens in Rotterdam. *New Atlas.* https://newatlas.com/recycled-park-rotterdam/55441 [accessed 05-12-2024].

Piccolotti F, Lovatelli A (2013). Construction and installation of hexagonal wooden cages for fish farming: A technical manual. In *FAO Fisheries and Aquaculture Technical Paper*, No. 576, Rome, Italy.

Ren N, Wu H, Liu K, Zhou D, Ou J (2021). Hydrodynamic analysis of a modular floating structure with tension-leg platforms and wave energy converters. *Journal of Marine Science and Engineering*, 9(4), 424.

Riggs HR, Ertekin RC, Mills TRJ (1998). Wave-induced response of a 5-module mobile offshore base. *Ocean Space Utilization Symposium,* Lisbon, Portugal.

Shihy AA (2024). A new approach for configuring modular floating cities: Assessing modular floating platforms by means of analytic hierarchy process. *City, Territory and Architecture*, 11, 8.

Song X, Liu W, Wu H (2023). Investigation on load characteristics of hinged connector for a large floating structure model under wave actions. *Journal of Marine Science and Engineering*, 11(4), 786.

Stanković J, Krasić S, Mitković P, Nikolić M, Kocić N, Mitković M (2021). Floating modular houses as solution for rising sea levels – A case study in Kiribati island. *Proceedings of the 39th International Conference on Education and Research in Computer Aided Architectural Design in Europe (ECAADe*), Novi Sad, Serbia, 1, 161–170.

Vincenzo B (2023). Modelling and design of a flexible connector for modular floating platforms. *Diploma thesis*, Politecnico Di Torino, Corso Di Laurea Magistrale in Ingegneria Meccanica, Torino, Italy.

Watanabe E, Utsunomiya T, Wang CM (2004). Hydroelastic analysis of pontoon-type VLFS: A literature survey. *Engineering Structures*, 26(2), 245–256.

Watanabe K, Ohya Y, Uchida T, Nagai T (2017). Numerical prediction and field verification test of wind-power generation potential in nearshore area using a moored floating platform. *Journal of Flow Control, Measurement & Visualization*, 5(2), 21–35.

Wong LH, Tan HS, Wang CL, Lim H, Ho HC, Wang CM, Tay ZY, Gao RP (2013). Floating wetlands at Punggol. *IES Journal Part A: Civil and Structural Engineering*, 6(4), 249–257.

Wu L, Wang Y, Xiao Z, Li Y (2016). Hydrodynamic Response for flexible connectors of mobile offshore base at rough sea states. *Petroleum Exploration and Development*, 43(6), 1089–1096.

Xiaozhou M, Guohai D, Yanjun M, Yufei W, Fang Y, Xiong L, Luyao Z (2024). Experimental study on the hydrodynamic performance of a flexible connected double-module floating structure. *Journal of Offshore Mechanics and Arctic Engineering*, 146(5), 051703.

Zhang X, Wang J, Li L, Sun S, Wang Z (2023). Load analysis of connectors for floating structures at sea. *Frontiers in Computing and Intelligent Systems*, 5(1), 95-99.