BIOACTIVE DEVICES AS SELF-SUFFICIENT SYSTEMS FOR ENERGY PRODUCTION IN ARCHITECTURE

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ABSTRACT

Using bioenergy systems in architecture provides energy by means of negative emissions technologies (NETs). It plays an important role in stabilizing CO_2 emissions at low levels. This depends on options of low life cycle emissions (for instance, a sustainable use of biomass residues), and on outcomes that are site-specific and rely on efficient integrated systems that convert biomass into bioenergy. The objective of this study is to develop self-sufficient systems that generate bioelectricity and offer safety, electricity generation efficiency, cost-effectiveness, waste treatment, integration in domestic use, ease of use, reproducibility and availability. The study also intends to elaborate a general design method of embedding and utilizing microorganisms into architectural elements to achieve design ecology, introducing a multidisciplinary research application through a design theory aspect. The study is based on previous experimental work conducted by the authors. Microbial fuel cell technology was applied to exploit the natural potential of a fungal strain that was identified and optimized to be implemented in microbial fuel cells (MFCs) to generate electricity. The outcomes were included in the self-sufficient cluster design that meets the aforementioned conditions. The novelty of this study is the direct use of a bioreactor of MFCs in a design application for bioelectricity production. It aims to reduce the currently high global CO_2 emissions that come from the energy supply sector (47%) and from the building sector (3%), as well as to eliminate the need for large-scale infrastructure intervention. This self-sufficient bio-electricity cluster therefore outweighs other abiotic renewable energy resources such as solar energy or wind power.

KEYWORDS

bioelectricity, bioreactors, microbial fuel cells, bioluminescence, biodigital design.

1. DESIGN CRITERIA FOR BIOACTIVE DEVICES IN COMPLEX INTELLIGENT SYSTEMS

The design of bioactive devices proposed in the present study includes special methods and tools to develop self-sufficient systems and design ecology by integrating function, form, time and space in the bioactive design process. It is approached by means of bioactive devices in complex

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intelligent systems, which usually emerge from a top-down planning of variables, interactions, and boundaries, etc. (Johnson, 2001). However, in many cases they adopt a bottom-up methodology, including various scales of complexity. **The main complexity and adequacy lie in utilizing an active organism that performs specific biological functions that have a certain value in design ecology such as generating electricity, obtaining natural bioluminescence, producing oxygen and food through photosynthesis, etc.**

2. FUNCTION

Designing the function in bioactive devices exploits organic intelligence and potentials, mainly to harmonize with the natural eco-system (Westerhoff et al., 2014). A distinction is made between the mechanistic explanation and biological explanation. The mechanistic explanation categorizes a system into a number of functional components. It describes how these components are arranged, how their activities are organized in time, and it relates these features to some phenotypes (Boogerd et al., 2005). Mechanistic models are mathematical models related to the activities of cellular reaction networks involving transport, metabolism, signal transduction, or gene expression. Understanding why certain mechanisms exist requires a biological design explanation (Wouters, 1995; Wouters, 2007). Bioactive devices are complex semi-open systems. They selectively interact with their environments by way of mass and energy exchange. The decrease of free energy in the environment (less light, less electrical current) is coupled with the increase of the response of the bioactive system itself (Westerhoff, 1987). In other words, there is always a flow of mass and energy through the system, causing the emergence of a certain function. Thus, proposing the design of a bioactive device relies on both a biological and a mechanistic explanation. The bioactive functional design criteria are listed below.

2.1 Achieving ecological and sustainable architecture

In this context, bioactive design of devices emphasizes the integration of alive agents as part of the built environment, maintaining all their natural environmental conditions and their bio-abilities. This is a wider and a more invasive application in design than biomimicry, as bioactive design goes beyond just imitating natural laws and puts the very natural and bioactive agents into action by themselves. In order to achieve the ultimate integration of natural laws that would be inherited and activated by default and in a spontaneous manner, it obviates the need for designing each single function in a separate complex system and avoids facing the consequences of problematic relations and synchronization between all these reciprocal systems and functions. Moreover, this bioactive design uses the natural potential of bioactive agents to carry out various functions within an ecologic performance (for example, the natural potential for electricity production, bioluminescence, etc.). Those functions are inherited physiological processes that the bioactive agent normally fulfills for living. Thus, the bioactive design achieves a double benefit: proposing natural ecological solutions for the required functions in the built environment, as well as maintaining and enhancing the existence and richness of biodiversity within the ecosystem. The ecological criteria of bioactive design are the following: **meeting human needs, sustaining the integrity of function of natural and engineered ecosystems in the bioactive device and in the built environment, embedding the inherent properties of nature in the functional systems of the built environment, conserving natural ecosystems and indigenous biodiversity at viable levels, increasing environmental literacy to build**

social support for sustainable development, resource conservation, and dealing with bioactive systems (Shu-Yang et al., 2004). These principles are applied to the design process and operation of bioactive design in the built environment as follows:

- **Maintaining ecological integrity**
  This is accomplished by maintaining environmental conditions that support biodiversity and natural communities while also providing critical support for the human initiative. As such, the purpose of bioactive design is to integrate human activities and the required functioning systems with the structure and dynamics of natural flows and cycles of materials, organisms, and energy. This begins with the development of an understanding of the ecological context of a particular design case, and working towards solutions that are consistent with these circumstances. To achieve this, the designer must have a clear idea of both the activity being contemplated with its requirements and operative conditions, and the limitations of naturally embedded bioactive systems to support the design enterprise. The designer needs a detailed understanding of local ecosystems and environments, including climate, topography, and resources (soil, water, flows of energy and materials, biotic communities, and critical habitat). This information can be used to define the carrying capacity of the study region for the proposed activity, allowing the bioactive eco-design to be accommodated within the identified ecological limits.
- **Biocompatibility**
  Biocompatibility ensures bio/chemical–compatibility between bioactive agents (organism or any of its specific parts), the host components and the structure inside the bioactive device. In addition to compatibility between the host components (chemically, biologically, physically) along different operational phases, it guarantees compatibility between the bioactive device throughout its life cycle (of emergence, evolution, decay loop) and the surrounding environment. It also supports biodiversity in the surrounding environment through the compatibility with different species.
- **Biodegradability**
  Biodegradability focuses on the ability of the bioactive system to be absorbed by nature and to join the natural life cycle of the ecosystem at the end of its own life cycle, and not to generate waste that affects the ecosystem. This criterion includes both bioactive agents and hosts. Bioactive agents should not produce any toxins or pollutants in any phase of the operational phases of the bioactive device, and should be further exploited in the closed-loop bioactive system or in other useful recycling applications.
- **Increasing sustainability consciousness**
  Environmental protection is a broad societal responsibility. The use of bioactive systems is proposed not only for specialist use, but also for a wide spectrum of non-specialized users, as it entails close cooperation among designers, governments, stakeholders, and citizens. This aspect also achieves human sustainability through **biophilic design**, which describes the innate tendency of humans to focus on life and lifelike processes. This concept was later expanded to suggest "the innately emotional affiliation of human beings to other living organisms" Kellert and Wilson (2008). It emerges from the increasing recognition that the human mind and body evolved in a natural biodiverse world that is critical to people's health, productivity, emotional, intellectual and spiritual well-being.

2.2 Functional morphogenesis

Function growth and morphogenesis mean the ability of the system to adjust transition in its outer and inner phenotypes according to the evolution of its internal genotypes. The change in the system's genotypes evolves from the continuous responsiveness to its outer environmental conditions and inner capacities. This level of synchronization and sophisticated intelligence could be achieved via genetic manipulation in the organisms embedded in the built environment. As long as microorganisms are, fast, resistant and controllable in scale, they are the perfect material for such hybridization. Functional morphogenesis depends on two main aspects: reading the inner and outer environment and acting responsively according to the imposed conditions with suitable functional morphogenesis. In bioactive devices, there is a limitation in functional shifting in terms of formal and spatial compatibility of the new imposed function, limiting the responsiveness abilities of the bioactive device to predefined design and limited functional shifting. **Time, functional customization, scale, spatial recognition, spatial propagation and spatial orientation are the main attributes of bioactive design criteria of functional morphogenesis.**

2.3 Functional time

Designing functional transition in time in bioactive design implies an accurate study of the embedded bioactive agent (gene, whole cell, tissue, etc.), and its required functional aspects. This study focuses on: the **latency period of performance**, including biochemical, and electrochemical reactions that occur on different scales according to the embedded bioactive agent, and on **the optimum efficiency** that includes the study of the time required to reach the maximum performance achieved by the bioactive agent in nature (for example, enzyme production). This is to ensure that, within the time margins, none of the living or non-living components of the device hinder the natural potentials of the bioactive agent. In some cases, it makes sure the device parts boost the natural potentials of the bioactive agent, and the **responsiveness synchronization** that defines the consumed time of functional adjustment to the new imposed function, in other words the functional shifting latency time.

2.4 Functional customization

Functional customization means the ability to perform different functions throughout the lifespan of the device. These different functions emerge from the continually changing environmental conditions and needs. Thus, the latency period is a defining aspect of the efficiency of this functional transition. The **latency period here includes the time consumed by the bioactive device to analyze the new surrounding environmental conditions, to study the required function that would fit that change, the latency period to organize its inner genotypes and the time consumed to translate these genotypes into the resulting behavior**. Although this is the most accurate defining characteristic of the bioactive design, it has not been completely achieved yet due to the variation and complexity in the unpredicted functions that is imposed by the continuously changing conditions in the surrounding environment and in the usage requirements. Making the bioactive device shift from generating bioelectricity to performing bioluminescence activity or sensing toxic compounds is but one example. This level of flexibility and smooth transition between varied and different functions requires a high level of biological complexity working on the genetic scale to control the complex network of feedback loops with multiple stimuli. Proper management of components, resources and materials is also necessary. **This could be achieved by mimicking biological networks that**

receive information from outside and inside the cells, integrating and interpreting this information, and then activating a response. Biological networks enable molecules within cells, and even the cells themselves, to communicate with each other and their environment (Westerhoff et al., 2014). One type of biological network that is essential for functional customization design in bioactive devices is the macromolecular network in microbes, which confers intelligent characteristics such as memory, anticipation, adaptation, reflection and network organization. Other biological networks are neural networks that also serve as potent intelligence networks in bioactive agents. Biological networks are mainly classified into two groups: **the feed-forward neural networks (FFNNs)** such as multilayer perceptron (MLP) and self-organizing map (SOM), and the **recurrent neural networks (RNNs)**. **The main feed-forward neural network motif to be applied in bioactive design is to reject transient input fluctuations/ noises and activate output only if the input is persistent, a so-called persistence detector** (Alon, 2007). This is in order to avoid malfunctioning of the bioactive agents caused by over-sensitivity to the environment. In addition, a multi-input feed-forward structure serves as a **coincidence detector** as the output is activated only if stimuli from two or more different inputs occur within a certain period (Kashtan et al., 2004).This motif is utilized for specific functional customization that requires more than one environmental condition shift to occur in the response of the bioactive agent.

Bioactive design of functional transition also needs decision-making intelligence to act and respond properly and on time in accordance with the imposed environmental challenges or internal requirements. In the microbial world, decisions are made by monitoring the current state of the system, by processing this information and by taking action with the ability to consider several factors such as recent history, the likely future conditions and the cost and benefit of making a particular decision (Westerhoff et al., 2014). The networks involved and the parameters controlling their interactions allow the microbes to monitor their environment, process the information and react effectively making a decision in an intelligent manner by taking into account such factors as the cost-benefit ratio and population survival strategies. Another important feature of bioactive design intelligence is the robust adaptation to the changes in the environments. It describes an organism's response to an external perturbation by returning state variables to their original values before perturbation. Almost all adaptation mechanisms involve feedback or feedforward loops. There are two types of robust adaptation intelligence in bioactive agents: **long-term adaptations** that often involve changes in genetic expression such as gene mutations, and **short-term adaptations** that typically involve regulation mediated by either protein-protein interactions in signal transduction pathways, or **direct substrate-product effects in metabolic networks** (Csete, 2002; He et al., 2013). Different regulation mechanisms in bioactive agents often operate at multiple levels simultaneously with a hierarchical structure. The present study focuses on microbial metabolic networks, in which the regulation of a reaction rate can be achieved by the modulation of either **enzyme activity through a substrate or product effect**, enzyme covalent modification via signal transduction pathway, or enzyme concentration via gene expression regulation.

Associative learning is another feature of bioactive devices. It allows the modelling of two or more features that co-vary and respond accordingly. This type of learning specifies how several features in the environment, or within cells, change together. It implies that the learner has a mechanism to encode mutual information. Associative learning in bioactive devices occurs when environmental variables are physically coupled, or somehow co-vary non-randomly. Examples are the increase in the level of light intensity, signals associated to changes in the environment such as an increase in temperature, etc. Bioactive devices weigh these physical associations to better adjust their physiology in specific environments (Bonneau, et al., 2007), to employ easily measured proxies as indications for other phenomena and, in some cases, even to use the cues themselves to prepare or anticipate subsequent alterations to the environment. Typically, associative learning in microbial populations involves some sort of social communication. Self-awareness is another crucial aspect of bioactive design in the functional customization of the bioactive agent. Self-awareness can be described as the ability to recognize oneself as an individual separate from the environment and other individuals (singularity and global behavior indicator). One essential example in microbial communities is quorum sensing. Quorum sensing provides the entire microbial network with the ability to recognize and adjust itself collectively once a specific population threshold is exceeded.

2.5 Functional scale

This aspect focuses on the physical ability to increase and maintain the functional potentials of the bioactive device. It includes the parameter of the reaction scale inside the device on the genetic, molecular or cellular level. The functional scale also includes the bioactive agent's density ratio to the hosting agent (material/ system), the bioactive agent's multiplication, which affects the ecological balance in terms of the bioactive agent's population and diversity included in a continuously growing system. It also deals with the growth in media or supplementary resources needed to support the growth of the bioactive agents, and to guarantee adequate functional relations between the systems' components without hindering the entire output. This aspect should be designed through extensive experimentation on scaling up the function(s) of the device, as computational simulation alone would not be an appropriate solution. The inverse restoration designs the bioactive system's ability to restore its previous scale. This is closely related to functional customization, assuming that environmental conditions will demand shrinkage in the system's scale and vice versa, and provided that growth in scale means multiplication in bioactive agents and propagation in volumetric properties of materials, components and resources. The decrease in scale would impose the need to specifically define the necessary population of the bioactive agents, the necessary number of media (resources, concentrations), and the bulk materials of the host. If controlling the growth in scale is a challenging aspect that needs extensive research, achieving the inverse restoration is even more challenging, especially when controlling micro-elements (concentration of media components that affects the required biological reaction and resulting function). Inverse restoration also deals with rearranging and managing resources of excess agents, as it is necessary to design how these excess agents will be recycled, flushed out of the system, employed in other supporting functions, or recycled through the system to be restored and redistributed when needed.

2.6 Cognition of functional-environmental conditions

This aspect focuses on analyzing environmental conditions in the surrounding space, using a kind of simulator that works dependently on a spatial dimensional scanner, to study the environmental conditions region by region in the target growth vector identified by the spatial scanner. The data obtained by this simulator control the decision-making of the spatial propagation, as it would either approve the next spatial spot for propagation if suitable in conditions, or cancel the propagation decision in this spot to begin a new simulation and analysis in the successive spatial region scanned. This could be achieved by feedback and feedforward loops that are based on mathematical models applying the specific rules of morphogenesis (cellular automata and agent-based modelling) of the specific bioactive agent that is used in the device to achieve ultimate coupling between functional customization and spatial configuration.

2.7 Functional spatial propagation in bioactive design

Bioactive devices do not reproduce in a biological fashion, except for the bioactive agents employed inside bioreactors. The hardware and components of bioreactors cannot reproduce themselves or grow utilizing fresh media or nutrients on their own. The spatial propagation of bioactive devices depends on interference determined by the user's definition, not by nature's default, and is obtained by different means of artificial automation (artificial intelligence or installation of new bioactive reactors by the designer or user). Bioactive devices have environmental sensing abilities only for their current spatial limits. They sense their zone, not the growing space. This implies that spatial propagation cannot be achieved naturally, but by the imposed growing requirements of the user. The designer decides whether they are embedded as added clusters for different ecologic functions or not.

3. FORM

3.1 Formal phase transition

Time controls form composition in bioactive devices as the form of the bioactive device changes over wide time variants. Each time fragment (seconds, minutes, hours, days, etc. according to the latency period of the bioactive agent) is a consequent phase of a continuous growth process that, together with other phases, composes the overall transition from a configuration to another in the form of the device. The designer must use computer animation of the design model based on mathematical modelling. Parametric modelling software based on the simulation of changing parameters (conditions) that control the transition between different phases in the emergence, evolution and decay of the bioactive agent activity in the bioactive device must be used. Conducting a simulation of the model allows the designer to capture every key frame in the transition process on the smallest reaction scale of the bioactive agent. These key frames will enable formal and aesthetical evaluation and spatial maneuver in the design process.

Cellular simulation by means of parametric software

Multi-cellular systems are inherently of a multi-scale nature. The current study on biology simulation of systems dedicated to time is directed towards populations of cells to complement sequence analysis simulation, as in gene expression profiles, signal transduction pathways and the analysis of biochemical systems. (Hoehme et al., 2010).

3.2 Formal scale and the fractal dimension

Formal scale in bioactive design depends on the formal cluster proliferation in a fractal wise. Thus, designing any bioactive device must be directed towards clustering its formal properties to enable the repetition of this cluster in different configurations. This criterion is strongly dependable and related to mass customization, as mass customization specifies design methods that control form clustering and proliferation. Bioactive scale design includes the fractal dimension controller that describes the measuring unit of the ability of the bioactive design to proliferate in spatial dimensions around 360 degrees (not just X, Y, Z). Consequently, this controller depends on various spatial relations between clusters (juxtaposition, interpolation, cross sectioning, repulsion, etc.). These spatial relations are specified in mass customization.

Formal mass customization, planar vs. spatial manipulation, bio-receptive vs. bioreactor.

The limitation of mass customization in bioactive devices stems from the fact that they depend on insulation, enclosure and separation between the bioactive agent, the host, and the environment taking the form of bioreactors. These bioreactors ensure the maintenance of certain growth conditions for different organisms that vary in their capacity of persistence in the open environment as well as their opportunity to cause pathogens. This is achieved by maximum enclosure and maintaining a certain temperature, pH, aeration status (aerobic or anaerobic) and certain concentrations of media substrates. Although bioreactors attain maximum safety in dealing with bio-agents (for instance, microbes), they hinder formal potentials in mass customization and spatial propagation aspects. There is a need for automation of the design growth as well as a need for users to interfere in the system in case of expanding the system or adjusting it according to the emerging needs or sudden environmental conditions. Bioreactors also require a specific design for each function, which may be complicated when it comes to supplies, fixtures, and a circulation system design. The formal limitations of a bioreactor are summed up as follows: **optimum enclosure** in design (including tight control of inlets of the medium and of outlets of the exhausted medium to ensure circulation efficiency), **orientation limits** (bioreactors need to be adjusted horizontally in a stable configuration as mechanical forces affect the biochemical reactions occurring inside the bioreactor), **spatial propagation limitations** (the sensitivity of the bioreactor to mechanical forces implies restrictions on orientation variations, thus limiting possible iterations of spatial orientation to a minimum). Moreover, spatial propagation and orientation in bioreactors depend entirely on the shape of the device that defines the proliferation and the axes of proliferation as well. Varying the shape of the bioreactor is limited by many functional constraints resulting in few formal design iterations. The concept of bio-receptive hosts varies in range from **engineered materials** that increase specific capacities in the bio-agent, (for example, to be non-pathogenic, to growing outdoors, and to resist changing environmental conditions) to **bio-receptive surfaces** that only form a passive host to the bio-agent. These bio-receptive surfaces are hard textured surfaces of biocompatible materials that do not react to and are not biodegraded by the bio-agent and enable it to colonize their surfaces by attaching the bio-agent to their niches. Bio-receptive surfaces limit the functional application that exploits natural potentials of different useful organisms to the simplest functional applications that do not include sophisticated physiological processes. They do not produce toxic chemicals nor do they pose any hazards. Bio-receptive surfaces are also limited in functional customization and functional shifting, unlike bio-integrated hosts or bio-engineered materials (bio-printed materials). Bio-integrated hosts are bio-designed materials and they are usually engineered by genetic manipulation. They are designed according to specific ecological functions that are integrated with the type and function of the bio-agent species. They thus attain the highest compatibility and integration of the bioactive hybrid enabling naturally inherited smoothness in functional and formal transitions with maximum freedom and infinite iterations while maintaining the function and the safety criteria.

Formal planar manipulation

This aspect controls the method of utilizing bioactive clusters to build a global form, and is strongly related to scale. When designing bioactive devices, each cluster is either a **differentiated pixel** as a part of the global form, or a **uniform pixel or fractal** that is repeated in the global form. Either way, the repetition or tessellation method is the pivotal attribute in controlling the resulting form. The tessellation method depends mainly on the **pixel's shape including**

dimension, orientation and relation between pixels, as the pixel's outer shape, edges, total dimension, and orientation affect the global form. The pixel edges define the suitable joinery method and define the formal transition between multiple pixels according to scale and population. The form of the pixel defines its ability of repetition or integration with other pixels. The **tessellation layers** focus on the consequent organization of tessellation groups controlling the **tessellation axis**, which is the orientation of the pixels or clusters along a specific path in the space. This path is a vector that has a starting point and a direction but should have an open or growing end allowing more clusters to be added in the future. This open-ended path should maintain the direction and orientation in building successive rows of joined pixels.This could be a challenging aspect in doubly curved, twisted, tangled and kinked paths. Maintaining the direction in the added clusters would entail functional path alteration. On functional demand, it would imply a different path. Tessellation axes must therefore be flexible enough to be redefined in space in more than one rail (at least three different rails) so as to enable reorientation in case of sudden changes in environmental conditions or user demands. This flexibility in tessellation axes is achieved in line with the dimensions, shape and joinery system of the tessellation cluster. **The tessellation joinery** system controls the **joinery flexibility of the tessellated tiles according to the rail**, as the tiles or clusters should be designed to fit to at least three different configurations of joinery systems in spatial orientation in compliance with the simulated rail iterations of the functional and environmental simulations. The tessellation joinery system also controls the **joinery flexibility of tessellated tiles according to layers**, supporting addition or subtraction of new layers that compose the global form. It monitors the **functional flexibility of tessellated clusters in the addition or subtraction of the bioactive system**, focusing on the functional joinery of the system's structure, suppliers and duct. Achieving flexibility in this aspect implies the usage of prefabricated flexible parts that can easily be installed by the user.

Formal spatial manipulation, propagation and orientation

Customized mass design focuses on adjusting formal design by means of pixels. It centers on how to pixelate the global formal mass into differentiated tiles, and how to differentiate the design of the tiles with regard to shape, dimension, joinery, layers, and axes to achieve the required design form without hindering function or visual continuity of the form. This design process is the opposite of tessellated planner manipulation. The pivotal difference between the two design processes is that planner manipulation focuses on the cluster uniform design and how it would be tessellated regardless of the final form that should previously be simulated to ensure functional and configurable sufficiency, while mass customization focuses on the final form (mass), and how it could be pixeled or tiled using the functional cluster.

4. BUILT ENVIRONMENT EVOLUTION

The aim of bioactive design is to redefine ecological architecture as a continuously evolving and active part of the natural environment and ecosystem. This extends beyond interior design to include architecture and urban design. Its purpose is to evolve to a megacity based on biological communities resulting from a symbiosis between the human, the built environment and the ecosystem. The evolving open system of bioactive design allows the integration of the natural capacities of organisms with human needs for various functional performances. This bioactive system is thus liable to rapid and accurate growth on demand and acts as a response to the changing conditions of the environment. This is achieved through the accurate aggregation of "cluster flexibility" as the bioactive design. In this case, it is based on cellular proliferation that enables the aggregation of clusters as elements of design to form the interior space, the architectural mass and the entire urban context. This clusterization ensures flexibility, reproducibility, resource sufficiency and accurate functionality. The evolution of the megacity of bioactive devices requires the independent installation of the bioactive systems. The clusterization achieved by the cellular bases of the bioactive design enables the independent installation of the cluster from the mega infrastructure of the architecture or urban context, as each cluster is fully equipped and functional on its own and has the ability to proliferate on demand and according to environmental conditions. Producing this design on a urban scale needs more controlled procedures to manage the resulting global electricity of the system, and to make the maximum use of it. It is also necessary to manage the wastes of the bioactive agents such as materials or parts of the device. To handle these aspects, the following procedures are required: **third party installation companies** to manage and monitor installation points as well as their distribution and relation to the whole system. They are in charge of the generated global electrical power, as power saving/ usage modes would be performed on larger scales including regions or districts. Monitoring the efficiency of the whole system, carrying out periodic maintenance, dealing with recharging processes, and recycling the wastes of the system is also their responsibility. Third party companies also control the **scale-up** of the bioactive system to the urban level, which involves scaling up the self-sufficient cluster, the microbial fuel cells. This requires a scale-up in the reactor design and extensive experimentation on reactions, which occur on a large scale. Scaling up depends on the ability of the host materials and the reactor parts to maintain the ecological system, and to protect and integrate bioactive agents in the design. **Recharging and maintenance points** on the urban scale require network design defining centers of recharging and maintenance to monitor and organize this process in each district. **Power-saving management and redistribution points to control** the resultant electrical power are also necessary.

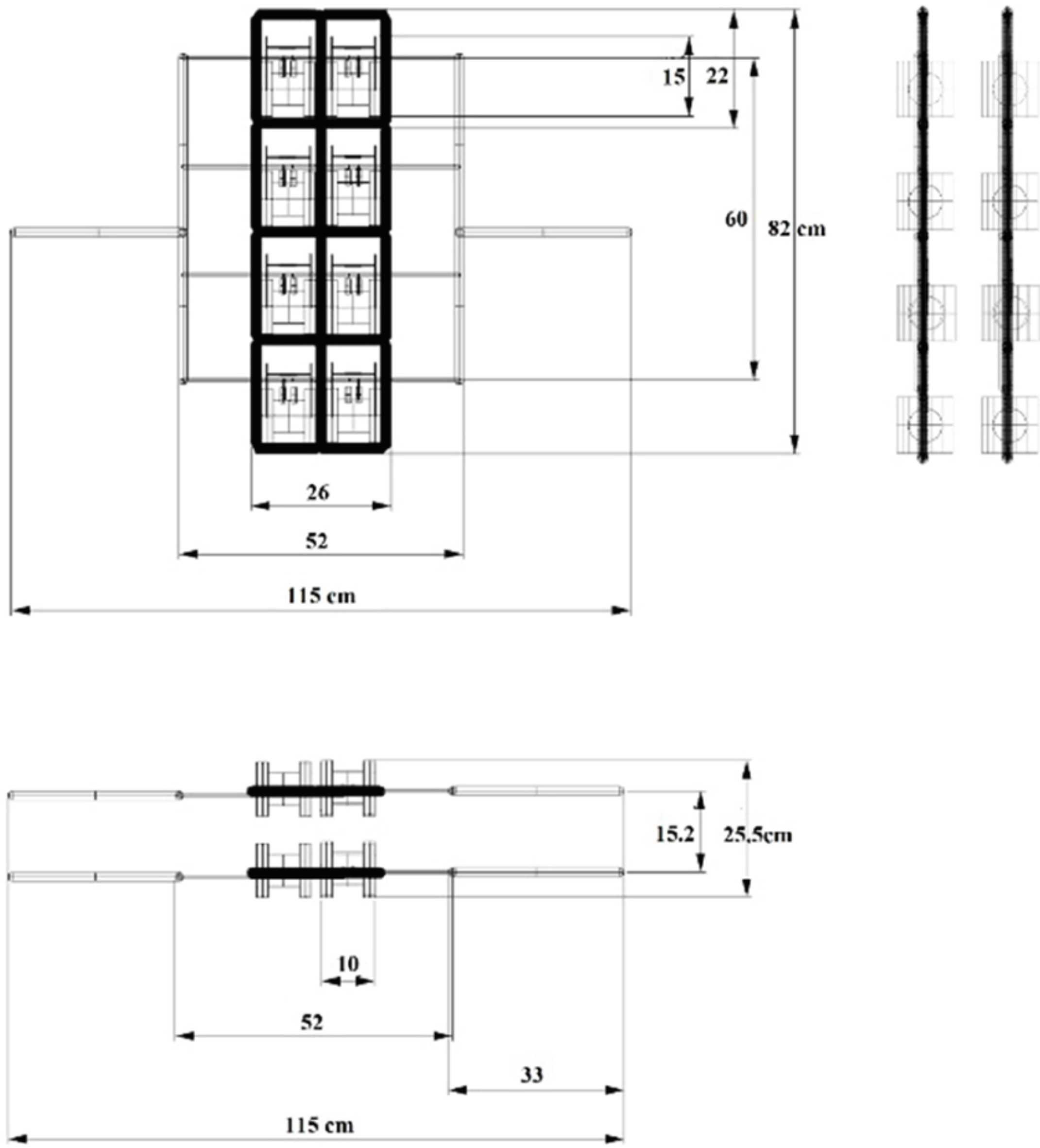
5. DESIGN PROPOSAL, NYKA 510 BIOACTIVE LIGHT GARDEN

The design is a self-sufficient power system to generate bioelectricity for domestic use **achieving design ecology by employing microbial fuel cells. It uses the natural potential of the fungal strain *Aspergillus sydowii* NYKA 510 to produce electricity. This design aims to achieve coupling between form and function, based on the cellular behavior of the fungal strain. It meets the bioactive design criteria set out in the previous section that were established by the authors.** The design is based on the statistical results obtained in the previous experimental study by the authors (Abdallah, et al., 2019) on maximizing electrical power by doubling the 8-cell system to a 16-cell system, in which each group of 8 cells is connected in separate series as shown in Figure 1. The 16-cell system produces 3 Watts. This design was clustered in a compact system with all the required circulation suppliers and ducts encapsulated in it, identifying inputs of fresh supplies and output of exhausted media. The bioactive cluster was then embedded in design iterations employing a cellular form that emerged from the cellular automata simulation of the used bioactive agent.

5.1 Design methodology

Parametric simulation software (Rhino 3D + Grasshopper – Biods plug-in) was used to simulate the cellular behavior of the bioactive agent of *Aspergillus sydowii* NYKA 510 in MFCs to generate bioelectricity. A mathematical equation developed by the authors was used to recreate the

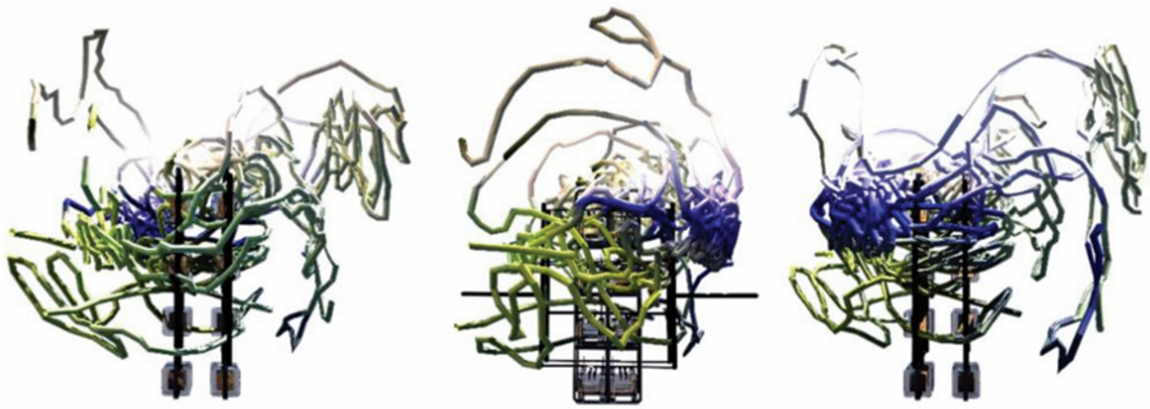
FIGURE 1. Schematic of a single self-sufficient functional cluster unit of MFCs. Authors'own work.



reaction that occurs inside the MFC and to find the form of the design in the specified space, as shown in Figure 2.

The equation was clustered and the model was repeated in accordance with the morphogenesis of the growing bioactive design: from an interior element to architecture to an urban design. The design grows from a single interior design element (see Figure 3) to a partition that extends from an interior space to a semi-open space and then to an outdoor space, and would continue its growth. As an interior design element, the functioning cluster contains a system of 16 MFCs to generate bioelectricity that is embedded inside the form obtained from the design equation. This design element is compact and fully clustered environmentally, functionally and

FIGURE 2. Self-sufficient cluster for bioelectricity generation using MFCs showing varied formal compositions around 360°. Side views and elevation. Authors' own work.



formally, which enables its repetition and distribution internally, externally and along various axes in space.

The finite state bioactive design includes design elements that stand alone and do not emerge into other contexts such as furniture, lighting units and lightweight structures for bioelectricity generation, as shown in Figure 4.

The self-sufficient cluster is equipped with power management and sensory systems that manage the generated electrical power depending on the light intensity necessary in the interior space. If the reading is lower than a certain threshold defined by the user, the power management

FIGURE 3. Formal design derived from a mathematical model for the self-sufficient cluster for microbial bioelectricity production as an interior design element acting as a partition and a lighting unit. Authors' own work.

FIGURE 4. Self-sufficient cluster for microbial bioelectricity device in urban design as a lighting unit. The images show two phases of the self-sufficient cluster: power saving mode at daytime and power usage mode at night. Authors' own work.

device starts using the stored electrical power. In case the light intensity value is higher than the threshold, the generated electricity is stored in power banks that could be used when needed. The system is easily recharged every 4 days. Each cluster includes an additional electrical current sensor so that when there is no longer any electrical current, the system automatically flushes the exhausted media into a tanker attached to the cluster. After that, the user injects fresh media into each cluster separately. The recharging process was created for each cluster separately and is in compliance with processing specification. As each cluster is located in a different spatial coordinate, light intensity values vary across various spatial points. This gives rise to different power consumption levels in each cluster and the different clusters along the space hence show different power levels. The design of the cluster meets the safety criteria of enclosure and mechanical stability. The container's design is open to allow aeration, which is necessary for the air-cathode MFCs and to access the MFCs for periodic maintenance and repair.

5.2 Achieving design ecology and sustainability

The design materials attain biocompatibility, as the MFC cells are made of plexiglass and do not interact with the bioagent or its enzymatic reactions. Furthermore, the outer container is made of silicon tubes that are biocompatible to enable future usage as tubes providing fresh media and bioagents for urban applications. The design materials are recyclable and could be reused in the same device or in other applications. In addition, the bioagents pose no hazards after flushing them with the exhausted media that could be further processed for other applications. This biophilic design engages the form of biological agents and raises environmental awareness as it exploits the biocatalytic abilities of the biological agents when generating electrical power. This proposed symbiosis between humans and bioagents is based on integration and mutual benefit. The design system protects the biological diversity and provides the agents with their optimum conditions of growth. The agents, in turn, provide users with a clean, cheap, and renewable source of electricity that can be maintained and repaired following the instructions described in the user manual and requires minimum knowledge of the system.

5.3 Functional morphogenesis of the design

Functional time

According to the experimental results obtained from the authors' previous work (Abdallah et al., 2019), when initializing each cluster, it takes approximately 50 hours to generate a considerable electric current but not the maximum efficiency of the MFC. This amount would not be sufficient for electrical devices starting from 1 Watt. Maximum efficiency is obtained 6 days after first using the system. The user manual explains the system needs 6 days before generating sufficient electricity. The user should not interrupt this activation process in order not to inhibit or delay the reaction responsible for generating bioelectricity. After 6 days, the system generates 3 Watt/cluster, which is sufficient to light LED bulbs and similar devices. The synchronized response is designed according to the sensory system of the light intensity. The designed response is related to power management, as it determines whether the generated electrical power is used or stored in accordance with a defined threshold of light intensity in the scanned spaces. This implies an automated response in real time to switch between the power saving or power usage modes without affecting the biocatalytic reaction and the power generation process, which continues to produce electric current.

Functional customization of the design

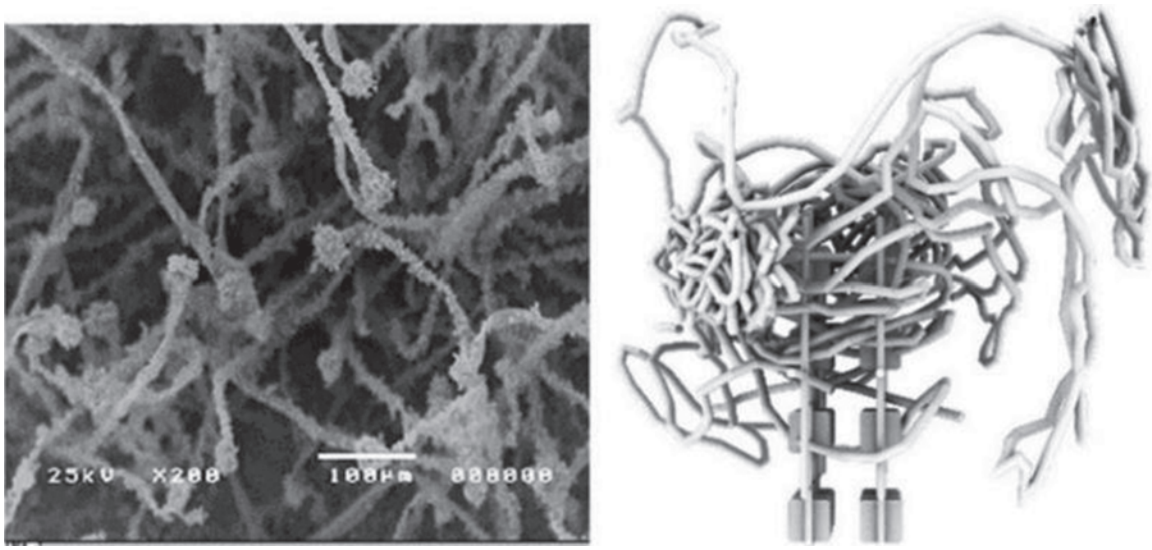
In the current study, the self-sufficient system does not alter its function, as it is directed mainly to generate electricity used inside the interior space. However, functional customization would be applied if the system used a bioagent type containing natural bioluminescence and bioelectrogenesis abilities, which is found in some bioluminescence bacterial strains. In that case, the system would customize the two ecological functions in conformity with the environmental responsiveness defined by the sensory system of the light intensity in the surrounding space. In case of insufficient light intensity, the system customizes the function choosing one of the following two options: activating bioluminescence when the required amount of lighting intensity is low (see Figure 5), or using biocatalysis when the amount of lighting necessary is more than the estimated intensity produced by natural bioluminescence.

Functional scale of the design

According to the experimental study conducted by the authors, the reaction happens on a molecular-cellular level between fungal cells and carbon sources in media. Although the effective scale to reach the objective of generating a considerable amount of bioelectricity is the cluster's unit of 0.4 Watt the functional scale here per single MFC (ACSCMFC-Air Cathode Single Chamber Microbial Fuel cell) is the MFC volume of 117.25 ml with specific concentrations

FIGURE 5. Left: self-sufficient cluster usage in an urban design showing the activation of the power usage mode using electric current harnessed in the MFCs responding to low light intensities. Right: use of bioluminescent, bio-electrogenic strain in the power usage mode showing activation of bioluminescence responding to low light intensity. Authors' own work.

FIGURE 6. Formal similarity between the scanning electron microscopy imaging of Aspergillus sydowii NYKA 510 culture inside the MFC, and the mathematical modelling simulating the bioelectricity generation reaction inside the MFC. The formal similarity is shown in the formal design of the self-sufficient cluster. Authors' own work.



of media substrates and a specific amount of inoculum (10 discs of 1cm each) obtained from a solid pure culture of *Aspergillus sydowii* NYKA 510.

Spatial recognition of the design

In this study, spatial recognition is limited to scanning environmental conditions in the regions surrounding each separate cluster. This scanning system measures the interior space temperature, the exposure to natural light and the oxygen percentage.

5.4 Design form

In the current study, the design form is affected by time, which is presented by the cumulative effect of the mathematical modelling equation that rules the cellular behavior of the bioactive agents. The algorithm was designed in a record history mode to draw the bioactive agent track throughout the whole simulation process in a non-stop line path. This path is the final design form per cell as shown in Figures 6, 7, 8.

Another aspect that achieves the formal time criterion is the factual growth with its distinguished features of the *Aspergillus sydowii* NYKA 510 fungal culture inside the MFCs. The growth phases change from clear media with dispersed spores (light yellow liquid) to forming hyphae with their distinguished texture (light green and bluish green) and then to the final dense textured culture as shown in Figures 9, 10.

All these changing phases contribute to the final design form and visual conception, as they are contained in transparent glass containers to integrate the bioactive agent functionally and formally into the design process. They also help building a new aesthetical perspective for users to accept the appearance of bioactive agents as a part of the design form. The effect of changing colors and textures was considered as a background hue in the form of pixels to create a smooth, blended and integrated effect of the organic appearance of the bioagent. Mass

FIGURE 7. Similarity between scanning electron microscopy imaging of Aspergillus sydowii NYKA 510 and the mathematical modelling simulating the behavior of the bioactive agents. Authors' own work.

FIGURE 8. Formal similarity between Aspergillus sydowii NYKA 510 culture in MFCs and the mathematical model simulating the reaction of fungal cells inside the MFCs applied in the self-sufficient system outdoors. Authors' own work.

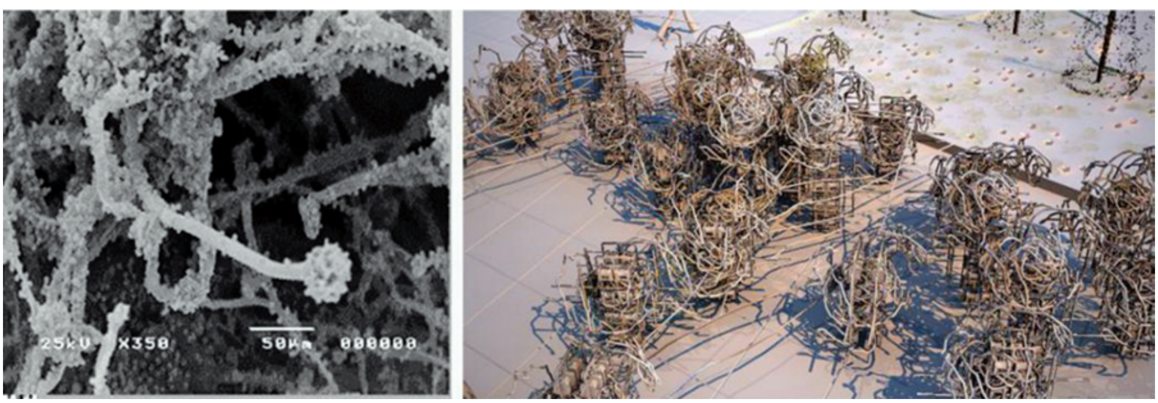


FIGURE 9. Chronological simulation of fungal culture growth showing changing colors and culture density. Authors' own work.

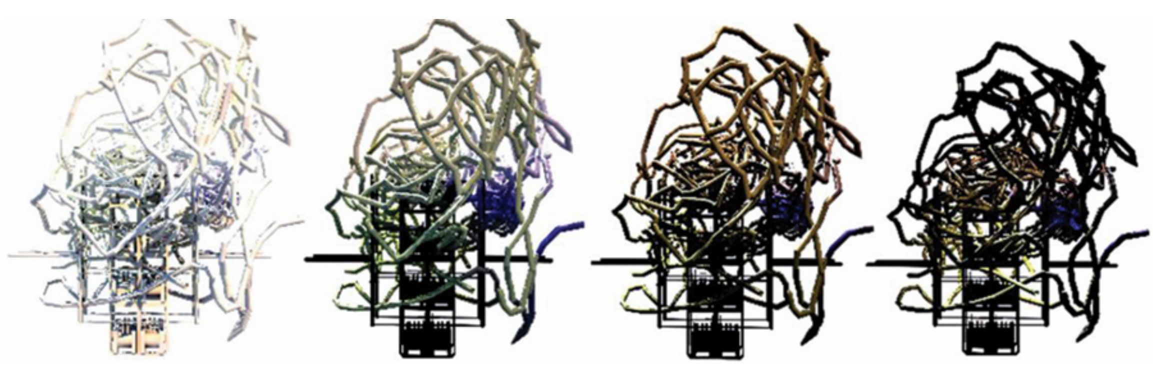
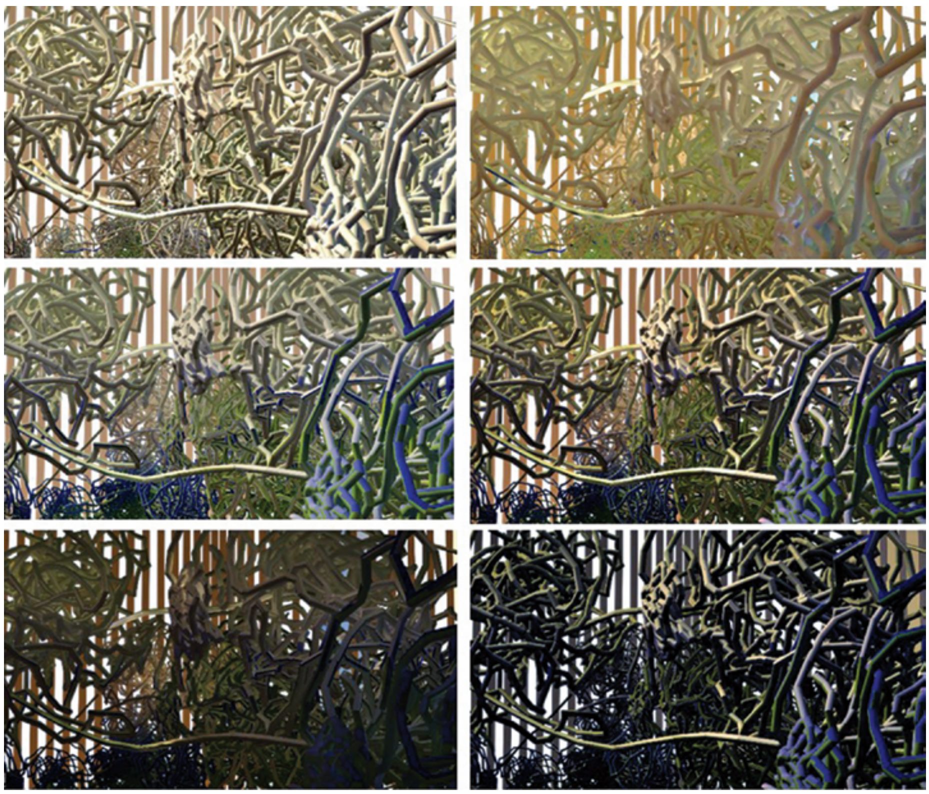


FIGURE 10. Detail of interior design installation of the cluster. Different time frames of growth simulation of the fungal culture of Aspergillus sydowii NYKA 510, injected and cultured in the silicon tubes, showing the growth phases and resulting change in color (blue-green) and density of culture. Authors' own work.



customization was also taken into consideration, as the phases present different growth features across different clusters. One cluster may be in the mature phase while another is at the initial phase, which means different clusters will exhibit different colors and textures of growth according to their growth condition.

- **Formal scale and fractal dimension of the design.** The design form of the cluster is open, meshed and allows transparency. These aspects balance the large dimensions of the cluster and enable repetition in the interior space without hindering clarity and visual acceptance.
- **Formal spatial propagation of the design.** This aspect arranges formal clusters in space and their relations according to the visual conception in different points around 360°. It is predefined by a mathematical modelling algorithm for multiple cell simulation defining the margins between different cells (clusters) and their location in space. In the current design case, the spatial orientation for the functional cluster (MFCs) is limited by the horizontal configuration. However, the formal cluster (container) is free in orientation because of its free fluid form that could be located in any position. The cluster design achieves both fluidity and pixilation of the final mass. The fluid mass is obtained in each formal cluster with the chaotic form on the level of the single

cluster and the scale of the element in the interior design, while pixilation is achieved by the ability to repeat the cluster infinite times in the space along different axes and in different orientations and relations. Since branching is the dominant proliferation and growth method of the bioactive agent, *Aspergillus sydowii* NYKA 510 hyphae, this proliferation results in electrical current generation as well as in changing formal features inside the functional cluster (MFCs). This branching method is the base of the mathematical model algorithm that generates the cluster's form. Thus, the branching proliferation method achieves coupling between form and function as well as spatial propagation along the aerial-longitudinal/ orbital axes. Morphogenesis is attained in the design through morphogenesis in growth phases of the fungal cells inside the MFCs that brought about different formal features and the emergence of the formal design of the whole mass. This design emerges from cluster repetition from the interior design element of a single cluster to a partition design to growing from interior to semi-open spaces to an urban design.

6. RESULTS AND DISCUSSION

Employing "case-based" design and a "multidisciplinary" study for synthesizing a bioactive device. A case-based design approach establishes experimentation in various interdisciplinary fields integrated into the specific case of design. This approach is also appropriate in terms of addressing ecological problems, as it considers the multi-scale interconnected relations that stem from the biological complexity of bioactive agents. A case-based design approach is optimum for modelling biological behavior through focusing on a specific objective and a specific search area. It should be noted that this approach does not hinder studying the biological complexity of biological behavior, on the contrary, it enables analyzing its sophistication and developing it in terms of a realistic translation and application in the design process achieved by the authors through experimental study. The bioactive device used the bioagent of the fungal strain, *Aspergillus sydowii* NYKA 510, identified by the authors (Abdallah, et al., 2019) in MFCs to generate bioelectricity. The bioactive device needed initialization time of 4 days to generate a steady current, and maintained a steady performance for 6 days before it had to be recharged with fresh media. The achieved electrical current was further amplified by staking a system of 2 sets of 4 MFCs each, connected in series. The self-sufficient cluster design included the inner system of the MFCs and the outer container, which gave the cluster its final form.

Power management of the bioelectricity system is a complex process in the case of networks. It includes managing decision-making options of singular or global behavior to control the electric current output of each cluster, based on the singular or global responsive behavior to the light intensity feedback from the surrounding light intensity sensors in the space. Developing such a system of power management requires flexibility to switch between singular and global behavior. However, such a complex system may seem contradictory, as the objective of this study is to provide "ease of use," "clusterization," and "cost effectiveness." It stresses singularity that refutes and rejects the need for complex systems or infrastructures that require large-scale intervention. It focuses more on a democratic and readily available bioactive device that could easily be installed in any space.

A self-sufficient cluster needs maximum enclosure, mechanical stability, a simple design in terms of access for maintenance and ease of use (initializing and recharging) by non-specialized users. The design's formal simplicity in this case is favourable because of the need of replication of the self-sufficient cluster as building blocks in the space. In addition, manipulating the derived biodigital forms and patterns achieves the required design complexity without hindering the main objective of generating electricity.

The life cycle of the bioactive device consists of three phases: emergence, evolution and decay or degradation. The first phase, emergence, includes the standard function of the device and the initial growth phases in time and function. **The second phase, evolution**, is significant when it comes to transformation in form and functional capacities resulting in continuous growth in time, as the scale of performance grows or decreases. In this phase, designers should consider growth margins of form/ function transformation respecting time frames and resources, using parametric simulation extracted from the behavior of the corresponding biological systems. **The last phase is decay or degradation**, where the designed bioactive device is absorbed by the natural eco-cycle, includes two possible scenarios: **finite decaying**, where all the device parts are biodegradable or recyclable, and **infinite evolution**, where the device has endless possibilities to adapt its form and function.

7. CONCLUSION

This study identifies the need of alternative renewable electricity sources, and addresses the increasing demand in power supply and consumption as well as the universal problem of global warming that is increasing dramatically. Based on the current rates of total emissions of CO_2, and on the fact that 47% of these global emissions comes from the energy supply sector, and 3% from the building sector, decarbonized electricity generation is key for stabilizing CO_2 emissions at low levels. The alternative of renewable electricity put forward in this study is the use of bioenergy systems. Employing bioenergy offers energy supply by means of negative emissions technologies. It depends on options of low lifecycle emissions and on outcomes that are site-specific and rely on efficient integrated bioenergy systems. The objective of this study is to design a method for creating self-sufficient systems of bioelectricity devices that provide the following: safety, efficiency of electrical power generation, cost effectiveness, waste treatment, ease of implementation in domestic use, ease of use, reproducibility and availability. It also intends to elaborate a general design method of embedding and using bioactive devices as design elements to achieve design ecology at different levels ranging from interior design to architecture to urban morphogenesis. The design methodology includes three main aspects: **achieving design ecology, the functional design of the bioactive device and the formal design of the device.** The functional design of the bioactive device includes functional bioelectrical bases of MFCs, incubation of bioactive agents, biocompatibility, morphogenesis, and device lifecycle. Numerous methods, amongst others mass customization and pixilation, were proposed for the formal design of the device. The bioactive device used in this study produced bioelectricity based on previous experimental work conducted by the authors utilizing MFC technology to exploit the natural potential of microbes to produce electricity. **The best performance of the bioactive device of MFCs was obtained at 2000 Ω achieving 0.76 V, 380 mAm^{-2}, 160 mWm^{-2}, and 0.4 W per cell. The MFCs needed initialization time of 4 days to generate a steady current, and maintained a steady performance for 6 days before the device had to be recharged with fresh media and dispersed spores.** In order to achieve coupling between form and function in the self-sufficient bioactive system, mathematical modelling of biological behavior was developed, followed by the simulation of the bioactive agent's behavior when generating bioelectricity inside the MFC. The results are analyzed in an extensive design study in line with the design method proposed by the authors and criteria of embedding bioactive devices as design elements to achieve design ecology through a case-based design approach.

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