JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN), Committee on Agronomic Sciences
Section of Land Reclamation and Environmental Engineering in Agriculture
Institute of Technology and Life Sciences (ITP)

JOURNAL OF WATER AND LAND DEVELOPMENT
2020, No. 47 (X–XII): 96–104
https://doi.org/10.24425/jwld.2020.135036

Available (PDF): http://www.itp.edu.pl/wydawnictwo/journal; http://journals.pan.pl/jwld

Received 06.10.2019
Reviewed 03.06.2020
Accepted 20.07.2020

Climate change-oriented design: Living on the water. A new approach to architectural design

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For citation: Januszkiewicz K., Gołębiewski J.I. 2020. Climate change-oriented design: Living on the water. A new approach to architectural design. Journal of Water and Land Development. No. 47 (X–XII) p. 96–104. DOI: 10.24425/jwld.2020.135036.

Abstract

The paper deals with the digital architecture concept which is trying to introduce a new spatial language into the context of water urbanism, using nature as a model, measure and mentor. The first part analyses Biomimetics with its design strategies and methods. The Problem-Based Approach (designers look to nature for solutions) and the Solution-Based Approach (biological knowledge influences human design) are defined here. In the second part of the research, the authors present selected examples to the topic. This case study has demonstrated that a new approach to architectural design is emerging. This approach redefines the process of architectural design, understood not as the traditional shaping of the object's form, but as a compilation of various factors resulting from changeable climate characteristics and ecology. The conclusions emphasize that not only the contemporary understanding of ecology should be changed, but also the way architects approach the built environment, especially in the aquatic environment.

Key words: *architecture, climate change, design, environment, floating cities, parametric architecture, water urbanism*

INTRODUCTION

Conceptualizing and envisioning the built environment for the challenges of climate change were initiated in the first decade of the 21st century. Since then, various architectural concepts have been created, opening new fields of research for the theory of contemporary architecture. Extreme weather events and the consequences of climate change – discussed during the 2015 World Climate Conference held in Paris – remind us how this theme is of central importance. UN-Habitat is looking at high-tech urban islands and self-sufficient floating cities as a potential survival kit for communities who have found themselves at risk from the rising sea levels [UN 2019]. These challenges urge architects and urban designers to develop innovative ideas on how to live on the water during and after the climate change era. The term "climate change" refers to a large-scale, long-term shift in the planet's weather patterns and average temperatures. The climate has always changed naturally, but when we talk about climate change, it means that the climate is changing at a more rapid pace than what it used to through the history of the Earth. Biomimetics offers strategies that professionals of the built environment can harness to adapt buildings to climate change. The first and most common one is responding to the anticipated direct impacts of climate change on the built environment. A second strategy is a comprehensive approach to altering the built environment so that it becomes more adaptable and resilient as a whole system.

The living world is made up of a variety of organisms that effectively solve the same problems that the built environment will face as climate change continues. According to [PURVIS-HECTOR 2000], while the potential impacts of climate change are numerous and dependent on local conditions, the list of organisms and ecosystems that effectively manage similar issues is also a long one. Research studies on aquatic environments that have been performed in the past decades demonstrate the advantages of mimicking eco-processes to create resilient and effective ecosystems. Typically, such systems mimic the aspect of ecosystems where waste becomes a resource for another component of the system, or where energy is shared which eliminates duplication of individual effort. The built environment is increasingly held accountable for global environmental problems, with vast proportions of waste, material and energy use, and greenhouse gas emissions attributed to the habitats that humans have created for themselves. Long-term responses to adapting the built environment to the impacts of climate change are urgently needed [ROAF *et al.* 2005].

The research aims to demonstrate the possibilities for the application of living nature metaphors in designing a floating built environment as well as to find an answer to the question of whether such inspired architectural forms are predisposed to adapt to conditions compatible with changeable climate characteristics and ecology.

In the 21st century, inspired by the biological evolution and morphogenesis of organisms, recent advances in the discipline of evolutionary computation propose an innovative approach in envisioning future opportunities to live on the water. Currently, there is, at least to a certain degree, an exchange of ideas and techniques between architecture and other disciplines such as biology, physics, chemistry, and mathematics to mimic the identified biological processes. The focus is mainly on natural processes of formation and adaptation which occur in Nature, on the instrumentalization of these processes through mathematical models and IT techniques, as well as on their simulations and digital visualizations. This approach to design diametrically changes an ancient concept of imitation and mimesis in the western tradition of aesthetics [KNIPPERS 2009].

In the first part of the research, the authors analyse design strategies and design processes which inspired new visions of living on the water. In the second part of the article selected examples of the visionary floating cities are indicated. These objects have been grouped according to the research criteria (object modelling and process modelling). Several noteworthy contemporary examples of biomimetic architecture or technologies in forming visions of floating cities will be examined in the following sections.

MATERIALS AND METHODS

THE ANALYSIS OF FACTORS INFLUENCING THE DESIGN OF FLOATING CITIES

The analysed examples of floating cities show how the above strategies allowed to solve design problems related to floating cities. As part of the research, a wide analysis of floating city projects, emerging from the 1960s to the present day, was conducted. Particular attention was paid to the analysis of diagnosed technical, functional, and material problems that must be solved to colonize sea waters safely and cost-effectively. The analysis unequivocally confirms that the transition to designing cities on the water depends primarily on their achievement of structural strength and self-sufficiency. The Table 1 is a summary of the query carried out among the vision of floating cities and presents the main challenges and problem issues that a man must meet to colonize seas and oceans.

Visions of floating cities emerging in 21 century show a trend in which solutions to these problems are sought in biomimetic. By colonizing the seas and oceans, we cannot shape the new human life environment in a way we know from our history. Floating cities should be made better than those we've built on land for centuries. They must be threat-resistant, self-sufficient, and environmentally neutral. Nature or, more broadly, biological sciences suggest

Table 1. Challenges in the design of floating cities and conditions that should be met

Challenge	Condition
Structural stability	resistance to sea waves and wind
Energy self-sufficiency	obtaining clean energy and diversification of energy sources
Independence and self-sufficiency of raw materials	acquiring environmentally neutral and ecological materials for building and developing floating cities
Independence and self-sufficiency in nutrition	traditional and aquaponic farming
Environmental neutrality	use of technologies limiting the negative impact on the environment

Source: own elaboration.

possible solutions. Examples could be organisms that have adapted to life in adverse conditions and are self-sufficient. We can also try to imitate the processes occurring in nature to optimize the process of formation and transformation of floating cities.

BIOMIMETIC DESIGN THINKING AND DIGITAL TOOLS

There is no real difference between the terms "biomimicry" and "biomimetics", however, "biomimicry" is used in developing sustainable design solutions, and "biomimetics" has been applied to technologies honed from bio-inspired engineering at the micro- and macro-scale levels [BENYUS 1997]. Biomimicry is used as a design strategy in the field of architecture. There are two distinct approaches to biomimicry as a design approach: the problem-based approach and the solution-based approach [ZARI 2007]. These approaches each have their advantages, disadvantages, and outcomes in terms of overall sustainability.

This problem-based approach was found to have different namings in various literature items such as "biologically inspired design", "problem driven biologically inspired design" [HELMS *et al.* 2008; 2009] and "top-down approach" [KNIPPERS 2009] (Fig. 1), all having the same meaning. In this approach, designers look to nature for solutions, recognize their design problem, and look at how organisms and systems in nature have solved similar problems. One possible drawback of this design approach is that the issue of how buildings correlate with each other and the ecosystem they are part of is not investigated. Therefore, the underlying causes of non-sustainable or even degenerative built environments are not necessarily addressed. Nevertheless, the problem-based approach may be a good way to begin the transition of the built environment from inefficient to a more sustainable one.

The solution-based approach is also referred to as "biology influencing design", "bottom-up approach" or "solution-driven biologically inspired design". In this approach, biological knowledge influences human design. One of its advantages is that the knowledge of biology may influence the design in ways other than the predetermined design problem. Digital morphogenetic tools can play a special role here. Integration of tools allowing imitation of processes such as material self-organization, digital

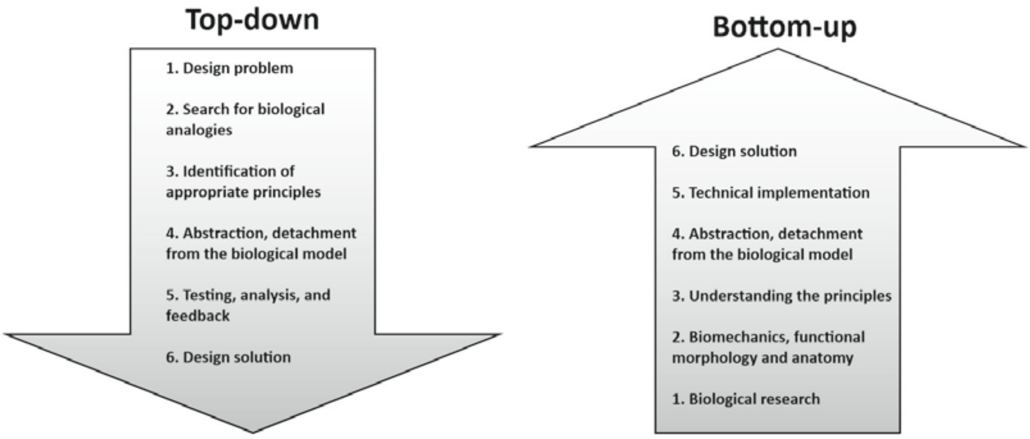

Fig. 1. Biomimicry top-down and bottom-up approaches; source: own elaboration

morphogenesis, associative parametric modelling, and computer added manufacturing is desirable. These tools allow imitating the form-forming processes that occur in living nature. One disadvantage is that in-depth biological research must be conducted, then the information gathered must be determined as relevant in a design context [ZARI 2007]. Over the years, the biomimetic approach to technology and innovation has increasingly received attention as an alternative for the ecosystem-destroying technologies of the industrial age. Such thinking might lead some to reconsider the very nature of architecture itself. Biomimetic design thinking as a way of viewing and valuing nature introduces an era based not on what we can extract from the natural world, but what we can learn from it. It is one of the fields where architects, biologists, environmentalists, to name but a few, can all work together for a better sustainable living.

RESULTS

MIMICKING AQUATIC PLANTS AND CREATURES

One of the most important problems facing the creators of water cities is the solution of structural problems. Until now, man constructed small housing units and placed them on the water – often in ports or bays – in a relatively safe environment. Building cities in open waters, such as oceans, presents us with completely new challenges – resistance to harsh weather conditions and the need to transfer very heavy loads – multi-functional, multi-story structures. Vincent Callebaut is one of the most attentive observers of nature, which inspires him to create bold visions of the future of human habitats. In Lilypad project the floating city draws on examples from the water plant from the Nympheas family (*Nymphaeaceae*) example. *Victoria amazonica* is a species of water lily characterized by high buoyancy, which reaches a size of up to 400 cm in diameter. Good structural properties of the leaf are obtained due to the education from below the ribs, which form slats, reaching up to 6 cm in height. These slats are made of tissue abundant in the air, thanks to which the plant perfectly floats slightly above the water. The leaf edge is folded up to prevent water from flowing in, while rainwater is drained through a system of small channels. Lilypad (Fig. 2) takes the example of *Victoria amazonica*'s structural solutions. The multi-rib, radially propagating structure provides the city with stability in ocean waters, protects against the threat of pouring water, and enables the construction of a multi-story, multi-functional structure. In addition, Lilypad absorbs carbon dioxide like other plants. With double coating, made of polyester fibers with a layer of titanium dioxide (TiO_2), Lilypad would neutralize air pollution. Trough the use of these technologies, the city will reach a positive energy balance at zero carbon emissions. According to the assumption, the Lilypad would be a multicultural floating Ecopolis, whose metabolism would be in perfect symbiosis with the cycles of nature [CHEN 2011].

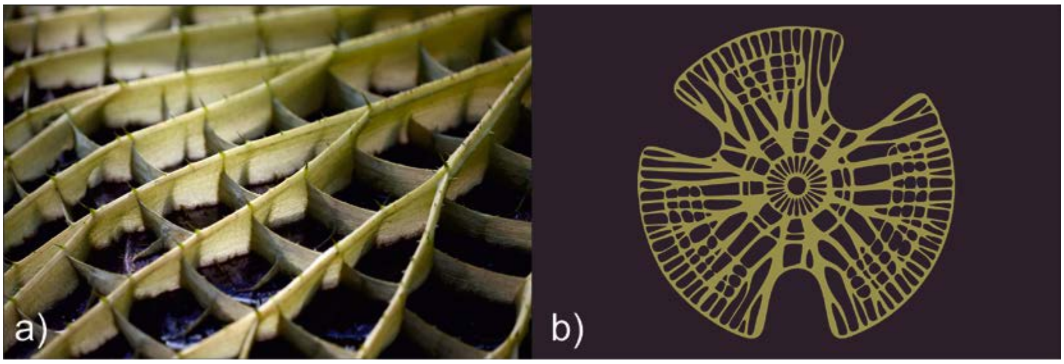

Fig. 2. Example of nature inspiring in architectural design: a) structure of the *Victoria amazonica* leaf (phot. Laitr Keiows), b) structure of Lilypad project by Vincent Callebaut; source: own elaboration, based on Vincent Callebaut Architectures [undated]

Aequorea – the underwater eco-village (2015) is another Callebaut project looking for structural patterns among organisms living in the water. Aequorea (Fig. 3) project imagines entirely self-sufficient, spiraling "ocean-scrapers" reaching to the seafloor. The shape of the city was inspired by crystal jelly (*Aequorea victoria*).

The main structure of the city would be constructed by using recycled plastics from the Great Pacific Garbage Patch. The expansion process would be continued by eco-friendly, natural calcification, by fixing the calcium carbonate contained in water. This phenomenon allows the self-building of the outer skeleton in the same way as in the seashells formation. The spiral form of the towers increases their resistance to hydrostatic pressure, and also makes the city resistant to water whirlpools. To provide the city with even better static, a double shell containing a ballast was created. When filled with water, it counteracts the Archimedean buoyancy. Innovative materials are also important for the project. By using aragonite in the transparent façades, an Aequorea can fix 2,500 tons of additional CO_2 per square kilometer. For the creation of internal partitions, it is planned to use synthesized chitin, which also forms a crust of organisms such as lobsters [Vincent Callebaut Architectures undated].

Examples presented above are the successful mixing of nature's shapes at all scales. This is almost simply copying natural shapes or forms in a plan, section, elevation, or in ornamentation, which is possible with digital 3D free-form modelling software based on NURBS (Non-Uniform Rational B-Splines). These shapes taken from nature are used to solve the design problems facing the creators of floating cities. Lilypad and Aequorea derive patterns from living organisms for design concepts defined in various ways. While Lilypad primarily colonizes the surface of the oceans, Aequorea also explores depths. The form of the water lily more closely matches the static role of Lilypad, while the jellyfish form is optimal for the drifting city of Aequorea. An important aspect of the projects is their energy neutrality as well as food and material self-sufficiency. The success of floating cities can only consist in becoming independent of the mainland. Transporting food or building materials would be uneconomical, risky and excessively burden the environment. Therefore, both projects provide their residents with independent access to food, clean and safe energy sources as well as building materials obtained directly from the ocean, thanks to which cities can achieve environmental neutrality, which is very important in the era of climate change. The phenomenon of Lilypad and Aequorea consists not only in effectively imitating the shapes of nature but also the integration of these forms with technological solutions, that can make cities on the water a better place to live than cities on land.

The Table 2 shows, achieving the expected self-sufficiency of floating cities is only possible with the synergy between efficient and purposeful imitation of nature, the use of digital design tools – enabling mapping of nature

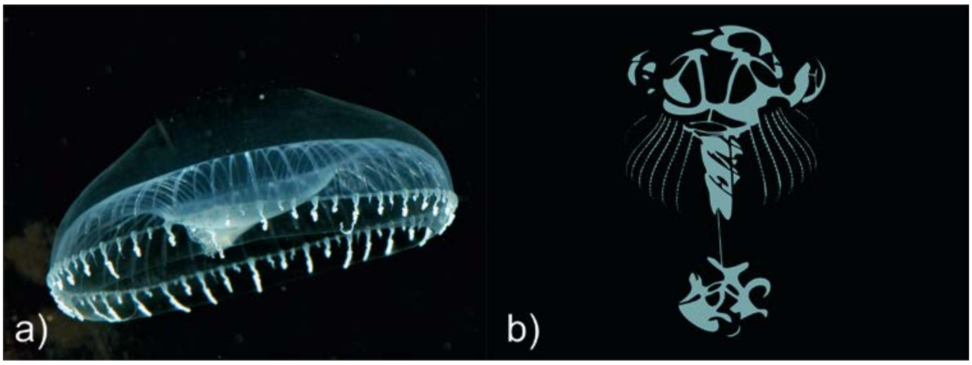

Fig. 3. Example of nature inspiring in architectural design: a) crystal jelly (Aequorea Victoria) (phot. *Sierra Blakely*), b) Aequorea project by Vincent Callebaut; source: own elaboration based on [Vincent Callebaut Architectures undated]

Table 2. Challenges and problems in the design of floating cities and their solutions contained in Lilypad and Aequorea projects

Challenge	Solution	
	Lilypad	Aequorea
Structural stability	stability based on the structure of *Victoria amazonica* leaf	stability based on the shape of crystal jelly – *Aequorea victoria*
Energy self-sufficiency	– solar, thermal and photovoltaic energies, wind energy, – hydraulic, tidal power station, – osmotic energies, – phytopurification, biomass	– ocean thermal energy conversion (OTEC), – tidal power station, – green-algae bioreactors
Independence and self-sufficiency of raw materials	– polyester fibres	– "algoplast" – a composite material that mixes algae with oceanic garbage, – chitin
Independence and self-sufficiency in nutrition	– biodiverse farming in the central lagoon	– algae, plankton and mollusks, – community horticultural greenhouses, – organic farming fields, – orchards and vegetable gardens
Environmental neutrality	– absorbing the atmospheric pollution by TiO_2, – collecting and purifying the rain waters	– CO_2 reduction due to the use of argonite in facades, – microalgae green-algae based bioreactors that recycle organic waste

Source: own elaboration.

as well as the integration of newly created forms with modern technologies, processes, and materials.

TOWARDS MODELLING PROCESSES AND DESIGNING BEHAVIOURS

The Floating Biotic City (2012) was developed by Jessica Hernandez, Edgar Garcia and Bing Bai at the Rensselaer School of Architecture as part of the "Geofutures" program (Fig. 4). The location was chosen to protect this area from further pollution. Using aggregation behaviour, the initial systems based on orthogonal mesh grow in two layers towards the most polluted area of the islands. After this process, the deformation behaviour is used to deform orthogonal mesh and to create habitats for animals and humans. The lower mesh has the ability to adapt to the

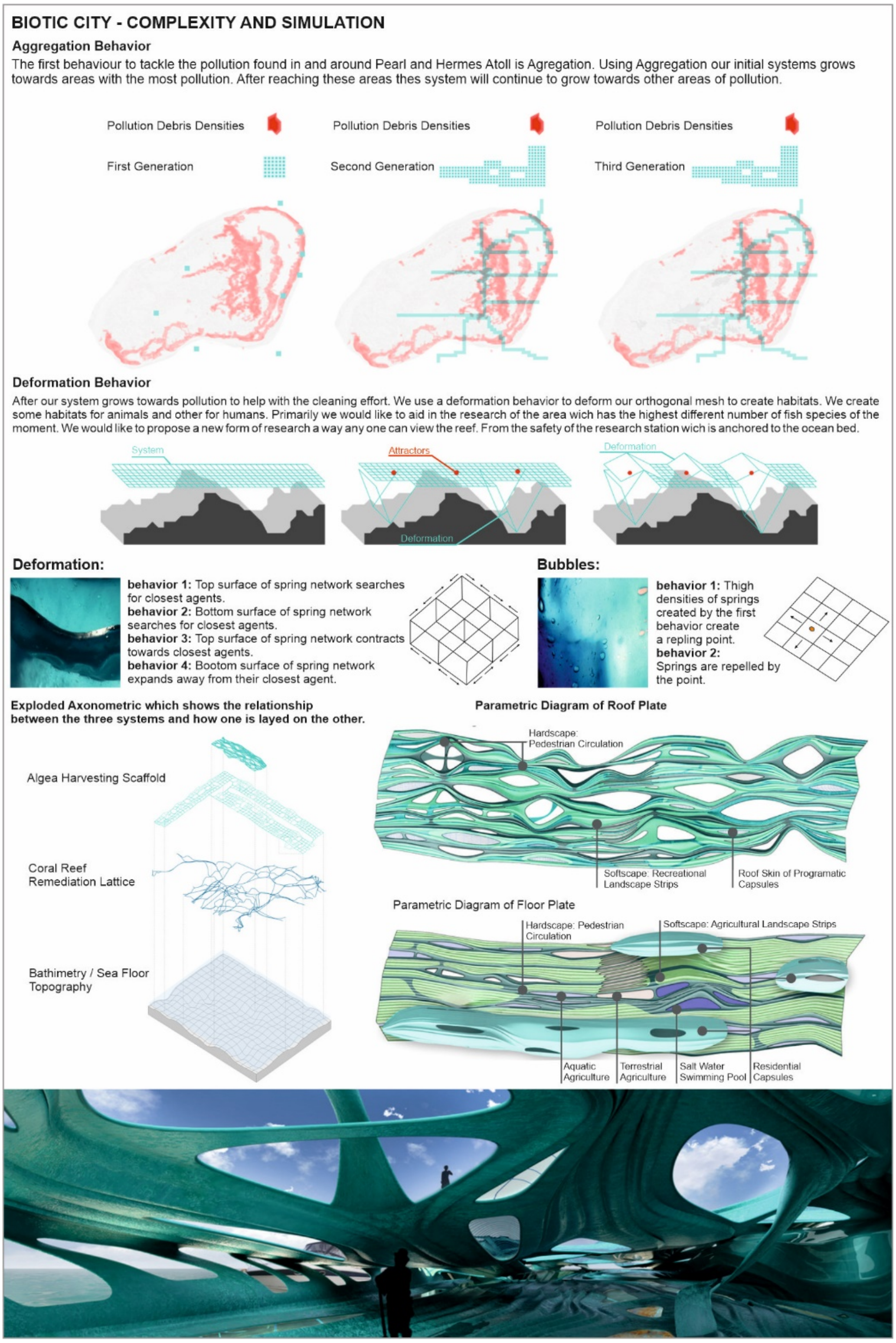

Fig. 4. The Floating Biotic City; source: COHAN [2013] and Neopictonic… [undated]

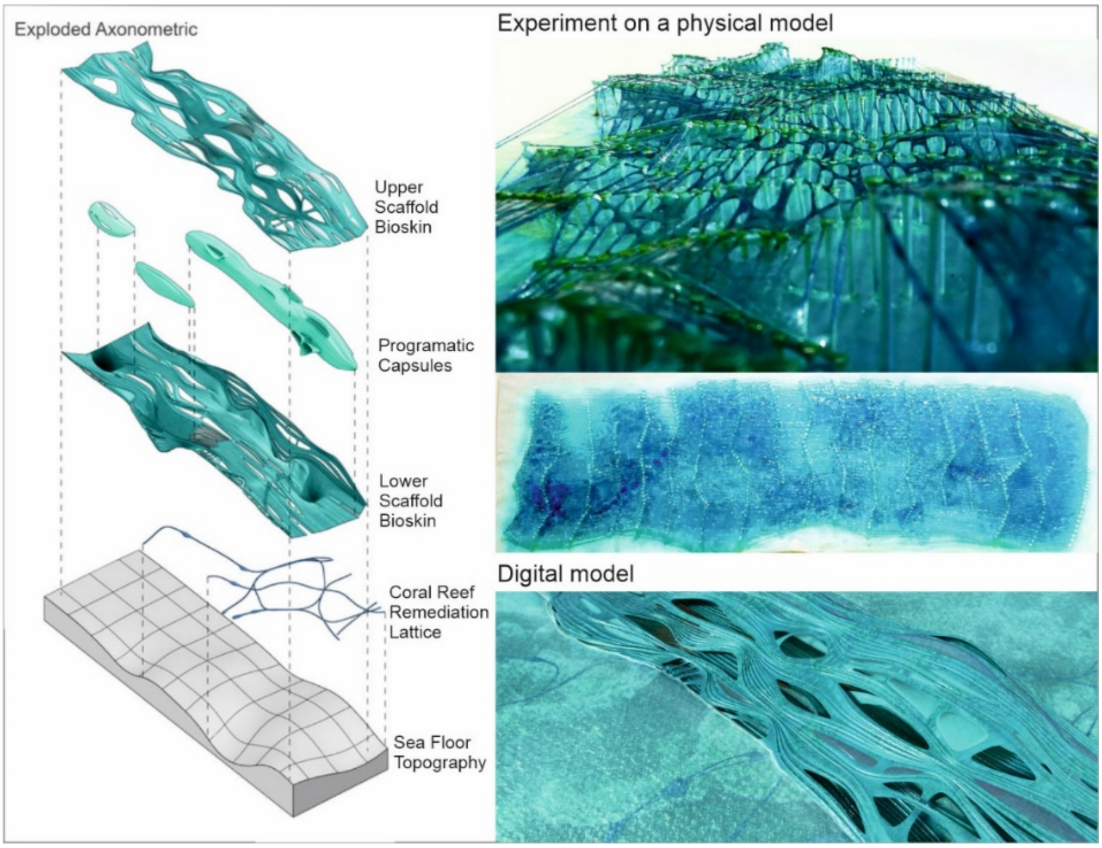

Fig. 5. The Floating Biotic City – main "layers" of the city structure; source: COHAN [2013] and Neopictonic… [undated]

seabed topography by creating niches that enable aquaculture and research. The upper mesh is deformed by attractors. At the same time, floating scaffold allows the growth and harvesting of seaweed, from which seaweed calcium and biopolymers are extracted to create the basic structure of the floating city. A complimentary part of the system is also coral reef remediation lattice, which levitates close to the seabed. This system collects pollutants from the area of coral reefs and discharges them out of the aquatic environment.

The city consists of two basic levels, accessible to residents: the lower and upper scaffolding. The scaffolding, through deformation, gains the target shape covered with bio-skin (Fig. 5). In the case of the bottom scaffolding, apart from public spaces and communication routes, there are areas for water and land farming. Residential and functional capsules are located between the two layers of scaffolding.

The Biotic City project is an attempt to combine local pre-industrial building practices with advanced digital technology from the post-industrial era. Thus, the project aims to rebuild more close relationships between man and nature in his habitat. In this case, the designers employ physical models expressed mathematically in the digital realm to mediate or iteratively map between the two distinct physical entities (environment and object) until convergence criteria are achieved [COHAN 2013].

A similar approach to new water urban planning was used in the Sea Garden City project (2013) by Huanyu Guo, Bhawy Joshi, and Sisi Qian, in which the authors are also looking for a model of coexistence of living space and food production (Fig. 6) [PERRY 2013].

In this case, the housing units are located among agricultural ranges and ponds desalinating water for the needs of the city. In the structure of agriculture belts, we can also find pools harvesting rainwater. At the same time, this structure provides shelter for various types of living organisms and animals. Thus, the project responds to the challenges of a new era in which the needs of people and nature will become closer. The urban tissue of this floating city is decentralized – composed of porous, annular structures, named by authors as the "urban loop". Its advantage is flexibility, which allows it to adapt to changing weather conditions prevailing in the oceans, as well as to variable population density. The urban loop consists of functional capsules strung on the structural and infrastructural lattice for human and resource circulation. Functional capsules play a residential, commercial, and cultural role, besides there are landscape capsules for recreation and ballast capsules that allow maintaining the stability of the entire structure on the ocean. Based on the structural lattice, the system of capsules can be expanded as needed. The building material is obtained from sea salt extracted in filtration pools. Water salinity also has a significant impact on the shape of the city. Using generative tools, models are created that determine the degree of density and shape of urban loops, based on the level of salinity in a given location. By technologies used in the project, Sea Garden City has an opportunity to become an example of post-territorial and post-national urban planning.

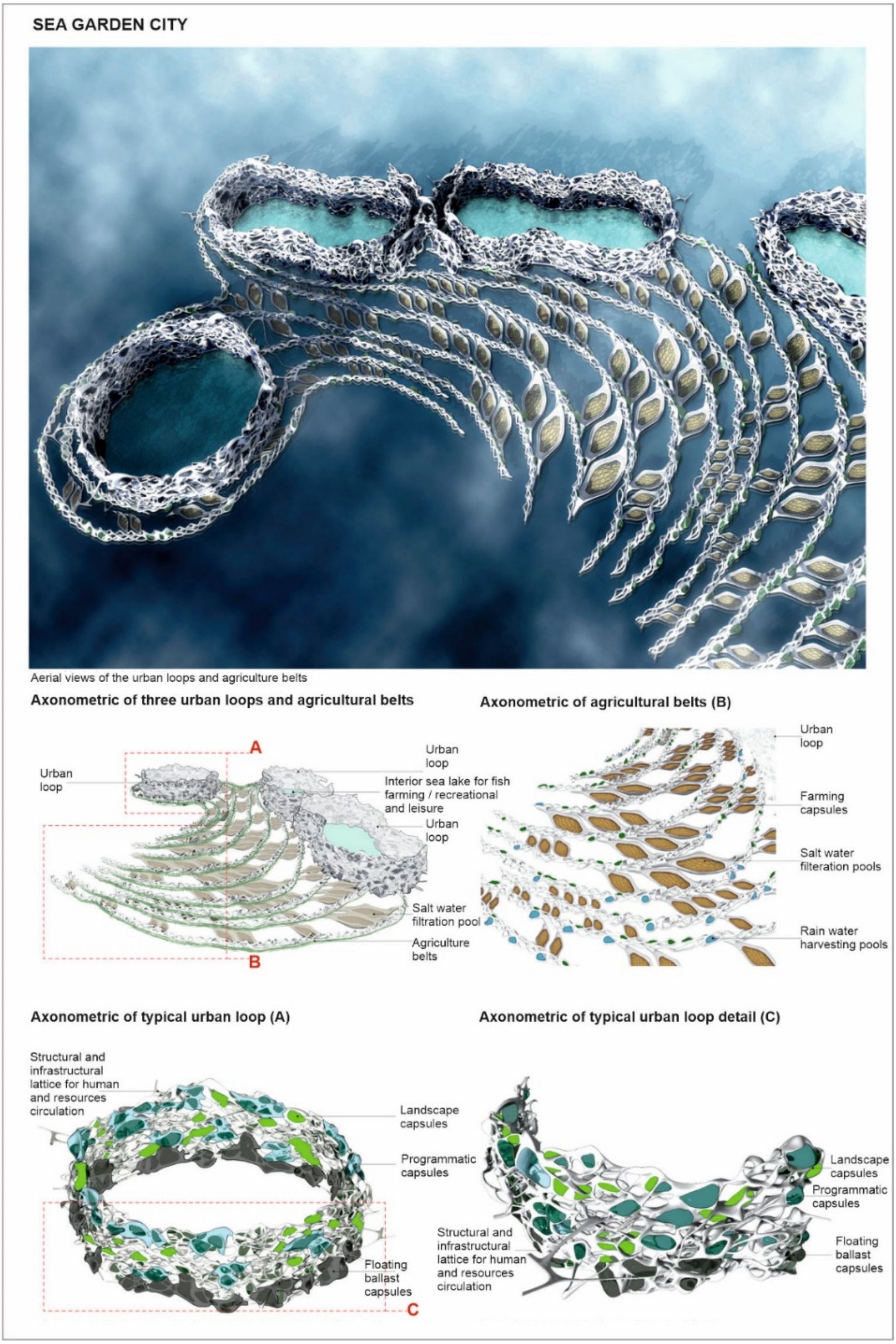

Fig. 6. Sea Garden City; source: Architizer [undated] and QIAN [undated]

In the examples presented, we also find solutions that provide floating cities with appropriate static conditions and self-sufficiency however, they are based on modelling processes and designing behaviours. An additional aspect undertaken here is increased sensitivity to the surrounding environment and adaptability to its changing conditions. In the case of Biotic City and Sea Garden City, the processes of interaction with the surrounding ecosystem are of great importance and they are the ones that largely decide on the final urban and architectural form. The Table 3 illustrates how the presented projects respond to defined problem issues regarding floating cities. As we can see, the authors of the projects focus on various issues related to ensuring cities' nutritional self-sufficiency or environmental neutrality, bypassing specific solutions for energy self-sufficiency. However, the examples presented should not be considered as fully developed implementation solutions. A variety of generative processes and the resulting structural and material solutions point to the great potential of a given strategy in the design of floating cities and contributions to further research.

Table 3. Challenges and problems in the design of floating cities and their solutions contained in Biotic City and Sea Garden City projects

Challenge	Solution	
	Biotic City	Sea Garden City
Structural stability	orthogonal mesh adaptable to the seabed topography	porous, annular structures with ballast capsules
Independence and self-sufficiency of raw materials	extracted seaweed calcium and biopolymers	material is obtained from sea salt extraction
Independence and self-sufficiency in nutrition	the structure creates spaces convenient for agriculture and aquaponic cultivation	desalinating water ponds structural agriculture belts pools for harvesting rainwater
Environmental neutrality	coral reef remediation lattice that collects pollutants	human and resource circulation – flexibility to population density

Source: own elaboration.

The case study of envisioning floating architecture and urbanism presented above (selected examples) has demonstrated that a new approach to design is emerging. The architecture has reached an exciting stage in its development, where structures are attempting to behave more like nature, which does not function as a static state, but as a complex grouping of symbiotic processes which are constantly evolving to adapt to environmental changes. The transition from computer-aided to computational design entails a shift from:

– modelling objects to modelling processes,
– designing shape to designing behaviour,
– defining static digital constructs to defining computing systems capable of reciprocal data exchange and feedback information [MENGES 2012].

This approach has shifted the process of architectural design from the traditional shaping of the object's form but as a compilation of various data from changeable climate characteristics and ecology. In the biomimetic design approach presented above, the physical constraints and material properties, together with the constraints of production, fabrication, and construction, can be encoded in generative computational processes.

The digital instrumentalization of morphogenetic and evolutionary or other emergence processes, along with the proposed methods and techniques, makes it possible to apply these patterns in the architectural and structural designs, and their use in designing eco-effective solutions for architecture. Any specific form or structure derived through these subsequent processes remains fully coherent with the logic and limits of materialization.

DISCUSSION

The conducted research into envisioning floating architecture and urbanism for the challenges of the climate change effects has also allowed to identify two important design strategies, such as the emergent morphogenetic design strategy and material ecology.

The emergent morphogenetic design strategy includes emergence, evolutionary optimization, or morphogenetic design. This strategy utilizes tools in parallel that have been developed independently by different disciplines, including theoretical mathematics, materials engineering, bio-mimicry, environmental studies, and digital technologies [GUNTER 2010]. Emergent morphogenetic designs provide a superior architectural response to programmatic, technical, structural, environmental, and spatial requirements that conventional unit-based architectural forms are too inflexible to fully address. This shift from knowledge-based to behaviour-based computational design and the related development of biomimetic computational design processes not only entails a change in the conceptualization of architectural performance but also in architectural aesthetics.

Material Ecology establishes a deeper relationship between the design object and its environment. The key to this strategy is the realization that the environment and the design object interact through multiple dimensions and a spectrum of environmental variables.

A simple analysis would show that the dimensionality of environment space is much larger than that of conventional design space. This strategy is denoting informed relations between products, buildings, systems, and their environment. Material ecology aims to bridge this gap by increasing the dimensionality of the design space through multifunctional materials, high spatial resolution in manufacturing, and sophisticated computational algorithms. In doing so, a holistic view of design emerges that considers computation, fabrication, and the material itself as inseparable dimensions of design which results in objects that are ecological from the outset [OXMAN 2010] or even from cradle to cradle.

However, it is important to be aware that not all solutions arrived at through evolutionary processes found in organisms will be perfect, or suitable for a human context. Despite this, the built environment needs to solve more urgent and difficult problems related to the impacts of climate change, it is appropriate to examine examples of how the same problems have been solved by other living organisms or ecosystems in the same climatic conditions as humans. If not providing full and easily transferable solutions, it may at least provide new areas of exploration.

CONCLUSIONS

The ideas posited in this paper demonstrate that the greatest potential of biomimetics to assist in the mitigation of anthropogenic phenomena and to adapt to climate change impacts is in the mimicry of living nature. By devising principles for the application of biomimetics to the built environment, it is anticipated that designers can begin to understand how to utilize ecology knowledge beyond the level of a metaphor. Advanced material and morphogenetic digital design technics and technologies call for a higher level of methodological integration which poses a major challenge for the next generation of multidisciplinary architecture research and projects. Floating architecture and urbanism have adopted new forms and systems which demand both new tools and a new approach to design.

A new approach to design is expected, which will be defined as an adjustment of conditions compatible with changeable climate characteristics and ecology. In architecture, the approach should redefine an architectural design process not as the shape of the material object alone, but as the multitude of effects, the milieu of conditions, modulation and microclimates that emanate from the exchange of object with its specific environment – as a dynamic relationship that is both perceived by and interacted with a subject. An intention of this kind of design should eliminate negative environmental impact through skillful, sensitive design. This requires a view broader than ever, with a heavy emphasis on various interdisciplinary aspects. The main mission of the climate change-oriented design would be to build its interpretation and implementation of the environmental systems thinking. However, responding to the direct impacts of climate change has several associated benefits and difficulties. To build the floating environment to live on the water, it is helpful to gradually respond to the impacts of climate change, particularly if the financial resources needed to research, develop and test technologies continue to be available.

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