DESIGNING LARGE-SCALE FLOATING STRUCTURE

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Abstract

This study explores the design and development of large-scale floating structures, addressing current challenges in floating architecture while focusing on technical feasibility, energy self-sufficiency, and sustainable water management. A mixed-method approach combining qualitative analysis of existing projects with quantitative modeling and simulation was employed. The research proposes a modular hexagonal design with a 25 m diameter and 6 m height, demonstrating structural stability with a metacentric height of 0.8 m. Each module can produce 96,500.99 kWh of energy annually using solar panels and collect 325 m³ of rainwater per year. The design incorporates water management systems, including separate treatment for wastewater. This study contributes to the growing field of floating architecture by offering a flexible, scalable, and sustainable solution for large-scale infrastructure in marine environments.

Keywords: *Floating Architecture, Floating Structure, Modular Structure, Airport Terminal*

I. Introduction

As sea levels continue to rise and urban areas face increasing land scarcity, large-scale floating structures have garnered significant attention in recent years. These structures offer potential solutions to pressing challenges such as climate change adaptation, urban expansion, and sustainable development in coastal regions. However, the design and implementation of such structures present complex engineering, environmental, and regulatory challenges that require careful consideration and new approaches.

This research aims to address these challenges by developing a comprehensive design framework for large-scale floating structures, with a particular focus on modular systems that can be adapted for various purposes, including infrastructure such as airport terminals. By integrating advanced materials, renewable energy systems, and sustainable water management techniques, this study seeks to expand the possibilities in floating architecture.

It is important to note that calculating the structural stability of floating structures is extremely complex due to numerous factors. External influences such as waves and wind significantly complicate these calculations. Additionally, the varying weight of the superstructure adds another layer of complexity to the stability analysis. This research acknowledges these challenges and aims to provide a foundation for further detailed engineering studies in this field.

This study contributes to the growing body of knowledge on floating structures and aims to provide a comprehensive guideline for the development of large-scale floating infrastructure. By offering practical insights and solutions, this research can serve as a valuable resource for the design and implementation of floating structures in various coastal environments.

II. Literature Review

2.1. Current Challenges in Large-Scale Floating Infrastructure

Despite growing interest, large-scale floating infrastructure faces several challenges. From a technical perspective, designing structures capable of maintaining stability in dynamic marine environments presents significant engineering hurdles. From an economic perspective, high initial costs and uncertain long-term benefits may discourage potential investors and developers (Wang *et al.*, 2022). While floating architecture offers many environmental benefits, it might disturb marine ecosystem during construction. Furthermore, it faces regulatory and legal challenges, as existing building codes and regulations are primarily made for land-based structures. Moreover, achieving energy self-sufficiency introduces additional technical complexities. These multifaceted challenges collectively impede the widespread adoption of large-scale floating infrastructure.

2.2. Main Types of Floating Structure

Floating structure can be roughly characterized into two types, semi-submersible and pontoon. The semi-submersible type has an elevated platform above the sea level and is suitable in high sea levels areas with big and unexpected waves and can sustain constant buoyancy force. Therefore, it is used in floating oil and gas drilling platforms. The pontoon type rests on sea surface and is designed to be deployed in calm waters, and therefore most of the existing floating architecture uses pontoon type structure (El-Shihy and Ezquiaga, 2019).

2.3. Case Study Analysis

Four existing floating architecture projects were selected to gain practical insight into the design and operation of floating structures. Each of them is different in scale and type. Table 1, shows the analysis of four projects (Appendix A).

Table 1. Overview of floating architecture case study.

Case Study	**Type**	**Shape**	**Material**	**Key Insights**
Schoonschip (Amsterdam)	Residential community	Rectangular houseboats	Concrete pontoon	Small-scale modularity works well for residential use but limited scalability for larger projects.
Floating Farm (Rotterdam)	Agricultural facility	Rectangular	Concrete pontoon	Efficient closed-loop water recycling but compact design limits expansion.
Floating Office Rotterdam	Office building	Long horizontal structure	Concrete pontoon	Modular design allows for future expansion but horizontal shape limits flexibility.
Sebitseom (Seoul)	Cultural/ recreational complex	Organic	Steel pontoon	Visually striking but high maintenance due to steel pontoons in river environment.

2.4. Reuse of Semi-Submersible Platforms

As the global oil and gas industry faces the challenge of decommissioning aging offshore infrastructure, the potential reuse of semi-submersible platforms has emerged as a topic of interest. However, the viability is subject to debate, considering structural, economic, regulatory, and environmental factors.

- Despite their robust design, long-term exposure to harsh marine environments significantly compromises structural integrity. Hajinezhadian and Behnam (2024) highlight that extensive corrosion and fatigue damage accumulate over decades of operation. This necessitates costly and complex retrofitting, potentially outweighing the economic benefits of reuse.
- Repurposing for alternative uses, such as floating infrastructure or renewable energy platforms, requires substantial modifications. Wilcox *et al.*, (2023) states that the costs associated with these adaptations often exceed those of total decommissioning.
- The regulatory landscape for platform reuse is complex and often prohibitive. Banet (2020) notes that many jurisdictions mandate complete removal of decommissioned platforms,

with limited exceptions. Navigating these regulations and securing approvals for reuse projects can be time-consuming and costly, deterring potential investors.

- Younes and Ficheme (2017) point out that the remaining liability remains with the original infrastructure owner, which may create uncertainty where the liability falls when it is reused for other purposes.

While the idea of repurposing semi-submersible platforms is appealing from a sustainability perspective, the practical, economic, regulatory and safety challenges present formidable barriers. The costs and risks associated with structural adaptation, regulatory compliance, and long-term environmental impact often outweigh the perceived benefits of reuse. As such, in many cases, purpose-built or alternative solutions may prove more viable and sustainable overall.

2.5. Material

The common materials used for floating structures are concrete, steel, steel-concrete composite, advanced concrete and plastics (Wang and Wang, 2015). Steel might be an environmentally friendly option compared to concrete; however, steel needs to be taken out every five to ten years to put on a coating (Hannema, 2021). Research shows that concrete incorporating 20% silica fume by weight to cement significantly improves durability and strength in marine environment (Seleem, Rashad and El-Sabbagh, 2010).

2.6. Shape

When using single continuum structure, huge bending moments occur which affects the safety and difficulty in manufacturing. Study shows that multi-module floating structure solves the problem and has ease in changing of scale, function and construction (Hanani *et al.*, 2023). EL-Shihy (2024) state that hexagonal platform scored the highest on seakeeping, modularity, zoning, circulation, and feasibility criteria in compared to triangular, squared, octagonal, and dodecagonal.

2.7. Floating Stability

Stability is an essential requirement in floating structure. It is important to prevent structural failure caused by bending moment and displacement (Ambica, 2015). To calculate structural stability, several factors should be determined since the structure will be affected by waves, wind or uneven load. For this research, it is assumed that the floating structure will be built in calm waters.

The position of the center of gravity remains unchanged when the floating structure is tilted, but the center of buoyancy shifts due to the change in the shape of the submerged portion. This causes a misalignment between the lines of action of gravity and buoyancy. The point where the line of action of the buoyancy intersects the line of gravity is called the metacenter, M (Ambica, 2015).

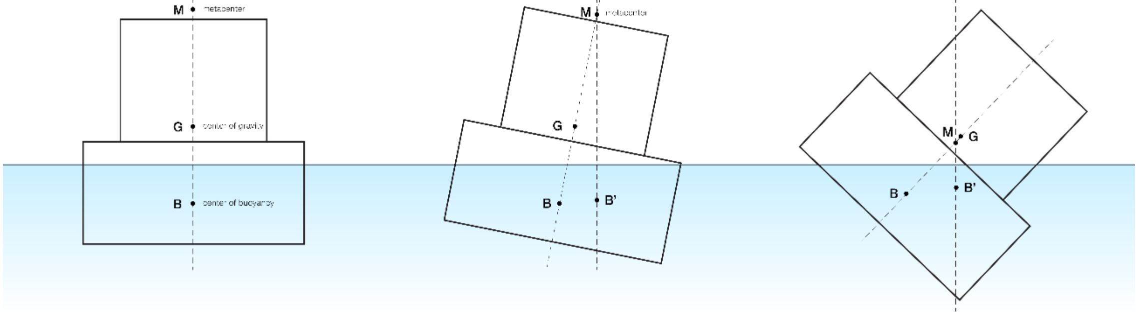

Figure 1. Metacenter and metacentric height

A metacenter is a crucial factor in determining the stability of floating structures. The metacentric height (GM) is the vertical distance between the metacenter and the center of gravity. The structure is stable when the GM is positive (Nakajima, Saito and Umeyama, 2022).

2.8. Connectors

Under harsh marine conditions, traditional rigid connectors are proven to undergo very high loads, and hinge connectors show better performance in modular floating modules (Zhao *et al.*, 2018). However, hinge connectors resulted in substantial material wear, complicating maintenance. Flexible connectors can effectively reduce the hydro-elastic response (Ma *et al.*, 2024).

III. METHODOLOGY

The research uses a mixed-method approach to develop an optimal modular design for large-scale floating structures. It addresses current challenges in floating architecture while focusing on technical feasibility, energy self-sufficiency, and sustainable water management. The methodology combines qualitative analysis of existing projects with quantitative modeling and simulation.

3.1. Literature Review and Case Study Analysis

A comprehensive review of academic papers, technical reports and design guidelines was conducted, focusing on types, materials, stability, energy supply, and water resource management of floating structures. Additionally, detailed case studies of Schoonschip, Floating Farm Rotterdam, Floating Office Rotterdam, and Sebitseom were analyzed to gain practical insights into design strategies and operational challenges.

3.2. Quantitative Modeling and Simulation

Based on the insights gained from the literature review and case studies, quantitative modeling and simulations were performed to optimize the design of the modular floating structure. This includes structural stability calculations using basic engineering principles, energy production and consumption calculations and water management system simulations, including rainwater collection and wastewater treatment.

3.3. Module Design Optimization

The module design was optimized based on the results from the quantitative analysis. A hexagonal module was chosen for its advantages in floating structures. For material selection, concrete incorporating silica fume was selected based on existing research that demonstrated its improved features in marine environments. Calculations for buoyancy, metacentric height, and maximum load capacity were performed for various module sizes and heights to verify the practical feasibility of the design.

3.4. Energy and Water System Design

For the solar power system, a theoretical model was developed to estimate annual energy production using local solar irradiation data, module size, and panel efficiency. A conceptual design for a rainwater collection system was developed, with collection volume calculated based on regional rainfall data and the proposed module size. For wastewater treatment, a literature review was conducted on various management processes, including greywater recycling methods, urine-diverting toilets, and potential biogas generation from blackwater.

IV. DESIGN AND PROTOTYPE DEVELOPMENT

4.1. Material

According to Engineering Toolbox, normal strength Portland cement concrete has a density of 2240-2440 kg/m^3, 20-40 MPa of compressive strength, 2-5 MPa of tensile strength, and 14-41

GPa of elasticity modulus. Based on the findings of Seleem, Rashad and El-Sabbagh (2010), which demonstrated that concrete incorporating silica fume significantly improves durability and strength, this research assumes enhanced properties for silica fume concrete. The assumed properties for silica fume concrete are: density of 2300-2400 kg/m³, 40-80 MPa of compressive strength, 3-7 MPa of tensile strength, and 25-50 GPa of elasticity modulus.

4.2. Floating Stability

Table 2. Formula and relationship of floating module.

Description	**Relationship / Formula**	**Source**
Hexagonal module diameter (D)	$D \propto \sqrt{(W / (n \times \rho c))}$	Derivation based on basic structural engineering principle
Module thickness relationship (t)	$t \propto W / (\rho w \times A \times fc)$	
Required number of modules (n)	$n \propto W / (\rho c \times D^2 \times t \times fc)$	
Moment of inertia for a cubical body (I)	$I = (5\sqrt{3} / 24) * (D / 2)^4$	Basic physics principle
Metacentric height (GM)	$GM \propto I / (\rho w \times V) - CG$	Naval architecture, ship stability principle
Maximum allowable load (Wmax)	$W_{max} \propto A \times t$	Basic structural engineering principle
Compressive strength capacity (Wcomp)	$W_{comp} \propto fc \times A \times t$	Basic structural engineering principle
Buoyant force (Fbuoyancy)	$F_{buoyancy} = \rho w \times V \times g$	Archimedes' principle

Glossary

W	Total weight (load)	fc	Concrete compressive strength
ρc	Concrete density	V	Displaced volume
ρw	Water density	CG	Height of the center of gravity
A	Bottom area of module	g	Gravitational acceleration

Archimedes' law states that the buoyancy force on an immersed body is equal to the weight of the displaced fluid. $F_{buoyancy}$ denotes the buoyant force and the expression is,

$$F_{buoyancy} = \rho \times V \times g$$

Where ρ is fluid density, which will be 1000kg/m³, V is fluid volume, the volume of the displaced liquid, and g is gravitational acceleration, which will be 9.81m/s².

In order to make the structure float, the weight of the structure should be smaller than the buoyant force. The maximum load, which is the additional load the structure can support, is the difference between buoyant force and weight of the structure. The expression of the maximum loads is,

$W_{max} = (\rho_w \times V \times g) - (W_s \times g)$

Where Ws is weight of the structure. To increase the buoyancy, the hexagonal module will be hollow in the inside. Therefore, it should take into account that the net volume excludes the internal volume when calculating the weight of the structure.

4.3. Development of the Model

The size of the floating structure is closely related to manufacturing and transportation. The large-scale floating infrastructure will be located in Hoek van Holland (Appendix B). If the floating concrete module can be manufactured in Rotterdam, they can be transported by Nieuwe Waterweg. The width of this waterway typically exceeds 200 meters, allowing no strict restriction to the size of the module.

The floating structure in the project 'Floating Office Rotterdam', has the dimension of 25m × 6m × 5m. The side walls are 20cm and the slabs are 30cm in thickness (Appendix A, Case 3). The analysis proceeds on the premise that the diameter of the hexagonal module has 40cm of wall and 60cm of slab thickness and the concrete density of 2400 kg/m³. Assuming the diameter of the module is 10m-30m and the height is 4m-8m, all combinations within these measurement float on water.

According to Ambica and Venkatraman (2015), floating structure should be at least 150mm above water when it is fully loaded. This prevents the water from spreading onto the slab. Taking into account the weight of the superstructure on top of the module, the following simulation assumes that the module is 300mm above water. Below shows the metacentric height of all combinations in surface plot graph.

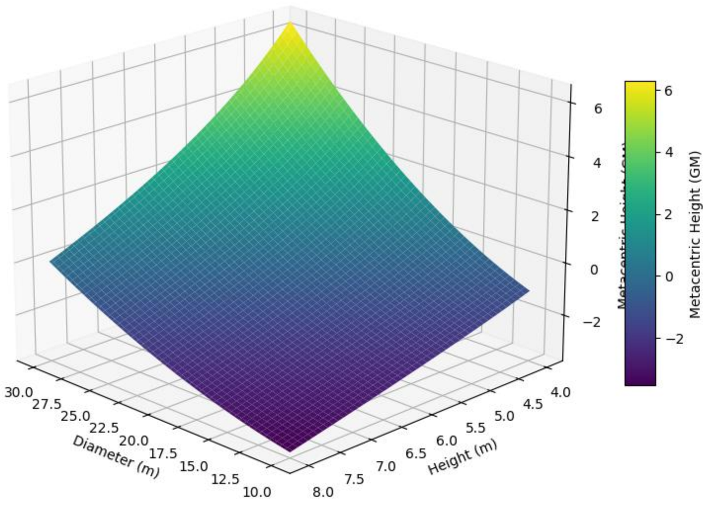

Figure 2. Module's metacentric height according to diameter and height

If the metacentric height (GM) value is positive, the structure is stable, whereas a negative metacentric height value indicates instability. The graph shows that the larger the diameter and the lower the height, the greater the metacentric height value, which enhances stability. This research will use a 25m diameter and 6m height module. The specific calculation is as follows.

Table 3. Specification of the module.

Content	Value	Calculation
Module area	405.95 m^2	$(3\sqrt{3} / 2) \times 12.5^2 = 405.95$

Module volume	145.72 m^3	A_outer = $(3\sqrt{3} / 2) \times 12.5^2 = 405.95\ m^2$ A_inner = $(3\sqrt{3} / 2) \times 12.1^2 = 380.38\ m^2$ $(405.95 - 380.38) \times 5.7 = 145.72\ m^3$
Displaced volume	2,313.915 m^3	$405.95 \times 5.7 = 2{,}313.915\ m^3$
Buoyancy force	22,699,506.15 N	$405.95 \times 5.7 \times 1000 \times 9.81 = 22{,}699{,}506.15$ N
Weight of walls	432,000 kg	$(6 \times 12.5) \times 6 \times 0.4 \times 2400 = 432{,}000$ kg
Weight of slabs	1,169,136 kg	$2 \times 405.95 \times 0.6 \times 2400 = 1{,}169{,}136$ kg
Module total weight	15,726,868.16 N	$(432{,}000 + 1{,}169{,}136) \times 9.81 = 15{,}726{,}868.16$ N
Maximum load	6,972,637.99 N	$22{,}699{,}506.15 - 15{,}726{,}868.16 = 6{,}972{,}637.99$ N
Inertia moment	8809.67 m^4	$(5\sqrt{3} / 24) * 12.5^4 = 8809.67$
Metacentric height	0.8 m	$(8809.67 / 2{,}313.915) - 3 = 0.8$

When multiple modules are connected and when the building is built on the module, the value changes. The center of gravity rises, causing the metacentric height to decrease. When multiple modules are connected, it increases the overall structural stability. Accurate calculations require consideration of the weight distribution and the shape of the entire structure. However, if the shape of the connected module is wide, unlike the long-shaped ships, it is expected to be stable (Grammatikopoulos and van der Heijden, 2024, personal communication).

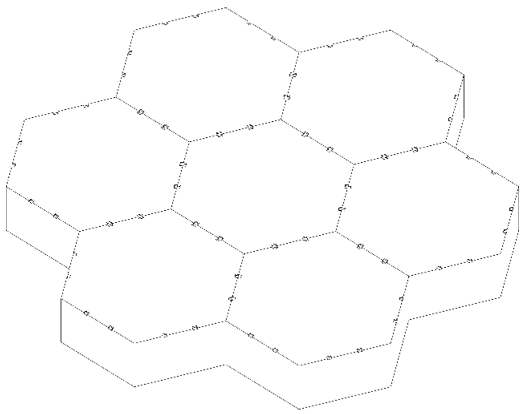

Figure 3. Hexagonal module connected with each other.

4.4. Energy Supply

Solar power was selected as the primary energy source for the floating structure based on the findings from the literature review. The case studies all utilized solar power as their main energy source, demonstrating its feasibility and effectiveness in floating structures. Additionally, Liu *et al.* (2017) reported that floating photovoltaic systems can achieve about 1.58-2.00% higher efficiency compared to land-based systems due to the cooling effect of water. The cooling effect creates a difference in operating temperature of about 3.5°C between floating and terrestrial PV systems.

A theoretical model was developed to estimate annual energy production using local solar irradiation data, module size, and panel efficiency. The relationship between the size of the hexagon module and its energy production is below:

$$E = A \times r \times H \times PR$$

Where E is annual energy production (kWh/year), A is surface area of the hexagonal module, r is efficiency of the solar panel (%), H is annual average solar irradiation (kWh/m^2/year), and PR is performance ratio.

According to European Commission's Photovoltaic Geographical Information System, the sea near Hoek van Holland has yearly in-plane irradiation of $1344.5kWh/m^2$ and performance ratio of the Netherlands is 80% (Kausika, Moraitis and Van Sark, 2018). Under the assumption that the LG NeON R product that has module efficiency of 22.1% and 440W of maximum power are used for the solar panels, energy production per one hexagonal module will be as below:

$$E = 405.95 \times 0.221 \times 1344.55 \times 0.8 = 96{,}500.99 \text{ kWh/year}$$

Supposing that Rotterdam the Hague airport terminal consumes energy of 1,278,000 kWh/year (Appendix B), fourteen modules are needed to meet the consumption.

314 panels can fit in one module, and each weigh 20.5 kg (LG Solar, 2021), so the weight of the solar panels installed in one module is 6,437kg. However, this figure does not include the weight of necessary substructures such as cables, mounting hardware, and other components. The actual total weight of the complete solar installation per module would be significantly higher than this base panel weight.

For the heating and cooling, heat pump will be used by using nearby water. As seen in the project Floating Office Rotterdam (Appendix A, Case 3), heat pumps are used to transform water ranging from -7 to 55 °C to 12 °C for the chilled water pipes, and 35 °C for the central heating system. To ensure solar panels can meet all the electrical demands of heat pump in floating architecture, a large-capacity battery system is necessary to compensate for periods of lower solar generation or unfavorable weather conditions. Battery capacity design needs to consider the power demands of photovoltaic generation and heat pump systems. According to the research by Linssen, Stenzel and Fleer (2017), the following factors should be considered when calculating battery capacity:

- Daily electricity consumption (including heat pump)
- Battery's Depth of Discharge (DoD)
- System efficiency
- Required days of autonomous operation

Considering these factors in battery capacity design can improve system stability and efficiency by compensating for the variability of solar power generation and unfavorable weather conditions. Additionally, using modular, stackable batteries can ensure flexibility and scalability.

4.5. Water Supply

For residential buildings, going off-grid in drinking water is feasible, but achieving this on a large-scale requires more research. Therefore, the prototype of this research will use municipal water supply.

Except for drinking water, the main water supply would be rainwater. Rainwater will be collected on the roof of the superstructure, integrated with the photovoltaic panel system. This combined approach optimizes space usage, balances the weight distribution on the floating modules, and creates synergy between energy generation and water collection systems. The collected rainwater can be used for irrigation, fire control systems, cooling towers. For rainwater collection, the equation is as follows:

$$Q = C \times I \times A$$

Where Q is collectable rainwater volume (m^3), C is runoff coefficient, which depends on roof material, I is rainfall intensity (m/hour), and A is collection area (m^2). The rainfall intensity could be derived from the annual average rainfall (R) as below:

$$I = R / (365 \times 24)$$

According to Appendix B, the annual average rainfall of Rotterdam is 891.55mm. Therefore, the rainfall intensity would be 0.1018mm/hour. Integrating with the photovoltaic panel, the roof material would be glass. The runoff coefficient of glass is 0.9-1.0 (Markovic, Kaposztasova, and Vranayova, 2014). Consequently, the collectable rainwater volume of a module would be as follows:

$$Q = 0.9 \times 0.0001018 \text{m/hour} \times 405.95 \text{ m}^2 = 0.0371$$

$$Q_{year} = 0.0371 \times 24 \times 365 = 325 \text{ m}^3$$

4.6. Wastewater Treatment

In project Schoonschip, greywater is collected separately and be treated by going through helophyte filter which is a natural purification system utilizing aquatic plants and microorganisms to remove contaminates, it can be then reused for toilet flushing. Blackwater is also collected separately by using urine-diverting toilets. These toilets separate urine from feces at the source (Metabolic, 2013).

To apply to larger infrastructure, several considerations should be involved. Inorganic membrane filtration coupled with advanced oxidation processes can be integrated to filter the wastewater (Zhang *et al*., 2024). Biogas made from blackwater could generate heat and electricity by going through combined heat and power cycle, reaching up to 90% of efficiency (Abanades *et al.,* 2022).

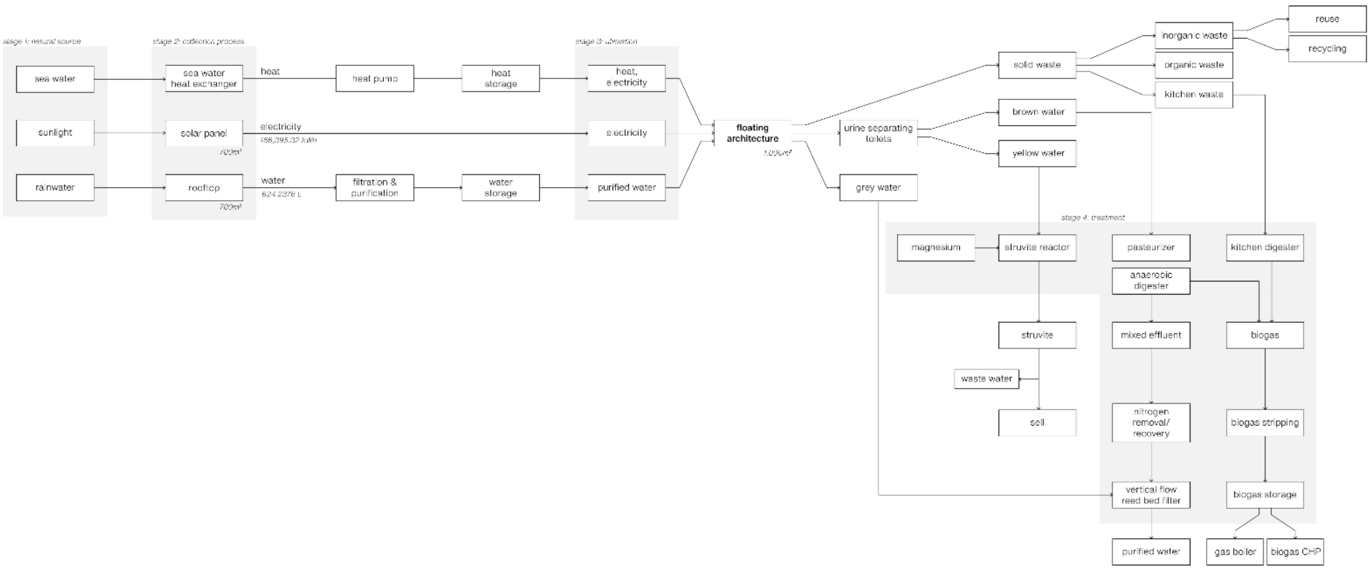

Figure 5. Energy and water cycle

4.7. Module Connection

Due to the scale of the floating structure, there will be high loads on the connections. Using flexible connectors makes the structure stable with the movement of the sea waves. Additionally, for the ease of offshore activities, such as maintenance, the connectors will only be located in the top part of the module. The connectors comprise with tension member and a shear key. It resists tension/splitting forces and does not transfer moment force. The shear key has an adjustable male component capable of vertical and horizontal movement to cater construction tolerances. A jack makes the vertical adjustment possible and the horizontal adjustment is achieved by inserting a shim plate.

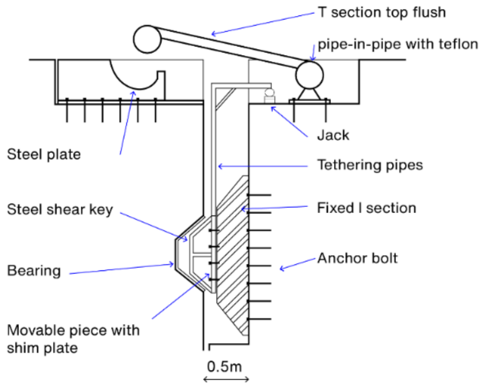

Figure 4. Connection design with steel shear key (Dai *et al*., 2021, p.6)

V. RESULTS AND DISCUSSION

5.1. Key Findings

The hexagonal module design with a 25m diameter and 6m height demonstrated structural stability with a metacentric height of 0.8m and a maximum load capacity of 6,972,637.99 N. The modular design offers flexibility for multi-purpose use and easy expansion. This adaptability is crucial for the evolving needs of coastal infrastructure, allowing for easy reconfiguration or relocation if needed.

Metacentric height is closely linked to initial static stability, affecting the structural stability against overturning. A lower center of gravity enhances stability, emphasizing the importance of lightweight superstructure. Lightweight structures can also maintain the shape of waterplane without significantly increasing the displaced volume.

Each module can produce 96,500.99 kWh of energy annually using solar panels. With 14 modules, the total energy generation reaches 1,351,013.86 kWh annually, exceeding the typical energy consumption of an airport terminal (1,278,000 kWh). This self-sufficiency in energy production represents a major step towards sustainable infrastructure.

The design incorporates water management systems, including rainwater collection system capable of harvesting approximately 325 m^3 of rainwater per year per module. This can reduce the reliance on municipal water supplies. The separate treatment systems for greywater and blackwater not only promote water conservation but also open possibilities for resource recovery, such as biogas production from wastewater.

Overall, this design demonstrates the feasibility of large-scale floating structures that are not only structurally sound and energy-efficient but also adaptable to various functions and environmental conditions.

5.2. Comparative Advantages

The proposed floating structure design offers several advantages over traditional land-based infrastructure. It can easily adapt to sea-level rise, addressing key challenges posed by climate change. It also provides greater flexibility in urban planning due to potential relocation and repurposing, while reducing land use in densely populated areas. Based on the findings of Wang *et al*. (2022), it can be competitive with traditional land-based structures in terms of construction cost.

5.3. Future Research

While the current design addresses some challenges, there are several aspects that need further research. These include long-term durability testing of materials and structures, detailed economic analysis to assess cost-effectiveness, environmental impact studies of large-scale implementation, logistical and technical issues with integrating with existing infrastructures, and public perception or concerns.

REFERENCES

1. Wang, X., Xu, S. Y., Leung, M. Y., & Liang, Q. (2022). A VALUE-BASED MULTI-CRITERIA DECISION-MAKING APPROACH TOWARDS FLOATING HOUSE DEVELOPMENT: A CASE STUDY IN HONG KONG. Journal of Civil Engineering and Management, 29(3), 223–237. https://doi.org/10.3846/jcem.2023.17571
2. El-Shihy, A. A., & Ezquiaga, J. M. (2019). Architectural design concept and guidelines for floating structures for tackling sea level rise impacts on Abu-Qir. Alexandria Engineering Journal, 58(2), 507–518. https://doi.org/10.1016/j.aej.2019.05.003
3. Hajinezhadian, M., & Behnam, B. (2024). A Corrosion- and Repair-Based Reliability Framework for Offshore Platforms. Journal of Marine Science and Engineering, 12(3). https://doi.org/10.3390/jmse12030504
4. Wilcox, L. B., Wiranegara, N. K., Martinez-Felipe, A., & Hastings, A. (2023). Repurposing an Offshore Oil and Gas Platform for Green Hydrogen Production: A North Sea Case Study. https://ssrn.com/abstract=4622137
5. Banet Catherine. (2020). Regulating the Reuse and Repurposing of Oil and Gas Installations in the Context of Decommissioning: Creating Incentives and Enabling Energy System Integration. In Pereira Eduardo G., Wawryk Alexandra, Trischmann Heike, Banet Catherine, & Hall Keith B (Eds.), The Regulation of Decommissioning, Abandonment and Reuse Initiatives in the Oil and Gas Industry: From Obligation to Opportunities (pp. 205–227). Wolters Kluwer.
6. Younes, A., & Ficheme, C. E. (2017). Safety, Human Factors, Culture and Lessons learnt from Decommissioning. In SYMPOSIUM SERIES NO (Vol. 162).
7. Wang, C. M., & Wang, B. T. (2015). Ocean Engineering & Oceanography 3 Large Floating Structures Technological Advances (Dhanak Manhar R. & Xiors Nikolas I., Eds.; 1st ed., Vol. 3). Springer. http://www.springer.com/series/10524
8. Hannema Kirsten. (2021, September 17). Keeping afloat in a changing climate. The RIBA Journal. https://www.ribaj.com/buildings/floating-office-rotterdam-maas-river
9. Seleem, H. E. D. H., Rashad, A. M., & El-Sabbagh, B. A. (2010). Durability and strength evaluation of high-performance concrete in marine structures. Construction and Building Materials, 24(6), 878–884. https://doi.org/10.1016/j.conbuildmat.2010.01.013
10. Hanani, N., Shaharuddin, N. M. R., Ali, A., & Sunarsih. (2023). Approximation method of the axial forces on network of connectors for modular hexagonal floating structures. IOP Conference Series: Earth and Environmental Science, 1166(1). https://doi.org/10.1088/1755-1315/1166/1/012054
11. EL-Shihy, A. A. (2024). A new approach for configuring modular floating cities: assessing modular floating platforms by means of analytic hierarchy process. City, Territory and Architecture, 11(1). https://doi.org/10.1186/s40410-024-00228-6
12. Ambica, A. (2015). Floating Architecture: A Design on Hydrophilic Floating House for Fluctuating Water Level. Indian Journal of Science and Technology, 8(1), 1–5. https://doi.org/10.17485/ijst/2015/v8i32/84304
13. Nakajima, T., Saito, Y., & Umeyama, M. (2022). A Study on Stability of Floating Architecture and Its Design Methodology. Lecture Notes in Civil Engineering, 158, 273–296. https://doi.org/10.1007/978-981-16-2256-4_17
14. Zhao, H., Xu, D., Zhang, H., & Shi, Q. (2018). A flexible connector design for multi-modular floating structures. Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE, 1. https://doi.org/10.1115/OMAE2018-78661
15. Ma, G., Zhang, C., Chen, H., Hou, W., Wang, W., & Zhang, J. (2024). Hydrodynamic analysis of floating photovoltaic system constrained with rigid connectors. Scientific Reports, 14(1). https://doi.org/10.1038/s41598-024-81245-w

16. Liu, L., Wang, Q., Lin, H., Li, H., Sun, Q., & Wennersten, R. (2017). Power Generation Efficiency and Prospects of Floating Photovoltaic Systems. Energy Procedia, 105, 1136–1142. https://doi.org/10.1016/j.egypro.2017.03.483
17. Kausika, B. B., Moraitis, P., & van Sark, W. G. J. H. M. (2018). Visualization of operational performance of grid-connected PV systems in selected European countries. Energies, 11(6). https://doi.org/10.3390/en11061330
18. LG Solar. (2021) 2021 Product Catalog LG NeON Solar Panels. [Product catalog] United States of America: LG Electronics U.S.A. Inc.
19. Linssen, J., Stenzel, P., & Fleer, J. (2017). Techno-economic analysis of photovoltaic battery systems and the influence of different consumer load profiles. Applied Energy, 185, 2019–2025. https://doi.org/10.1016/j.apenergy.2015.11.088
20. Markovic, G., Kaposztasova, D., Vranayova, Z., Markovič, G., Kaposztásová, D., & Vranayová, Z. (2014). The analysis of the possible use of harvested rainwater and its potential for water supply in real conditions. https://www.researchgate.net/publication/268130556
21. Metabolic. (2013). CLEANTECH PLAYGROUND a cleantech utility in Amsterdam North. Metabolic Lab. https://www.metabolic.nl/projects/schoonschip/
22. Zhang, C., Yuan, R., Chen, H., Zhou, B., Cui, Z., & Zhu, B. (2024). Advancements in Inorganic Membrane Filtration Coupled with Advanced Oxidation Processes for Wastewater Treatment. Molecules, 29(17), 4267. https://doi.org/10.3390/molecules29174267
23. Abanades, S., Abbaspour, H., Ahmadi, A., Das, B., Ehyaei, M. A., Esmaeilion, F., el Haj Assad, M., Hajilounezhad, T., Jamali, D. H., Hmida, A., Ozgoli, H. A., Safari, S., AlShabi, M., & Bani-Hani, E. H. (2022). A critical review of biogas production and usage with legislations framework across the globe. In International Journal of Environmental Science and Technology (Vol. 19, Issue 4, pp. 3377–3400). Springer Science and Business Media Deutschland GmbH. https://doi.org/10.1007/s13762-021-03301-6
24. Dai, J., Hellan, Ø., Watn, A., Keng Ang, K., & Want, A. (2021). Modular Multi-Purpose Floating Structures for Space Creation. In Piątek Łukasz, Lim Soon Heng, Wang Chien Ming, & de Graaf-van Dinther Rutger (Eds.), Proceedings of the Second World Conference on Floating Solutions, Rotterdam (pp. 257–272). Springer.
25. Wang, X., Xu, S. Y., Leung, M. Y., & Liang, Q. (2022). A VALUE-BASED MULTI-CRITERIA DECISION-MAKING APPROACH TOWARDS FLOATING HOUSE DEVELOPMENT: A CASE STUDY IN HONG KONG. Journal of Civil Engineering and Management, 29(3), 223–237. https://doi.org/10.3846/jcem.2023.17571

APPENDIX A

I. CASE STUDIES

As shown in Table 1, a total of 4 case studies were explored. These provide broad coverage of the energy self-sufficiency and water recycling strategies for knowledge capture and learning.

Table 1. Comparison of material, type and shape.

Case Study	Material	Pontoon Type	Construction Time
Schoonschip	Recycled materials, wood	Concrete pontoon	2018-2020
Floating Farm Rotterdam	Steel, glass	Concrete pontoon	2018-2019
Floating Office Rotterdam	Timber, glass	Concrete pontoon	2020-2021
Sebitseom Floating Islands	Steel, glass	Steel pontoon	2009-2011

Table 2. Comparison of energy and water recycling.

Case Study	Energy Source	Energy Self-Sufficient Level	Water Recycle System	Sustainability Approach
Schoonschip	Solar panels, heat pumps	Fully self-sufficient	Grey water recycling, rainwater harvesting	Decentralized renewable energy
Floating Farm Rotterdam	Solar panels, biogas	Fully self-sufficient	Rainwater harvesting	Closed-loop system using solar and biogas
Floating Office Rotterdam	Solar panels, river water cooling	Highly self-sufficient	River water cooling, likely greywater recycling	Renewable energy with natural cooling
Sebitseom Floating Islands	Solar panels	Partially self-sufficient	Greywater recycling, integrated water management	Renewable energy integration

II. CASE 1: SCHOONSCHIP, AMSTERDAM

2.1. Brief

Schoonschip is a floating residential neighborhood located in Johan van Hasselt Canal, Amsterdam, Netherlands. The project aimed to create one of the most sustainable floating communities in Europe. After more than a decade of development, Schoonschip now consists of 46 floating homes across 30 water plots, providing housing for over 100 residents. Completed in 2020, the community has become a model for sustainable urban living on water. The design and development of Schoonschip were led by the architecture firm Space&Matter, with sustainability consultancy by Metabolic providing expertise on environmental technologies. Each home is equipped with solar panels and connected to a smart grid, allowing residents to generate and share the energy. In addition to energy self-sufficiency, the community incorporates water management systems, including greywater recycling and nutrient recovery from wastewater. The residents were deeply involved in the design process, fostering strong social cohesion within the community. They share resources such as electric vehicles and participate in working groups focused on sustainability topics like energy management and waste reduction (CrAFt Cities, 2023). This collaborative approach has made Schoonschip a beacon for sustainable urban living, demonstrating how floating infrastructure can address challenges such as land scarcity and climate change while promoting community engagement (ArchDaily, 2021).

2.2. Material

Schoonschip utilizes a variety of sustainable materials in its construction. The houses are primarily built using recycled and bio-based materials, with wood being a predominant choice. This aligns with the project's commitment to sustainability and circular design principles. The use of these materials not only reduces the environmental impact but also contributes to the overall energy efficiency of the structures.

2.3. Shape

The shape of Schoonschip's floating homes is diverse, reflecting the individual designs chosen by each household. The neighborhood consists of 30 water plots, with 15 of these containing two households in a semi-detached arrangement. This variety in design creates a visually interesting and dynamic community while still maintaining a cohesive overall appearance. The houses are connected by a smart jetty, which serves both as a social connector and a functional infrastructure for utilities.

2.4. Type of Pontoon

Writing in progress

2.5. Energy Self-Sufficiency

Schoonschip achieves a high level of energy self-sufficiency through various innovative systems:

- The community features 516 solar panels and 60 solar thermal panels, providing renewable electricity and heat.
- Each home is equipped with heat pumps that extract heat from the canal water for space heating.
- A smart grid system connects all households, allowing residents to trade excess energy among themselves.
- The neighborhood operates on a private smart grid with a single connection to the municipal electricity grid, optimizing local energy supply and demand.
- Battery storage systems (30 batteries of 7.5kW each) are used to store excess energy.

These combined systems enable Schoonschip to generate 100% renewable electricity and aim for 100% renewable heat and hot water supply.

2.6. Water Recycling

Schoonschip implements comprehensive water management and recycling systems:

- Rainwater is collected and used for toilet flushing and plant irrigation.
- Greywater from kitchens, showers, and washing machines is treated and reused within the community.
- Blackwater is separated and will be fermented to produce energy through a partnership with water supplier Waternet.
- Some homes have the option of a fully self-sufficient water purification system for drinking water.

The community aims for 100% water self-sufficiency and 60-80% nutrient recovery from wastewater and organic waste treatment. These systems demonstrate Schoonschip's commitment to closing the water cycle and maximizing resource efficiency within the floating neighborhood.

III. CASE 2: FLOATING FARM, ROTTERDAM

3.1. Brief

The Floating Farm in Rotterdam is the world's first floating dairy farm, located in the Merwehaven, part of the city's old port. The project was initiated by Peter and Minke van Wingerden of Beladon, a company specializing in waterborne architecture. The farm was designed to address two major global challenges: the scarcity of agricultural land due to urbanization and the increasing threat of flooding caused by climate change. Opened in 2019, the farm houses around 40 cows that produce fresh dairy products, such as milk and yogurt, which are processed and sold directly to local consumers.

The Floating Farm is not only a commercial dairy operation but also an educational hub, showcasing how food production can be localized and made more resilient to environmental changes. It aims to shorten supply chains by producing food close to where it is consumed, while also promoting circularity through resource reuse

3.2. Material

The Floating Farm is constructed using a combination of concrete for buoyancy and structural stability, along with lightweight materials like polycarbonate for transparency. The design is based on nautical principles to ensure that the structure remains stable on water while housing both cows and dairy processing facilities (Goldsmith Company, 2019). The farm's transparent façade allows visitors to observe its operations without disturbing the animals or production processes (ArchDaily, 2019).

The materials used are chosen for both durability and sustainability. The concrete pontoons provide a stable foundation for the structure, while polycarbonate panels offer lightweight protection and transparency, making it easier for visitors to engage with the farm's educational aspects (Goldsmith Company, 2019).

3.3. Shape

The Floating Farm is a compact, multi-level structure designed to maximize space efficiency on water. It consists of three connected levels:

- The lower level houses technical installations such as water recycling systems.
- The middle level contains spaces for milk processing and manure handling.
- The top level is a cow garden where the animals can graze and rest.

The farm's design is highly functional, with each level serving a specific purpose related to dairy production or animal welfare (Goldsmith Company, 2019). The building's layout ensures that all processes—from feeding to milking—are automated and organized efficiently within a small footprint.

3.4. Type of Pontoon

The Floating Farm is supported by three large concrete pontoons that provide buoyancy and stability. These pontoons are connected beneath the structure to ensure even weight distribution across the platform. The use of concrete pontoons allows the farm to remain stable even during fluctuating water levels or adverse weather conditions (Goldsmith Company, 2019; Dezeen, 2019).

Concrete was chosen for its durability and ability to withstand long-term exposure to water without degrading. Additionally, concrete pontoons provide sufficient stability for heavy equipment like milking robots and manure cleaning systems located on the farm (Floating Farm Rotterdam, 2020).

3.5. Energy Self-Sufficiency

The Floating Farm is designed to be energy self-sufficient through the use of renewable energy sources. It generates electricity from floating solar panels installed on its roof. These solar panels provide all the energy needed for daily operations, including powering automated systems like milking robots and manure-cleaning robots (Dezeen, 2019; Floating Farm Rotterdam, 2020).

By generating its own renewable energy on-site, the Floating Farm minimizes its reliance on external power sources and reduces greenhouse gas emissions associated with food production (Holland.com). Additionally, electric vehicles are used for transportation within the city, further reducing carbon emissions from logistics (Floating Farm Rotterdam, 2020).

3.6. Water Recycling

Water management is a key feature of the Floating Farm’s design. Rainwater is collected on the roof of the structure and then purified for use in daily operations. This system ensures that fresh water is available without relying on external water sources (Dezeen, 2019; Holland.com).

In addition to rainwater collection, greywater recycling systems are integrated into the farm's operations. Wastewater from cleaning processes is treated and reused within the facility. Manure produced by the cows is also recycled into natural fertilizer for urban green spaces in Rotterdam (Floating Farm Rotterdam, 2020). This closed-loop system helps reduce waste while contributing to local sustainability efforts.

IV. CASE 3: FLOATING OFFICE ROTTERDAM

4.1. Brief

The Floating Office Rotterdam (FOR) is a state-of-the-art floating office building located in the Rijnhaven port of Rotterdam. Designed by Powerhouse Company and completed in 2021, it serves as the headquarters for the Global Center on Adaptation (GCA), an international organization focused on climate change solutions (Dezeen, 2022). The building is a model of sustainability, designed to adapt to rising sea levels and operate off-grid. It is the largest floating office in the world and showcases how architecture can respond to the challenges posed by climate change (Sempergreen, 2021).

The Floating Office is part of a broader redevelopment of the Rijnhaven port, transforming it from an industrial area into a vibrant mixed-use space. The office not only houses GCA but also includes public amenities such as a restaurant and even a swimming pool integrated into the Maas River (Powerhouse Company, 2021).

4.2. Materials

The Floating Office Rotterdam was constructed using a combination of sustainable materials, with a focus on minimizing its carbon footprint:

- The primary structure is made from cross-laminated timber (CLT), a renewable material that stores carbon dioxide. This choice significantly reduces the environmental impact compared to traditional concrete or steel construction (Dezeen, 2022).
- The building's foundation consists of concrete pontoons, which provide buoyancy and stability. These pontoons contain integrated systems for heating and cooling, making them multifunctional (LoopNet, 2022).
- The roof features both solar panels and a green roof. The green roof includes sedum plants and herbs that enhance biodiversity while providing insulation and reducing urban heat island effects (Sempergreen, 2021).

4.3. Shape

The Floating Office has a long, horizontal shape designed to fit within the constraints of Rotterdam's waterways. The building has three stories:

- The ground floor includes office spaces and public amenities like a restaurant.
- The second floor houses additional offices.
- The top floor is dedicated to meeting rooms and executive offices.

The building's design is modular and based on a repeating grid system that ensures symmetry and balance on water. This helps maintain stability as the tides in Rotterdam cause the office's elevation to fluctuate by up to two meters throughout the day (LoopNet, 2022). Overhanging balconies provide natural shading for large windows, enhancing energy efficiency by reducing heat gain (Powerhouse Company, 2021).

4.4. Type of Pontoon

The Floating Office rests on 15 concrete pontoons, each measuring 6 meters by 6 meters. Each pontoon has 20cm of wall thickness and 30cm of slab thickness (Schoof, 2022). These pontoons are anchored together to create a stable floating foundation that can withstand tidal fluctuations in the Rijnhaven port (Dezeen, 2022). Concrete was chosen over other materials like steel because it requires less maintenance; steel would need to be removed from the water every five years for re-coating, while concrete can remain submerged for up to 50 years without significant degradation (RIBAJ, 2021).

The pontoons also contain an integrated pipe system that functions as a heat exchanger, using water from the Maas River to cool the building in summer and warm it in winter. This dual functionality makes the pontoons an essential part of both the structural and energy systems of the building (LoopNet, 2022).

4.5. Energy Self-Sufficiency

The Floating Office Rotterdam is designed to be energy-positive, meaning it generates more energy than it consumes:

- The southern side of the pitched roof is covered with 870 square meters of solar panels, which generate around 154 megawatt-hours of electricity annually**—**109% of what is required to run the building (LoopNet, 2022).
- Excess energy produced by these solar panels is fed back into Rotterdam's grid, making FOR not only self-sufficient but also a contributor to local energy supplies (Powerhouse Company, 2021).

- In addition to solar power, the building uses a water-based heat exchange system that draws thermal energy from the Maas River. This system provides passive cooling in summer and heating in winter without relying on external energy sources (Dezeen, 2022).

4.6. Water Recycling

Water management is another key aspect of FOR's sustainability strategy:

- The green roof not only improves insulation but also helps manage rainwater runoff. Rainwater is collected and filtered through the green roof before being reused within the building for non-potable purposes like irrigation or toilet flushing (Sempergreen, 2021).
- By incorporating rainwater management into its design, FOR reduces its reliance on municipal water systems while also mitigating urban flooding risks during heavy rains—a common issue in cities like Rotterdam.

V. CASE 3: SEBITSEOM

5.1. Brief

Sebitseom (also known as Sebit Dungdungseom) is a group of three artificial floating islands located on the Han River in Seoul, South Korea. Opened in 2011, Sebitseom was developed as part of Seoul's efforts to revitalize the Han River and create new cultural and recreational spaces. The islands are designed to resemble blooming flowers, symbolizing vitality and growth. Each island serves a different purpose: Gavit is used for performances and conventions, Chavit for dining and exhibitions, and Solvit for water sports and leisure activities (Korea Tourism Organization, 2022).

Sebitseom is a key part of Seoul's urban development strategy, blending architecture with nature to create a multifunctional space that attracts both locals and tourists. It is one of the largest floating structures in the world and represents an innovative approach to urban waterfront development.

5.2. Materials

The construction of Sebitseom involved using a combination of steel, glass, and concrete. The islands are supported by steel pontoons, which provide buoyancy while ensuring stability in the river's fluctuating water levels. The superstructure of each island is made primarily from steel and glass to create a modern aesthetic while allowing natural light to penetrate the interior spaces (Naeway News, 2023).

The use of steel pontoons was chosen for their durability and flexibility in water-based environments. Steel allows for greater structural adaptability compared to concrete pontoons, which are heavier and more difficult to modify (YouTube Video, 2023).

5.3. Shape

Sebitseom consists of three floating islands shaped to resemble blooming flowers:

- Gavit: The largest island, used for performances and conventions, has a petal-like design with curved edges.
- Chavit: This island is designed for dining and exhibitions, with a more rectangular layout but still featuring organic curves.
- Solvit: The smallest island, dedicated to water sports, has an angular design that contrasts with the softer shapes of Gavit and Chavit.

The overall design emphasizes fluidity and connection with nature, reflecting the movement of water while also providing functional spaces for various activities (Korea Tourism Organization, 2022).

5.4. Type of Pontoon

Sebitseom uses steel pontoons as its floating foundation. These pontoons provide buoyancy while ensuring that the islands remain stable even during fluctuations in the Han River's water levels (Naeway News, 2023). Steel was chosen over concrete due to its flexibility and ease of maintenance. Steel pontoons also allow for future modifications or expansions if needed.

The steel pontoons are anchored securely to the riverbed using a combination of mooring chains and tension cables. This system ensures that the islands remain in place while allowing some movement to accommodate changes in water levels or currents (YouTube Video, 2023).

5.5. Energy Self-Sufficiency

While Sebitseom incorporates some sustainable technologies such as solar panels, it is not entirely energy self-sufficient. Solar panels installed on the islands provide supplemental energy for lighting and other electrical needs, but the majority of power is still sourced from external grids (Naeway News, 2023).

The integration of renewable energy sources like solar panels reflects Seoul's broader commitment to sustainability; however, the islands rely on conventional energy systems for larger power demands such as heating, cooling, and event operations.

5.6. Water Recycling

Sebitseom features an integrated water management system that includes greywater recycling. Water used in restrooms and cleaning processes is treated on-site before being reused for non-potable purposes such as irrigation or flushing toilets (Naeway News, 2023).

Additionally, rainwater harvesting systems are installed on each island to collect rainwater for use in landscaping and maintenance tasks. These systems reduce reliance on municipal water supplies while contributing to more sustainable water usage practices.

REFERENCES

1. Bekhuis K., (2018). *Way of living: An evaluation of the energy system at De Ceuvel* [Bachelor's thesis]. University of Utrecht. https://studenttheses.uu.nl/bitstream/handle/20.500.12932/31201/Bekhuis_Kyra_5553318.pdf?sequence=2
2. Klaversma E., & Roest K., (2016). Applicability of Decentralized Versus Centralized Systems for Wastewater Treatment.*Proceedings of the 14th International Conference on Sustainable Water and Wastewater Systems*. http://uest.ntua.gr/swws/proceedings/pdf/SWWS2016_Klaversma.pdf
3. Ortner F., et al., (2021). *Micro-Infrastructures: Architecture in Data-Driven Amsterdam*. ResearchGate. https://www.researchgate.net/publication/350311978_Micro-infrastructures_Architecture_in_Data-driven_Amsterdam
4. Pistoni R., & Bonin S., (2017). *Urban metabolism planning and designing approaches between quantitative analysis and urban landscape*. *City Territ Archit* 4(20). https://doi.org/10.1186/s40410-017-0076-y

5. Rethinking Urban Living (2021). *Participatory Design in Circular Neighborhoods*. University of Edinburgh Journals. https://journals.ed.ac.uk/rethink/article/view/4306/7471
6. Roest et al., (2017). Applicability of Decentralized Versus Centralized Systems for Wastewater Treatment.*Libre PDF*. https://d1wqtxts1xzle7.cloudfront.net/83362833/17_Roest_16-libre.pdf
7. Metabolic. (2015). Schoonschip. [online] Available at: https://www.metabolic.nl/projects/schoonschip/.
8. Prosdocimo, D. (2021). > *Schoonschip sustainable community on floating houses | ARCHIVIBE*. [online] ARCHIVIBE architecture and design news. Available at: https://www.archivibe.com/schoonschip-community-on-floating-houses/.
9. Arko, S. (2021). Meet Schoonschip, a sustainable floating neighbourhood in the Netherlands. Institute for Innovation and Development of University of Ljubljana. https://iri.uni-lj.si/en/meet-schoonschip-asustainable-floating-neighbourhood-in-thenetherlands/
10. Cutieru, A. (2021). Amsterdam's Floating Neighbourhood Schoonschip Offers a New Perspective on Circularity and Resiliency. ArchDaily. https://www. archdaily.com/964050/amsterdams-floatingneighbourhood-schoonschip-offers-a-newperspective-on-circularity-and-resiliency
11. Space&Matter. (n.d.). Schoonschip A Sustainable Floating Community. https:// www.spaceandmatter.nl/work/schoonschip
12. Floating Farm Rotterdam Official Website (2020). Floating Farm. https://floating.farm
13. Goldsmith Company (2019). Floating Farm Dairy / Goldsmith Company. ArchDaily. https://www.archdaily.com/919542/floating-farm-dairy-goldsmith-company
14. Dezeen (2019). Floating Farm in Rotterdam Is Now Home to 32 Cows. https://www.dezeen.com/2019/05/24/floating-farm-rotterdam-climate-change-cows-dairy/
15. Holland.com (2022). The Floating Farm in Rotterdam. https://www.holland.com/global/tourism/get-inspired/current/greener-cities/floating-farm-in-rotterdam.htm
16. Dezeen (2022). Floating Office Rotterdam: Powerhouse Company Builds Off-Grid Floating Office. https://www.dezeen.com/2022/10/24/floating-office-rotterdam-powerhouse-company/
17. Sempergreen (2021). Floating Office Rotterdam – A Unique Office Building with Green Roof. https://www.sempergreen.com/en/about-us/news/floating-office-rotterdam
18. LoopNet (2022). Floating Office Rises Above Threats of Climate Change. https://www.loopnet.com/learn/floating-office-in-rotterdam-rises-above-threats-of-climate-change/1601197803/
19. Powerhouse Company (2021). Floating Office Rotterdam. https://www.powerhouse-company.com/floating-office-rotterdam
20. Schoof, J. (2022). *Floating Office Rotterdam by Powerhouse Company*. [online] Detail.de. Available at: https://www.detail.de/de_en/floating-office-rotterdam-von-powerhouse-company.
21. RIBAJ (2021). Floating Sustainable Office in Maas River. https://www.ribaj.com/buildings/floating-office-rotterdam-maas-river
22. Korea Tourism Organization (2022). Sebitseom: Floating Islands on the Han River. https://english.visitkorea.or.kr/enu/ATR/SI_EN_3_1_1_1.jsp?cid=1998219
23. Naeway News (2023). Sebitseom Floating Islands. https://www.naewaynews.com/666
24. YouTube Video [Sebitseom Floating Islands Overview]. (2023). https://youtu.be/n4HahNDVlrE?si=XPVDotcYa25_ZTzd

APPENDIX B

I. AIRPORT TERMINAL AS A LARGE-SCALE INFRASTRUCTURE

This research uses Rotterdam the Hague airport terminal as a case of large-scale infrastructure. This section discusses the energy and water consumption.

II. AIRPORT TERMINAL ENERGY CONSUMPTION

Getting annual energy consumption report of the airport was not possible due to the report is reserved for internal use. Therefore, the energy consumption will be assumed by comparing to Nanning airport in China. According to Xianliang et al, 2021, average value of energy consumptions including terminal buildings and cooling plants were 180 kWh/m2/year. Among the total airport terminal energy consumption, the cooling plant remained as the largest single source constituting 31.8-33.8%, and HVAC systems followed with a percentage of 15.9-17.4%. In the assumption that the Rotterdam the Hague airport is 7100m^2 in total, the terminal building will consume 1,278,000 kWh of energy per year. Apart from cooling plant and HVAC, the research will proceed with the assumption as below.

Table 1. Comparison of energy and water recycling.

Annual energy consumption: 180 kWh/㎡/year **Total Annual Energy Consumption: 1,278,000 kWh/year**	
Systems	**Energy consumption**
Cooling plant	406,404 kWh/year (31.8%)
HVAC	222,372 kWh/year (17.4%)
Lighting & Electrical	255,600 kWh/year (20%)
Baggage handling	127,800 kWh/year (10%)
Commercial facilities	153,360 kWh/year (12%)
Elevators / Escalators	102,240 kWh/year (8%)
Other systems	10,224 kWh/year (0.8%)
Total daily consumption: 3,501 kWh/day	

However, since Nanning is in subtropical monsoon climate zone and Rotterdam is in oceanic climate zone, they will show difference in energy consumption. According to Weather Spark, average summer temperature in Nanning ranges between 26 to 32°C and Rotterdam ranges between 13 to 21°C. Nanning will show a significantly increased demand in cooling energy, and Rotterdam will account a large portion of building energy consumption in heating system. Therefore, overall HVAC energy consumption is likely to be higher in Nanning.

III. AIRPORT TERMINAL WATER CONSUMPTION

Airports has large water consumption. According to (Vurmaz & Boyacioglu, 2018), consumptions are generally for non-potable purposes such as water cooling systems, fire control, cleaning and washing vehicles, runways and aircrafts. The research also showed that the water consumption of an airport located in Turkey was about 436000m^3/year. Irrigation, fire control system, cooling towers, and terminal WC accounted with rate of 23%, 7%, 26% and 20%. Water used for WC ranged between 6-8.5L per passenger, and 1-1.5L per passenger for food consumption. According to an annual report in 2014, the drinking water consumption per passenger of Rotterdam the Hague airport was 9.6 litres (Royal Schiphol Group, 2014). This includes all drinking water used at catering outlets, toilets, drinking fountains and the offices above the lounges. The number of passengers this research uses was 12 million. There were 2.2 million people travelled through Rotterdam the Hague airport in 2023 (Royal Schiphol Group, 2024). Therefore, using this ratio, this research will use the assumption as below:

Table 2. Comparison of energy and water recycling.

Water Consumption per Passenger: 9.6L(=0.0096m^3) **Total Annual Water Consumption: 105,600m^3**	
Activities	**Water consumption**
Irrigation (23%)	24,288m^3
Fire control system (7%)	7,392m^3
Cooling towers (26%)	27,456m^3
Terminal WC use (20%)	21,120m^3
Others (24%)	25,344m^3

IV. PRECIPITATION OF ROTTERDAM

According to Royal Netherlands Meteorological Institute, monthly and yearly precipitation sums is as follows:

Table 2. Comparison of energy and water recycling.

YY	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Sum**
2014	803	801	333	276	902	264	665	1471	161	695	521	1127	8019
2015	1043	718	573	177	435	211	831	1453	1158	319	1425	601	8944
2016	1477	731	686	718	501	1619	248	733	223	698	938	139	8711
2017	648	675	546	326	324	449	1408	862	1852	842	946	1488	10366
2018	781	340	684	1072	540	209	137	720	917	600	262	937	7199
2019	639	686	920	265	463	914	575	559	939	1041	1171	674	8846
2020	405	1373	578	138	75	1363	764	666	882	1518	527	1007	9296
2021	976	461	323	524	1168	760	778	658	288	1430	601	524	8491
2022	457	1005	119	316	526	794	104	233	1838	457	1215	895	7959
2023	1476	210	1100	710	406	51	1067	904	788	1839	1796	977	11324
Average annual rainfall: (801.9+894.4+871.1+1036.6+719.9+884.6+929.6+849.1+795.9+1132.4)/10=891.55mm													

References

1. Xianliang, G., Jingchao, X., Zhiwen, L., & Jiaping, L. (2021). Analysis to energy consumption characteristics and influencing factors of terminal building based on airport operating data. Sustainable Energy Technologies and Assessments, 44. https://doi.org/10.1016/j.seta.2021.101034
2. Özlem Vurmaz, M., & Boyacioglu, H. (2018). Airport Water Consumption Footprinting. Environment and Ecology Research, 6(6), 519–524. https://doi.org/10.13189/eer.2018.060601
3. Schiphol.nl. (2021). Schiphol | Archive of Schiphol Group's Annual Report. [online] Available at: https://www.schiphol.nl/en/schiphol-group/archive-annual-reports/ [Accessed 14 Jan. 2025].