ALGAE-CRAFT

AN INNOVATIVE APPROACH FOR BIOMATERIALS IN THE ARCHITECTURE FIELD. RESEARCH AND DESIGN OF A MODULAR ADAPTIVE FACADE SYSTEM ABLE TO OPTIMIZE BUILDING THERMAL LOAD.

POLITECNICO
MILANO 1863

FIRST SEMESTER 2023/2024

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MILANO 1863

DIPARTIMENTO DI ARCHITETTURA,
INGEGNERIA DELLE COSTRUZIONI
E AMBIENTE COSTRUITO

ALGAE-CRAFT

Supervisor:

Alessandra Zanelli

Co-Supervisor

Amirhossein Ahmadinia

Students:

Anna Camilla Ambrosini
Yasaman Taghipour

Academic year 2023_2024
October 5th

Abstract

One of most significant problems impacting modern society, as will be argued in this book, is global climate change and the implications that flow from it. Housing and technological trends must be taken into account as essential factors if the overall goal is to reduce human impact on the environment. In light of this scenario, the research has been driven by the desire to analyze the primary solutions currently offered by architecture in terms of sustainability, materials, and technology.

The research method intends to accomplish two key goals: first, to minimize energy consumption, which will enable us to meet at least some of the Paris Agreement's obligations; and, second, to self-produce energy. The integration of algae as a design element has emerged as a promising avenue for advancing sustainability in architecture. By leveraging the inherent properties of algae, such as its capacity for carbon capture and oxygen production, the research project aims to devise novel architectural applications that mitigate the adverse impacts of climate change.

Similarly, the adoption of a modular facade as a technical system holds great potential for enhancing the sustainability and flexibility of architectural designs. By employing modular components, the research project seeks to enable efficient construction processes, resource optimization, and adaptability to changing needs and contexts, all while minimizing environmental footprint.

In essence, the research project aspires to bridge the gap between theory and practice, by harnessing theoretical knowledge and empirical insights to develop innovative design solutions that address the global challenges of climate change and sustainability in architecture.

Abstract

Una delle questioni più importanti che riguardano la società moderna, come sarà discusso in questo libro, è il cambiamento climatico globale e le sue implicazioni. Le tendenze in materia di costruzione e tecnologia dovrebbero essere considerate fattori essenziali se l'obiettivo globale è ridurre l'impatto umano sull'ambiente.

Di fronte a questa situazione, la ricerca è stata guidata dalla volontà di analizzare le principali soluzioni attualmente offerte dall'architettura in termini di sostenibilità, materiali e tecnologia.

Il metodo di ricerca si propone di raggiungere due obiettivi chiave: in primo luogo, minimizzare il consumo di energia, il che ci consentirà di soddisfare almeno alcune delle obbligazioni dell'Accordo di Parigi; e, in secondo luogo, produrre energia in modo autonomo. L'integrazione delle alghe come elemento di design si è rivelata una strada promettente per avanzare nella sostenibilità dell'architettura. Sfruttando le proprietà intrinseche delle alghe, come la capacità di catturare il carbonio e produrre ossigeno, il progetto di ricerca mira a sviluppare nuove applicazioni architettoniche che mitigano gli impatti negativi del cambiamento climatico.

Allo stesso modo, l'adozione di una facciata modulare come sistema tecnico offre grandi potenzialità per migliorare la sostenibilità e la flessibilità dei progetti architettonici. Attraverso l'impiego di componenti modulari, il progetto di ricerca mira a consentire processi di costruzione efficienti, ottimizzazione delle risorse e adattabilità alle mutevoli esigenze e contesti, il tutto riducendo al minimo l'impronta ambientale.

In sostanza, il progetto di ricerca aspira a colmare il divario tra teoria e pratica, sfruttando le conoscenze teoriche e le intuizioni empiriche per sviluppare soluzioni di design innovative che affrontino le sfide globali del cambiamento climatico e della sostenibilità nell'architettura.

Key words

CLIMATE-CHANGE
RETROFITTING-FACADE
RESPONSIVE-ARCHITECTURE
THERMAL RESPONSIVE STRATEGY
MATERIAL-BASED TECHNOLOGY
THERMOPLASTIC-POLYMER
ALGAE
BIO-FUEL
BIO-REACTOR
ENERGY-INDEPENDENT
LONG TERM ECONOMIC BENEFITS

Key words

CAMBIAMENTO CLIMATICO
FACCIATA IN RETROFITTO
ARCHITETTURA RISPOSTIVA
STRATEGIA A RISPONDENZA TERMICA
TECNOLOGIA BASATA SUI MATERIALI
POLIMERO TERMOPLASTICO
ALGHE
BIO-CARATTERE
BIO-REATTORE
INDIPENDENTE DALL'ENERGIA
BENEFICI ECONOMICI A LUNGO TERMINE

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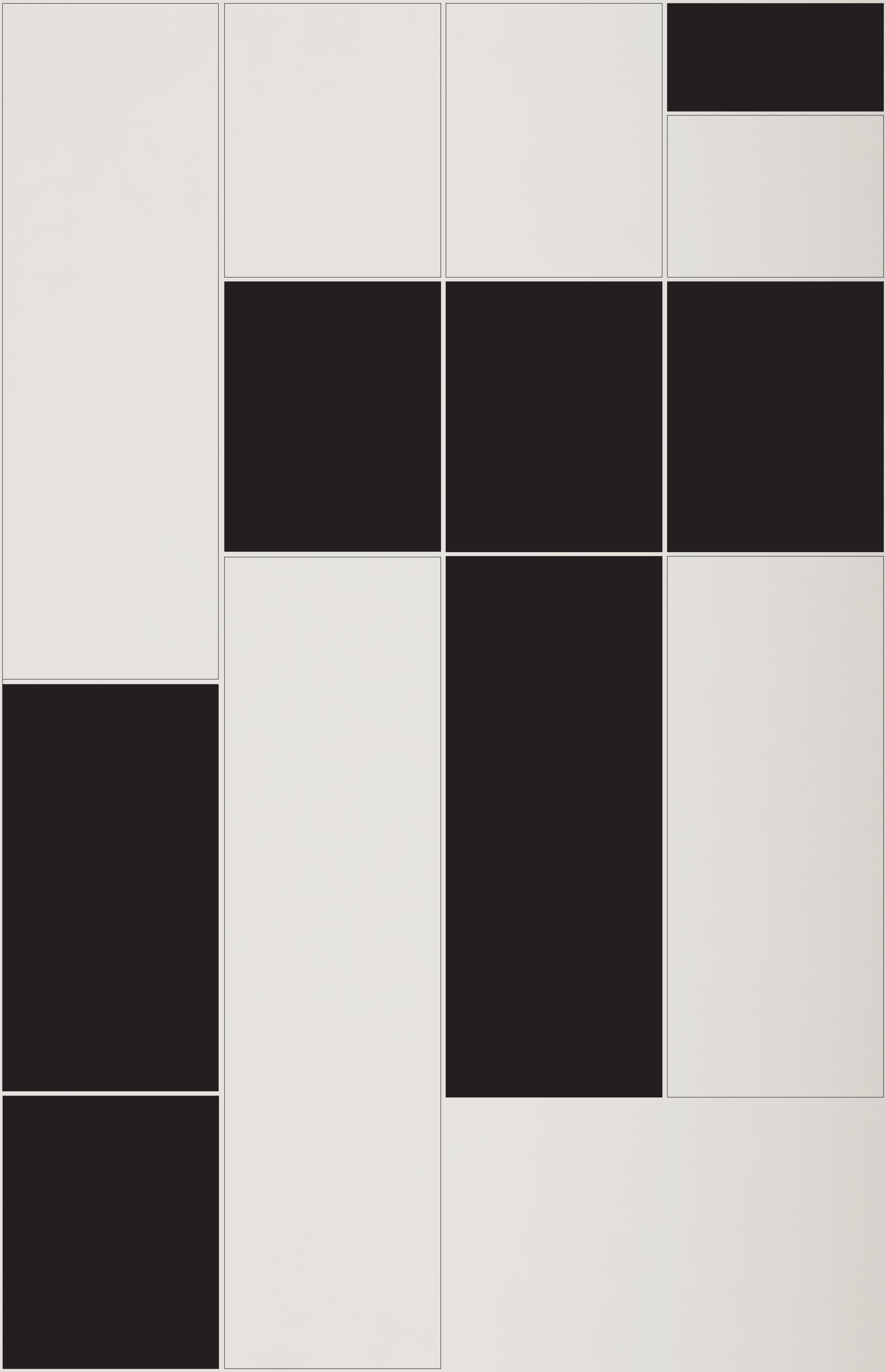
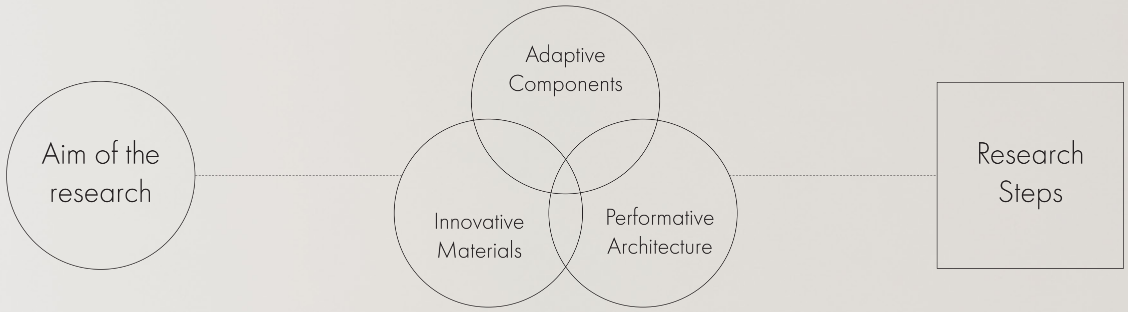


1 Introduction



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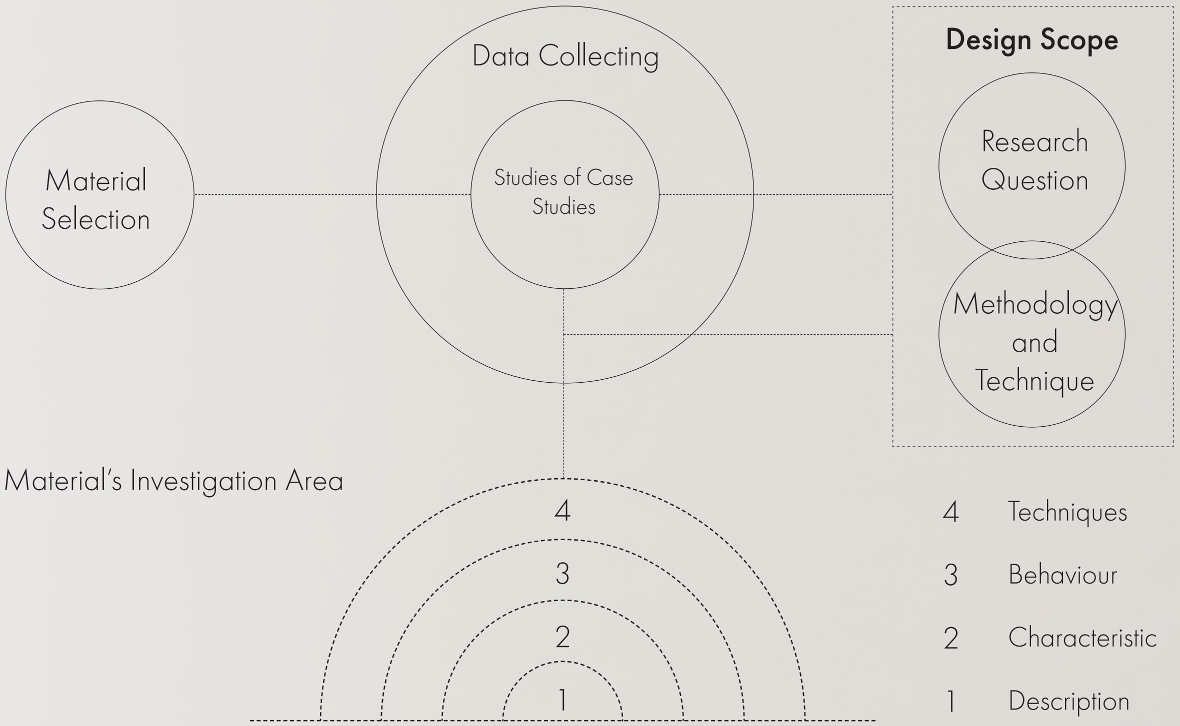

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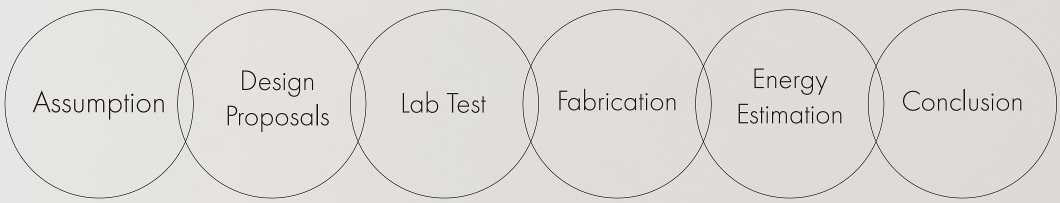

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ALGAE-CRAFT

FIRST SEMESTER 2023/2024
POLITECNICO DI MILAN

INTRODUCTION

1. Overview
2. Thesis Structure
3. Data Collection

The following section is divided into three subsections. The first part is devoted to an introductory section and offers an overall perspective of architecture and its surroundings. The subsequent sections additionally addressed the publication framework and the approaches utilized to obtain information.

1. OVERVIEW

In the 2023 scenario, with global warming being experienced and the consequent massive increase in housing demand due to a society of 8 billion, sustainability becomes a crucial topic in every field, especially Architecture. Sustainability may imply the modification of current trends and the search for new solutions in terms of materials, technology, and strategies, among others. Furthermore, the requirement for sustainability, which is one of the major vital concerns that must be addressed by humanity, can be generally defined as the accomplishment of certain essential aims in both the short and long term, all concerning the human impact on the planet. (*United Nations.Sustainable Development Goals-https://www.un.org/*)

When it comes to the Architecture field, this trend is composed of two distinct approaches, which are occasionally merged. One option is to invest in research, with the aim of developing innovative energy-saving technologies, alternative fuels being employed, and machinery being optimized. The other option involves attempting to adapt existing circumstances by considering their present state and succeeding with novel ideas for utilizing the existent to meet sustainability objectives. Each of these strategies should not be viewed as a separate approach to issue solving; instead, the combination of these strategies frequently provides the most appropriate solution to the same problem.

The objective of the present research is focused on evaluating the efficiency of novel materials and implementing them in atypical fields, among them architecture, to enhance their efficiency.
The opinion held is that each construction is an alive, breathing element of a complex system termed the environmental sphere, which is both harmonious and natural. As an element of this, an immense effect on the surroundings can potentially be had by it; simultaneously, however, a critical role in guiding such an approach to achieve the optimal outcomes is played by architecture.

On top of the prospective of keeping the energy consumptions for heating, cooling, and lighting activities under control, further research also

focuses on the secondary production, meaning natural products that are ready to be used in irrelevant fields.
The energy efficiency of a single building depends on various factors, a few of which can be quickly listed: the quality and typology of materials used for walls and partitions, the ratio between opaque and transparent elements, daylight intake, the distribution of functions, the orientation of the building itself... Of course, the energy performance of a building will be impacted by all of these factors, with specific climate conditions of the area where it is located being referred to.

Designing new buildings by keeping in mind the characteristics of a specific location might be seen as the best solution, but this method will be optimal mostly in the "third world countries," where the population is constantly growing and, as a consequence, the house request is also arising. The other possible scenario can be seen as an useful strategy in the western countries, where material sustainability, heritage preservation, and a physical lack of free areas for new constructions need to be taken into consideration as crucial aspects. On the other hand, in terms of energy efficiency, the building standards are not satisfying the modern requirements. In this case, such buildings have been adapted during the last century to meet the needs of a society that is used to consuming electricity for almost every basic activity.

This kind of optimization, rather than being complete and systematic, has been characterized by the initiative of private owners.It is by analyzing this kind of condition that the absence of an appropriate methodology that can bridge the gap between the outdated and innovative has been acknowledged.

Accordingly, this area of study has been selected as the initial objective of this research. The choice has been made to focus the research on the design of an adaptive facade system, capable of working as a second skin on the existing building, and improving its own energy efficiency and its impact on the urban context.

2. THESIS STRUCTURE

The work that is being presented in this book represents the culmination of an exceptionally intense and rigorous period of research. This extensive research endeavor has been carried out with utmost dedication and has encompassed both the **theoretical** and **practical** domains, ensuring a comprehensive exploration of the subject matter.

Chapter I of this book serves as a comprehensive introduction, providing a detailed overview of the main topics that are addressed within the booklet. Additionally, it delves into the core structure of the book, outlining the logical progression and organization of the content. Furthermore, the chapter elucidates the meticulous methodology that has been employed throughout the process of data collection, ensuring the reliability and validity of the findings presented.

Chapter II, titled "State of the Art," a deep and comprehensive analysis of the current approaches and solutions to sustainability within the realm of Architecture is presented. This chapter goes beyond a mere superficial examination and instead offers a profound understanding of the various strategies and practices that are currently being employed. To illustrate this, the chapter draws upon a rich array of case studies from the past decade, each showcasing the application of innovative nature-based systems. Through a meticulous evaluation of these case studies, the chapter not only sheds light on the successful implementation of sustainable practices but also identifies and critically evaluates the prevailing challenges that are inherent within this evolving field.

Chapter III, aptly titled "State of Work," the chapter begins by reiterating the previously established problem statement. Subsequently, it delves into the key research questions that have been formulated to guide the inquiry undertaken in the subsequent chapters. These research questions have been meticulously crafted to provide a comprehensive exploration of the topic at hand, ensuring a robust and holistic analysis. Additionally, the chapter clearly articulates the primary goals and objectives of the research, thus setting the stage for the subsequent chapters and creating a framework within which the research findings can be understood and interpreted.

Chapter IV constitutes the crux of the book, providing a comprehensive and in-depth summary of the voluminous information that has been amassed over the course of several months of diligent study. This chapter delves into the chosen nature-based material, algae, exploring its characteristics, properties, and potential applications within the context of sustainable architecture. Extensive references are made to numerous reports, books, and documents that have been instrumental in obtaining a nuanced understanding of this material. Moreover, the chapter delves into the intricate details of the machinery employed in the harvesting process of algae, and the complex regulatory frameworks that govern its conversion into biofuels. By delving into these specificities, the chapter ensures that the readers gain a comprehensive and well-rounded knowledge of the subject matter.

Chapter V assumes the role of elucidating the design methodology that has been adopted in the research project. It takes into careful consideration the overarching goal of developing an adaptive facade model that can effectively respond to dynamic environmental conditions. The chapter delves into the meticulous planning and execution of the design process, with a particular emphasis on the integration and combination of individual modules to create a cohesive and adaptable architectural system. Moreover, the chapter expounds on the advanced software and cutting-edge programs that have been employed to facilitate the design process, ensuring precision and efficiency in the development of the proposed adaptive facade model.

Chapter VI, aptly titled "Fabrication," offers an in-depth exploration of the practical aspects of the research project. This chapter describes the rigorous laboratory tests that have been conducted to validate and refine the proposed concepts and methodologies. It delves into the intricate details of the experiments carried out, meticulously examining the various parameters and variables that have been meticulously calibrated to achieve optimal results. The chapter further explores the most effective techniques for harvesting algae, the precise circulation patterns of fluids, and the geometric configuration of the samples that have been devised to ensure seamless integration with the proposed architectural system. By rigorously testing and refining these aspects, the chapter ensures the feasibility and practicality of the proposed solutions.

Chapter VII represents the culmination of the entire research endeavor, providing a comprehensive and holistic overview of the final output of the thesis work. This chapter synthesizes the key findings, highlighting the critical points that have emerged throughout the research journey. Additionally, it offers a reflective analysis of the research outcomes, identifying areas that may require alternative approaches or further investigation in future endeavors. Moreover, the chapter presents an insightful examination of the advantages and disadvantages associated with the adoption of the proposed system within existing buildings, thereby providing valuable insights for practitioners and decision-makers.

Chapter VIII serves as a comprehensive repository of all the references and sources that have been consulted throughout the research process. It includes an extensive bibliography comprising relevant scholarly works and other authoritative sources, ensuring that readers have access to a wide range of reference materials for further study and exploration. Additionally, the chapter presents a detailed list of figures, meticulously cross-referencing each figure with its corresponding depiction in the book, facilitating easy navigation and comprehension for readers.

In conclusion, this book represents a contribution to the field of sustainable architecture, providing a comprehensive and rigorous examination of the subject matter. The expansive research, meticulous analysis, and thoughtful insights presented within these pages serve as a valuable resource for researchers, practitioners, and all those interested in furthering the cause of sustainability within the field of architecture.

Research

Data

Process

Conditions

Analysis

Results

3. DATA COLLECTING
METHODOLOGY

Given that the study topic is grounded in theory as well as practice, it has gone through multiple stages of development—sometimes simultaneously.

As a result, it is appropriate to highlight the two types of information classifications presented in this research. A number of scientific and technical facts that have been obtained through a lengthy search process, with sources including official publications, journals, open-source documents, and additional ones. Also, by employing what already had been there to establish what was not present and which issue would be ideal to prioritize in order to invest in a more accurate research process following, we were able to build an overview.

As the subject of smart material behaviour has been explored in numerous projects, meanwhile a number of case studies from the design, engineering, and architecture areas were studied. While some of these represented potential new study routes and significant steps in the formulation of our research objectives, others were themselves dead ends and could not be taken into account.

A few projects were chosen from among the many that were considered. The leading cases demonstrating the use of smart materials, both natural (algae) and synthetic (aluminium). Each case study has been thoroughly examined, and aids in illustrating a varied application of such materials in the creation of either changeable façades, or environment-responsive buildings. The studies that demonstrate two potential approaches to designing a finite product that can respond to environmental input are outlined on the pages that proceed. Several examples demonstrate how scientists and designers have been successful in being able to use the qualities of a number of natural substances, by emphasizing their behaviour in order to optimally utilize their reaction and developing specialized structures that enhance such mechanisms.

In this particular instance, the primary emphasis is on a climate-responsive design that does not require any mechanical or electrical sensors to be engaged and is entirely based on the properties of the material its own (printed wood).

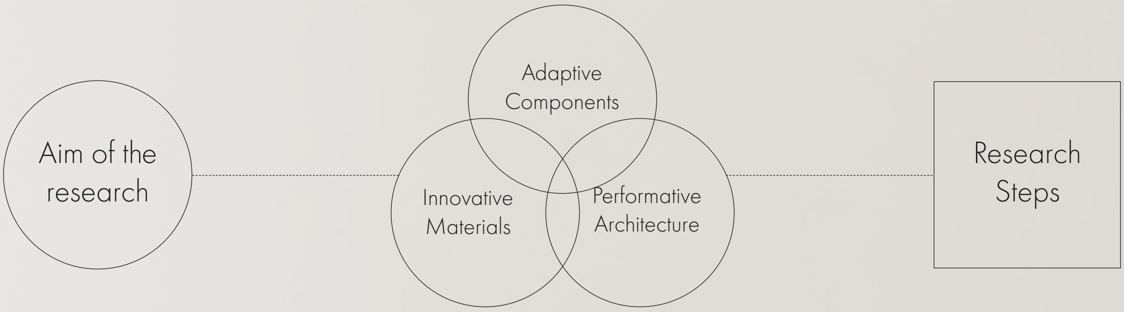
These last situations involve scenarios which utilize a no-tech strategy based on the notion of using the material for its main drive. Following the scenario of previous scientists, there are additionally a few experiences of buildings that can develop spontaneously over time. The result is that they will change visual in reaction to stimuli from the outside, and in some situations, they will be capable of producing secondary products.

The fundamental objective of the present research and analysis has been to classify any past relevant examples with the intention to take into account what has been accomplished and determine the ultimate research goals.

The first stage required to gather all the data and information available regarding the work that has been performed so far in the field of smart materials.

The following phase needed to establish the research topics. By using this framework, we have been capable to focus the study on one natural element, algae, and one technical framework, the modular facade.

A new phase of the study procedure started with a particular concentration on each of those topics. The information gathered in this stage are empirical, based on laboratory observations, whereas it references the database's information for guidance, it also creates fresh data that can be examined. The data that was obtained during the research procedure is summarized in the project's final proposal and then analysed in the publication's final chapter, complemented by a list of future limitations and possibilities.



II

STATE OF ART

This part will go over the issue in further depth. In the first section, the importance of environmental sustainability in architecture was discussed. In the follow-up, unique case studies and their components were analyzed into and studied. Furthermore, the final section emphasizes the current gap between the ideal scenario and current realities, allowing the study to carry on by one step.

1. THE NECESSITY OF SUISTANABILITY IN ARCHITECTURE

It has been widely acknowledged in the field of Design and Architecture that the desire for sustainability is a relatively new phenomenon (*Smith, Designing for Sustainability, 2017*). This growing trend has spurred numerous studies and research efforts aimed at exploring methods that can lead to more efficient and sustainable outcomes (*Johnson et al., Sustainable Design Practices, 2020*).

When compared to other industries, household activities have been found to account for a significant portion of consumption (*Brown & White, Sustainable Consumption Patterns, 2019*). This highlights the importance of focusing on the construction industry to implement energy-efficient practices and reduce resource consumption (*Jones & Green, Energy Efficiency in Construction, 2018)*. By addressing energy efficiency and consumption reduction, the construction industry can make substantial contributions to decreasing the overall resource consumption attributed to households.

The implementation of sustainable solutions in the construction industry has been the subject of ongoing research and innovation (*Miller & Williams, Sustainable Construction Technologies, 2022*).

Various initiatives have been explored over the past few decades. However, the effectiveness of these solutions has been hindered by factors such as the challenges associated with producing the required devices, the complexity of systems, and the economic investment needed (*Thomas et al., Overcoming Barriers to Sustainable Construction, 2016*). For instance, the integration of solar panels into architectural designs has been recognized as a viable solution for generating renewable energy, but their widespread adoption has been limited due to these challenges.

The current scenario underscores the necessity for a systematic and coherent effort from the different stakeholders involved in the construction process (*Anderson & Garcia, Collaboration for Sustainable Construction, 2018*). Achieving sustainable solutions in the construction field requires collaboration between architects, engineers, policymakers, and other stakeholders to overcome the existing barriers and drive impactful change.

One important aspect of sustainable design is the search for new and inventive materials that align with ecological principles (*Wang et al., Sustainable Materials for Architecture, 2021*). Utilizing natural-based materials not only fosters a greater understanding of the environment but also opens up fresh opportunities for integrating nature within architecture. Responsibly harvested wood, reclaimed materials, and recycled elements are examples of natural materials that inherently possess resource efficiency and contribute to the development of a circular economy, thus minimizing the depletion of non-renewable resources.

Another critical aspect often overlooked is energy use and fuel sources, which have significant implications for global warming (*Chen et al., Energy Solutions for Sustainable Architecture, 2019*). Addressing these issues can help mitigate the catastrophic consequences of climate change. Natural materials with lower carbon footprints offer a sustainable alternative by reducing carbon emissions associated with construction.

Moreover, innovative solutions such as algae and photo-bioreactors have shown promise in sequestering carbon dioxide through photosynthesis (*Garcia & Martinez, Bio-inspired Solutions for Sustainable Architecture, 2020*).

In addition to their environmental benefits, natural and sustainable materials contribute to creating healthier indoor environments by minimizing the presence of harmful substances commonly found in conventional construction materials (*Smith & Brown, Healthy Buildings: Integrating Sustainability and Well-being, 2018*).

This positive impact on human well-being is important to consider in sustainable design practices. Furthermore, natural materials offer opportunities to promote biodiversity and habitat preservation by supporting local ecosystems, sustainably sourcing materials, and considering the life cycles of construction products.

The potential for algae and photo-bioreactors to contribute to sustainable habitats for marine life is a promising avenue for future research and innovation.

As the momentum for sustainable practices continues to grow,architects have a responsibility to adopt natural and sustainable materials (*Smith & Johnson, Sustainable Architecture: Principles and Practices, 2022*). By indirectly referencing algae and photo-bioreactors, architects can inspire further research and innovation in these areas, thereby shaping a more sustainable and environmentally conscious built environment.

What is one of the main challenges that society will have to face during the next decade ? →	*CLIMATE CHANGE*
From a worldwide problem to the possibilities that concerns each nation →	*PARIS AGREEMENT*
Different strategies aiming to reduce energy consumption →	*ENERGY EFFICIENCY IN THE CONSTRUCTION FIELD*
Targeting down the typologies of buildings with the highest consumption level →	*RESIDENTIAL HOUSING*
Strategy to adopt in order to reach the final aim →	*REDUCE THE DIRECT SUN HOURS*
	ADAPTIVE FACADE

2. LITERATURE

2.1 SHADING SYSTEM AND FAÇADES

Solar shading systems are essential for maximizing energy efficiency and enhancing occupant comfort in buildings. By effectively managing sunlight penetration, these systems reduce heat gain, minimize glare, and optimize natural lighting.

- **FIXED SHADING SYSTEMS** → Fixed shading systems are stationary elements installed on the building's exterior. They provide consistent shading and can be designed to complement the architecture. Examples include:
  - OVERHANGS & AWNINGS → These horizontal extensions block direct sunlight from entering windows and protect against rain. They are commonly used in residential and commercial buildings.
  - LOUVRES & BRISE-SOLEIL → Vertical or angled elements placed on the facade to limit direct sunlight while allowing for ventilation and views. Louvres can be fixed or adjustable.

Fixed shading systems offer permanent shading solutions that reduce solar heat gain, minimize glare, and enhance visual comfort.

Solar shading systems are essential for maximizing energy efficiency and enhancing occupant comfort in buildings. By effectively managing sunlight penetration, these systems reduce heat gain, minimize glare, and optimize natural lighting.

- **RETRACTABLE SHADING SYSTEMS:** → Retractable shading systems provide flexibility by allowing adjustment of shading levels based on changing needs. They offer control over sunlight penetration and can be manually or automatically operated. Examples include:
  - Retractable AWNINGS → These shading systems can be extended or retracted to provide shade when needed. They are popular for outdoor spaces such as patios and terraces.
  - MOTORIZED BLINDS → Motorized blinds can be controlled remotely or programmed to adjust automatically based on time of day or sunlight intensity. They provide precise control over shading levels.

Retractable shading systems offer convenience and adaptability to changing solar conditions and occupant preferences.

Solar shading systems are essential for maximizing energy efficiency and enhancing occupant comfort in buildings. By effectively managing sunlight penetration, these systems reduce heat gain, minimize glare, and optimize natural lighting.

- DYNAMIC SHADING SYSTEMS: → Dynamic shading systems utilize advanced technologies to optimize shading based on real-time data. They can adjust shading elements dynamically, providing optimal solar control. Examples include:
  - SMART GLASS → Smart glass incorporates electrochemical or thermochemical technologies that allow for automatic tinting based on sunlight intensity. It provides adaptive shading and reduces the need for manual adjustments.
  - AUTOMATED LOUVRES → These shading systems use sensors to detect sunlight and adjust the angle of the louvres accordingly. They offer precise control over shading and solar heat gain.

Dynamic shading systems maximize energy efficiency, comfort, and daylighting while minimizing the need for manual intervention.

Solar shading systems are essential for maximizing energy efficiency and enhancing occupant comfort in buildings. By effectively managing sunlight penetration, these systems reduce heat gain, minimize glare, and optimize natural lighting.

- DOUBLE SKIN FAÇADES → Double skin façades are multi-layered systems that incorporate an outer layer of glass or other materials to provide shading. They create an insulating air gap between the layers, reducing solar heat gain and optimizing thermal performance. Double skin façades offer several advantages, including:
  - SOLAR CONTROL --> The outer layer acts as a shading device, reducing direct sunlight and heat gain.
  - NATURAL VENTILATION --> The air gap allows for natural airflow, reducing reliance on mechanical ventilation.
  - AESTHETICS --> Double skin façades offer design versatility and visual appeal.

2. LITERATURE

2.1 SHADING SYSTEM AND FAÇADES

Double Skin Facade (DSF)

Shading System Typologies and Development in Architecture.
The double-skin facade has emerged as an innovative and effective shading system typology in contemporary architecture. This architectural feature combines the benefits of passive solar design with advanced building technologies, offering enhanced energy efficiency and occupant comfort. The development of shading system typologies, including double-skin façades, modular systems, and adaptive solutions, has broadened the scope of design possibilities for architects and engineers alike. This article explores various shading system typologies and their impact on architectural design, energy efficiency, and occupant comfort.
2. Components of Double Skin Façades

2.1.1 DOUBLE SKIN FACADE

The double-skin facade is a relatively recent innovation in shading system typologies. It consists of two layers of glass separated by an air cavity, with the outer layer acting as a buffer zone to reduce solar heat gain and improve thermal insulation. The space between the two layers can be naturally or mechanically ventilated, depending on the desired level of energy efficiency. Doubleskin façades offer numerous advantages, including improved thermal comfort, reduced energy consumption, and enhanced acoustic performance.

2.1.2 DSF S COMPONENTS

2.1.2.1 Outer Skin

The outer skin of a double-skin facade is typically made of glass, with the primary function of providing solar protection. This layer can incorporate various shading devices, such as louvres, fritted glass, or photovoltaic cells, to control the amount of sunlight entering the building. The outer skin can also be designed to improve the building's appearance and overall aesthetics.

2.1.2.2 Inner Skin

The inner skin of a double-skin facade is typically the primary thermal barrier and is often made of high-performance glazings, such as Low-E glass or triple-pane insulated glass units. This layer is responsible for maintaining a comfortable indoor environment by reducing heat transfer between the interior and exterior of the building.

2.1.2.3 Air Cavity

The air cavity between the inner and outer skins serves as a thermal buffer, reducing heat

transfer and improving the overall energy efficiency of the facade. This space can be naturally or mechanically ventilated, depending on the design intent and specific performance requirements.
Additionally, the air cavity can be used to house integrated shading devices, such as blinds or louvres, which can be adjusted to control daylighting and glare.

2.1.3 SHADING DEVICES

Shading devices within a double-skin facade can be integrated into the outer skin, the air cavity, or the inner skin, depending on the desired performance characteristics. These devices can be fixed or adjustable and can include louvres, blinds, fritted glass, or even photovoltaic modules.
The choice of shading device will depend on factors such as climate, building orientation, and desired energy performance.

2.1.4 BENEFITS OF DSFS

2.1.4.1 Energy Efficeincy

Double-skin façades can significantly improve a building's energy efficiency by reducing solar heat gain, improving thermal insulation, and optimizing daylighting. By minimizing the need for mechanical cooling and artificial lighting, these systems can contribute to lower energy Consumption and reduced operational costs.

2.1.4.2 Thermal Comforts

By creating a buffer zone between the interior and exterior environments, double-skin façades not only enhance energy efficiency but also significantly contribute to occupant comfort. This buffer zone acts as a thermal barrier, regulating temperature variations and reducing the impact of external weather conditions, ensuring a more pleasant and consistent indoor environment.

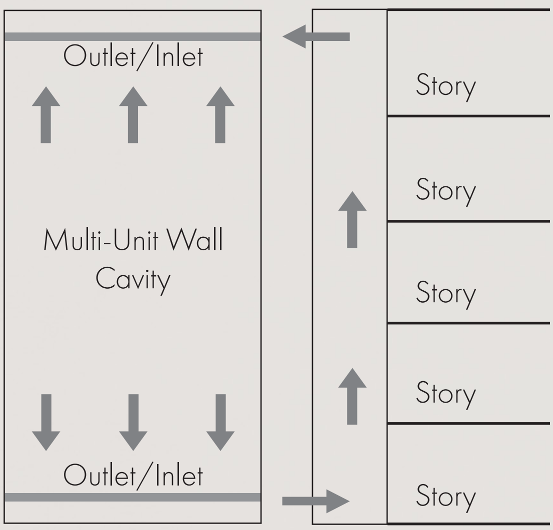
Double Skin Facade (DSF)

2.1 SHADING SYSTEM AND FAÇADES

Double Skin Facade (DSF) (*classification*)

1. High Rise Double Skin Building

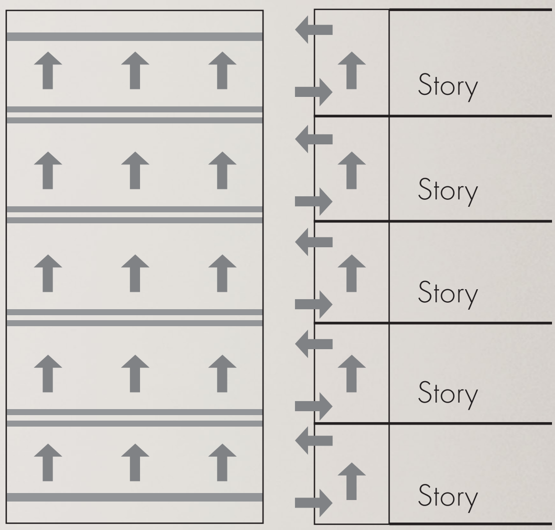
- Vertical airflow is not restricted throughout the height.
- Air inlet is usually located near the bottom of the building.
- This type of DSF is not suitable for natural ventilation, as the ventilation rate is not balanced throughout the building.
- Fire protection and noise transmission between floors are a concern.



DSF Elevation DSF Section

2. Story-High Double-Skin

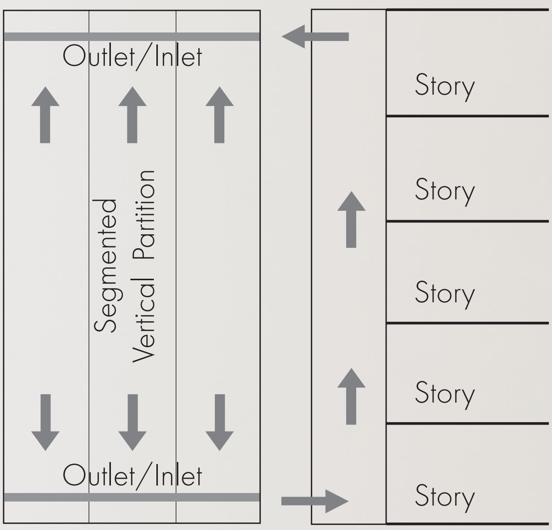
- Vertical airflow is restricted to one floor.
- Horizontal airflow is not restricted.
- Air inlets and outlets are located at the bottom and top of each floor.
- This type of DSF enables natural ventilation and improves fire protection.



DSF Elevation DSF Section

3. Box Double-Skin Facade

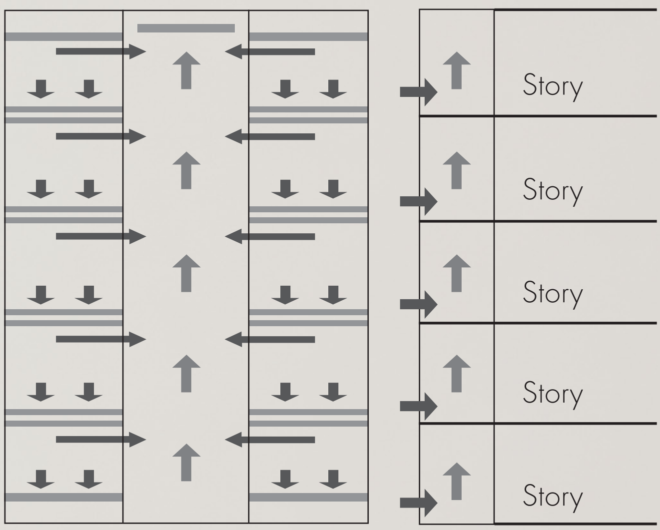
- Airflow is restricted by vertical partitions on each floor and horizontal partitions at each box unit.
- Natural ventilation and better sound insulation within the cavity can be achieved.



DSF Elevation DSF Section

4. Shafted Facade

- Combines story-high cavity and vertical building-high shafts.
- Air flows into the story-high cavity through the inlets on each floor and
- Converges at the vertical shafts.
- Natural ventilation is made possible even with little airflow from outside due to buoyancy in the shaft.



DSF Elevation DSF Section

2. LITERATURE

2.2 CASE STUDIES

As previously stated, the following steps will be analysis of data and case study overview.
To facilitate understanding, each project has been categorized into subcategories. The factors taken into account are the year of construction, the state of construction, the type of project (exhibition, canopy,...), user responsiveness, self sustaining, and Biomass Production.

Having optimal outcomes is one of the fundamental components of this study, thus another factor to examine is the possibility of each project supply secondary output.

Since this section takes into account all aspects of a project and its timeliness, a more detailed description has been presented for each case, which can be studied on the subsequent sections. The analysis covers algal construction investigations. The locations and designers differ from one another and none of them were completed prior to 2011.

The majority of the cases are in Europe, and the materials used are mainly focused on application of algae. The techniques used to develop the project will be covered in the analysis.

Secondary output is considered as an extra capability of outcome from bioreactors. Growing and harvesting algae, as well as purifying urban air, are just two ways to describe algae production. Despite the fact that the production is vast, the adaptive one and the facade system are the interesting projects that will be considered and analysed.

The emphasis during the analysis process is on understanding how the mechanisms and projects have evolved over the last few years, as well as attempting to better understand the pros and cons, as well as the parts that remain incapable of responding to design requirements.

The diagram on the right side of the page will help to clarify the variables are considered and their importance; the larger the circle, the more significant it is. The colour has been inspired from the vibrant green algae colour.

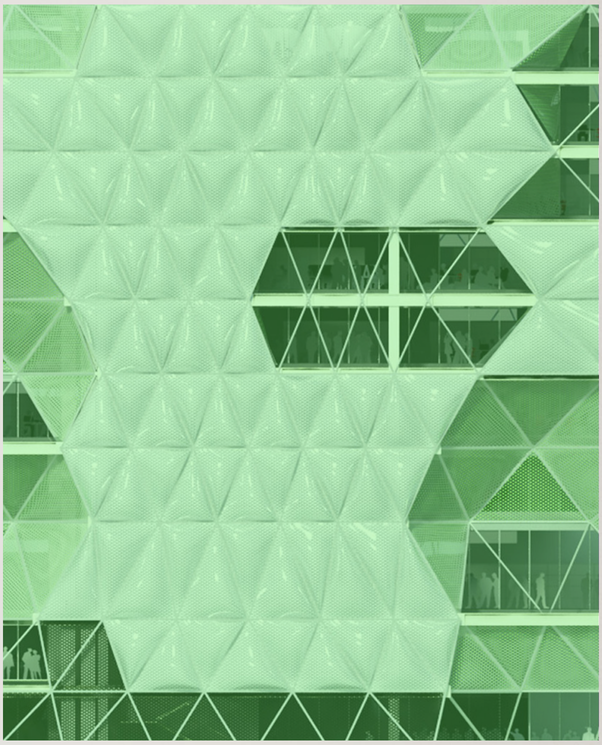

Building
Exhibition
Realized
Biomass Production
Self-Sustaining
Secondary Output
Media-TIC
BIO.BOLLA
Air Bubble
Bio-Series
BIQ Building
Urban Algae Canopy
A Modular Kit

MEDIA-TIC

LOCATION: Barcelona- Spain

DESIGNER: CLOUD 9 - ENRIC RUIZ-GELI

PROJECT YEAR: 2011



The Media-TIC Building, located in Barcelona, is an iconic architectural project that reflects innovative design principles and sustainability. This case study aims to analyse the key features, design concepts, and the impact of the Media-TIC Building on the urban landscape and the technology sector.

The Media-TIC Building is a vibrant hub for technology and innovation, designed to foster collaboration and creativity among its occupants. The architectural concept behind the building revolves around the idea of a "smart skin" that adapts to environmental conditions and user needs.

The building's most distinctive feature is its colourful and dynamic façade, composed of a series of moveable panels. These panels can rotate and adjust to optimize natural lighting, solar shading, and energy efficiency. The façade acts as an interactive membrane that responds to external factors, creating a dynamic and visually striking appearance.

The Media-TIC Building is a flagship example of sustainable design and green architecture. The moveable façade panels contribute to energy efficiency by reducing solar heat gain and allowing for natural ventilation. This passive design approach helps minimize the building's energy consumption and reliance on artificial cooling systems.

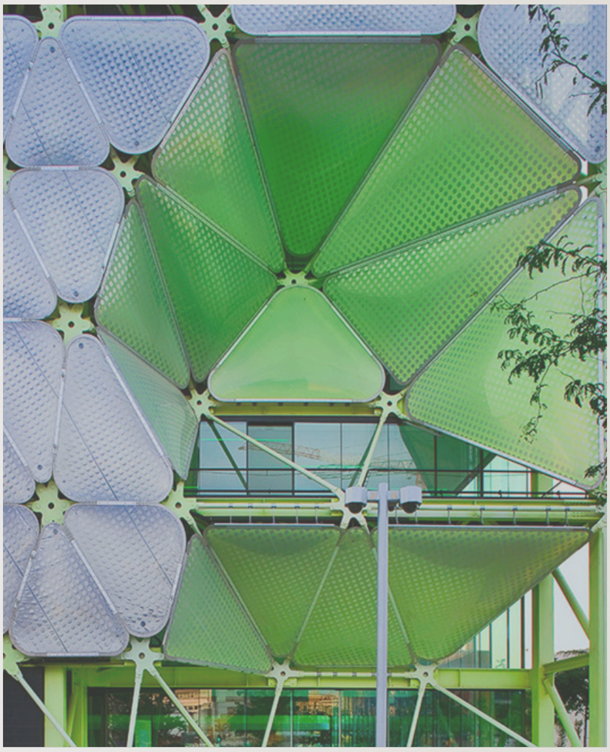
Additionally, the building incorporates renewable energy sources. Photovoltaic panels are integrated into the façade and roof, generating clean energy and contributing to the building's power supply. The use of renewable energy reduces carbon emissions and promotes a more sustainable operation.

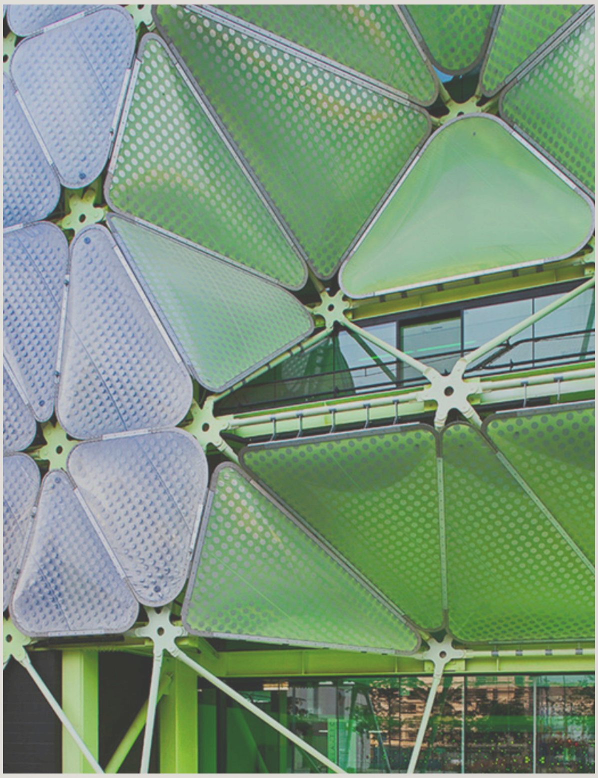
The Media-TIC Building has made a significant impact on the urban landscape of Barcelona, symbolizing the city's commitment to innovation and technological advancement. It has become an iconic landmark, representing the city's status as a hub for technology and entrepreneurship.

Moreover, the building has created a conducive environment for collaboration and knowledge sharing within the technology sector. Its open and flexible spaces, along with shared amenities and common areas, promote interaction and the exchange of ideas among professionals and start-ups.

The Media-TIC Building's innovative design and sustainability features have also inspired other architects and developers to embrace green design and building technologies in the region.

1 HTTPS://en.wikiarquitectura.com/building/media-tic/



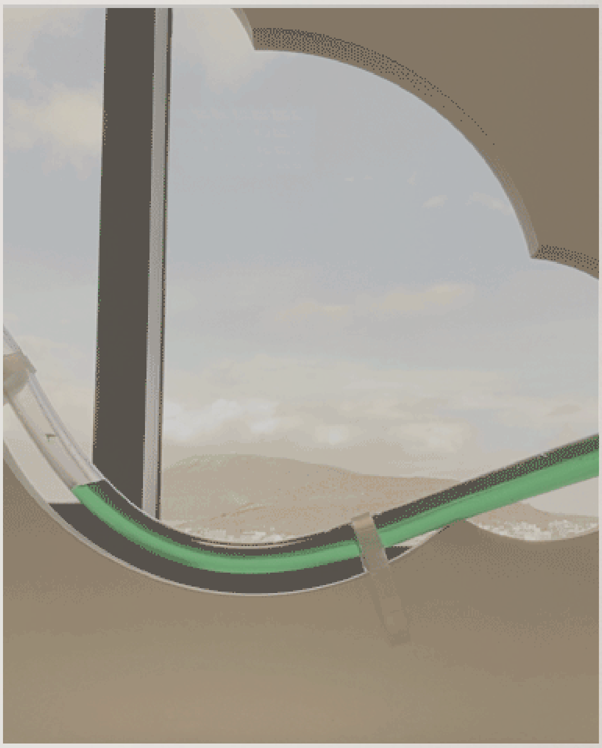


BIO.BOLLA

LOCATION: Italian Embassy in Arona

DESIGNER: EcoLogicStudio

PROJECT YEAR: 2023



The BioBolla project, developed by ecoLogicStudio, is a ground-breaking initiative that explores the intersection of biology, design, and technology. This case study aims to analyse the project's key design features, its sustainable aspects, and its contribution to the advancement of bio-digital architecture.

The BioBolla project is a living structure that combines biotechnology and architectural design principles. It takes inspiration from natural systems, particularly the behaviour of bio-organisms, to create an interactive and dynamic architectural installation.

The structure consists of a series of interconnected bubbles made of transparent, biodegradable materials. Within these bubbles, living micro-organisms, such as algae and bacteria, are cultivated. The micro-organisms respond to environmental stimuli, altering their growth patterns and creating an ever-changing, organic aesthetic.

The BioBolla project showcases the potential of bio-digital architecture to contribute to sustainable design. By integrating living organisms into the structure, the project promotes the use of natural processes to enhance environmental performance.

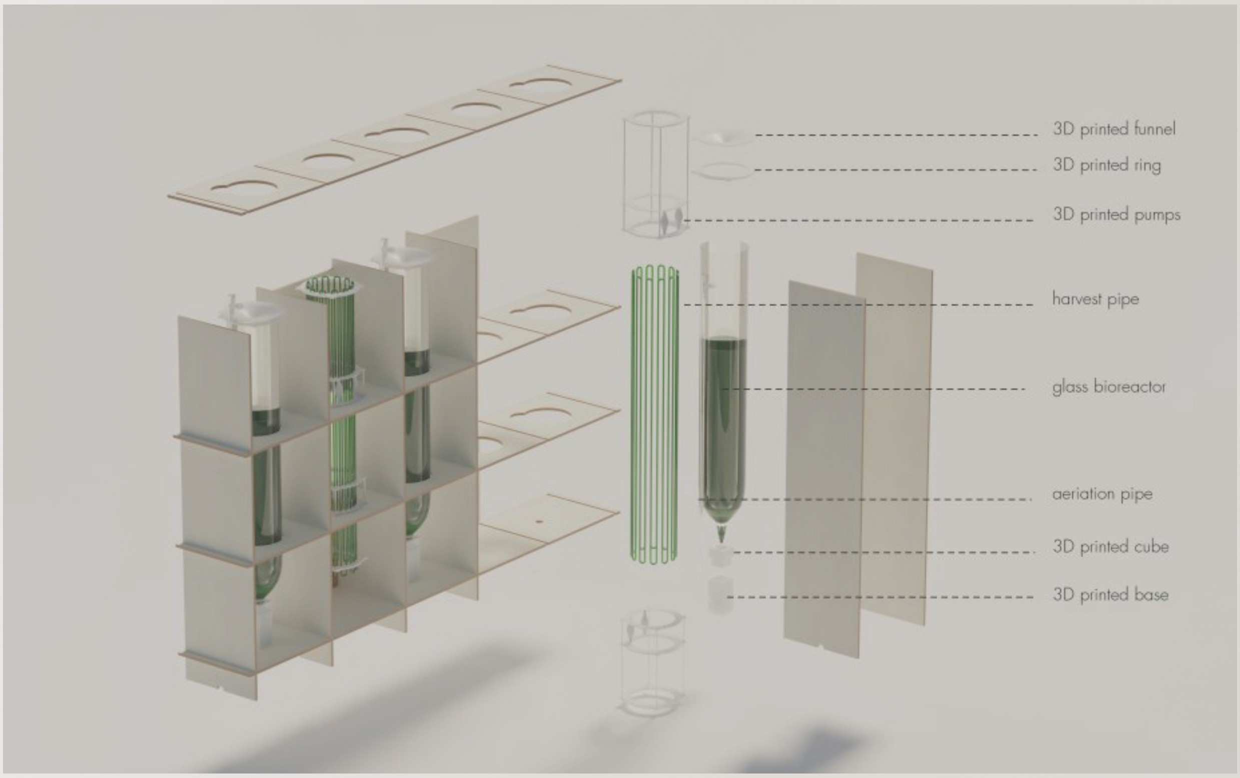
The micro-organisms within the bubbles perform functions such as carbon sequestration, air purification, and oxygen production through photosynthesis. These biological processes help improve air quality and reduce the carbon footprint of the structure, making it more environmentally friendly.

Furthermore, the use of biodegradable materials in the construction of the bubbles ensures minimal environmental impact. The materials can break down naturally over time, eliminating waste and reducing the structure's long-term ecological footprint.

The BioBolla project offers an impressive experience that engages visitors in a dialogue about the potential of bio-digital architecture and its impact on society. By showcasing the integration of biology and design, it fosters a deeper understanding of the interconnections between nature, technology, and the built environment.

The project also highlights the importance of sustainable practices and the role of architecture in addressing environmental challenges. It encourages individuals, architects, and policymakers to consider innovative solutions that embrace nature-inspired design principles and promote ecological awareness.

 https://www.ecologicstudio.com/projects/biobolla


3D printed funnel
3D printed ring
3D printed pumps
harvest pipe
glass bioreactor
aeriation pipe
3D printed cube
3D printed base

AIRBUBBLE

LOCATION: Poland- Warsaw

DESIGNER: EcoLogicStudio

PROJECT YEAR: 2018

The Airbubble Playground and Exhibition, developed by ecoLogicStudio, is an innovative project that combines art, technology, and sustainability. This case study aims to analyse the project's key features, design principles, and its impact on the environment and society.

The Airbubble Playground and Exhibition is a unique architectural installation that utilizes bio-digital design principles. Inspired by the study of plants and their ability to perform photosynthesis, the project integrates living organisms, such as micro-algae, with responsive technologies to create an interactive and dynamic environment.

The installation consists of a series of transparent, inflatable bubbles that host micro-algae cultures. These bubbles are interconnected and respond to environmental stimuli, such as temperature, light, and air quality. Visitors can interact with the installation by triggering changes in the bubble's appearance and the behaviour of the micro-algae within.

The project's main objective is to explore the potential of micro-algae as a renewable and sustainable resource. Micro-algae are capable of absorbing carbon dioxide and producing oxygen through photosynthesis, contributing to the reduction of greenhouse gas emissions. By incorporating micro-algae within the bubbles, the project acts as a living air filter, improving air quality and enhancing the overall ecological performance of the space.

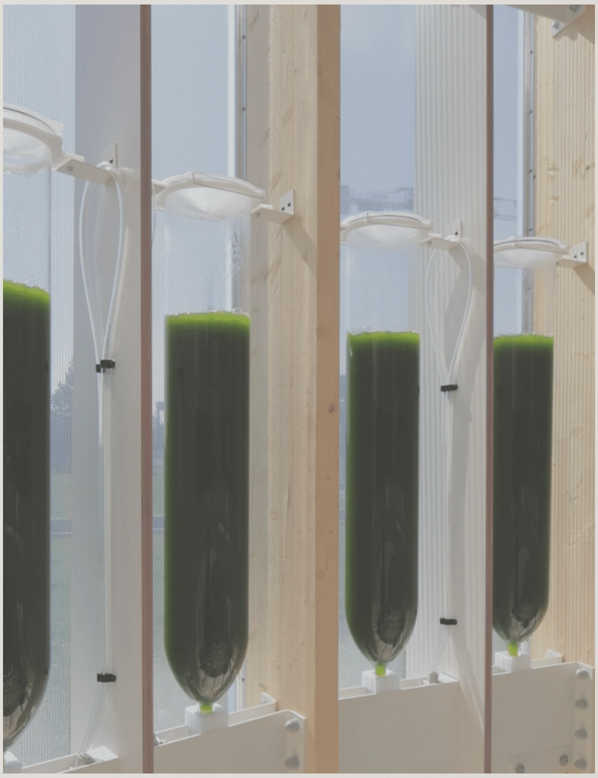
Moreover, the Airbubble Playground and Exhibition demonstrates the integration of renewable energy sources. The bubbles are equipped with photovoltaic cells, which generate electricity from solar energy. This sustainable energy supply powers the technological components of the installation, reducing reliance on conventional energy sources.

The project aims to raise awareness about the potential of bio-digital design and its applications in creating sustainable and interactive urban environments. By providing an engaging and impressive experience, the Airbubble Playground and Exhibition encourages visitors to reflect on the interconnection between nature, technology, and human activities.

The project has developed a new potential of biotechnology in shaping the cities of the future.

 https://www.ecologicstudio.com/projects/airbubble-playground-and-exhibition



BI.O.SERIE

LOCATION: Frankfurt -Germany

DESIGNER: EcoLogicStudio

PROJECT YEAR: 2020

The Bi-O Series project, developed by ecoLogicStudio, is a pioneering initiative that explores the potential of biotechnology and biofabrication in architecture. This case study aims to analyse the project's key design elements, its sustainable features, and its contribution to the advancement of sustainable architecture.
The Bi-O Series project is a collection of biologically inspired, 3D-printed structures that blur the boundaries between architecture, art, and biology. The project leveraged bio-fabrication techniques to create intricately designed, porous structures that mimic natural forms and functions.
These structures are generated through the interaction between living micro-organisms and an advanced robotic fabrication system. The micro-organisms, known as diatoms, are microscopic algae with unique shapes and patterns. By manipulating the growth patterns of the diatoms, the project produces complex architectural elements with high levels of detail and aesthetic appeal.
The Bi-O Series project showcases the potential of biotechnology in creating sustainable architectural solutions. By utilizing the growth capabilities of diatoms, the project offers a sustainable alternative to traditional manufacturing processes that often contribute to environmental degradation.
The use of bio-fabrication techniques significantly reduces the consumption of energy and resources compared to conventional construction methods. Additionally, the project employs biodegradable materials, such as biopolymers, which minimize the environmental impact during the life cycle of the structures.
Furthermore, the porous nature of the Bi-O Series structures allows for improved ventilation, natural lighting, and thermal regulation. This bioclimatic design approach reduces the need for artificial lighting and HVAC systems, resulting in energy savings and a lower carbon footprint.
The Bi-O Series project holds the potential to revolutionize the architectural and design industry by integrating living organisms and advanced fabrication technologies. It serves as an inspiration for architects, designers, and researchers to explore the possibilities of biotechnology in creating sustainable, functional, and aesthetically pleasing structures.

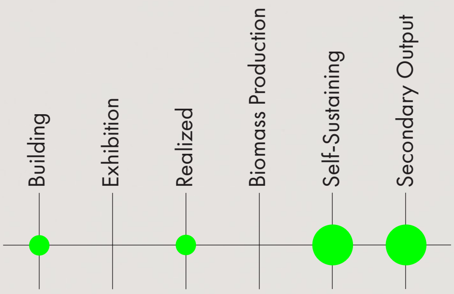
 https://www.ecologicstudio.com/projects/bi-o-serie

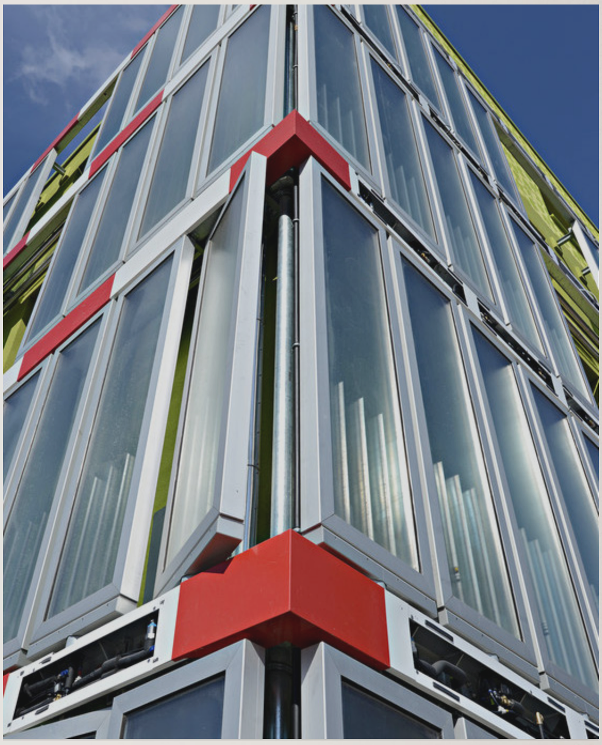
BIQ-BUILDING

LOCATION: Hamburg, Germany

DESIGNER: BPR Facade System

PROJECT YEAR: 2013





The International Building Exhibition (IBA) Hamburg is a renowned project that showcases innovative approaches to urban development and sustainable architecture. This case study aims to analyse the key objectives, design principles, and the impact of IBA Hamburg on the city's built environment and society.

The IBA Hamburg is an international platform that brings together architects, urban planners, and experts to address pressing urban challenges and develop sustainable solutions. It focuses on transforming existing neighbourhoods, developing new urban districts, and improving the quality of life for residents.

The IBA Hamburg encompasses various architectural and urban planning projects, each demonstrating a commitment to sustainability, social inclusion, and innovative design. The exhibition showcases projects that explore topics such as energy efficiency, mobility, social housing, public spaces, and climate resilience.

The projects within the IBA Hamburg employ a diverse range of design strategies, including adaptive reuse, energy-efficient building materials, green infrastructure, and participatory planning processes. The integration of sustainable technologies, such as renewable energy systems and intelligent urban management systems, further enhances the projects' environmental performance.

The IBA Hamburg has had a profound impact on the city's built environment and society. By implementing sustainable and innovative architectural and urban planning solutions, it has revitalized existing neighbourhoods, created new vibrant urban districts, and improved the overall quality of life for residents.

This knowledge exchange has contributed to the ongoing transformation of Hamburg into a model city for sustainable urban environments.



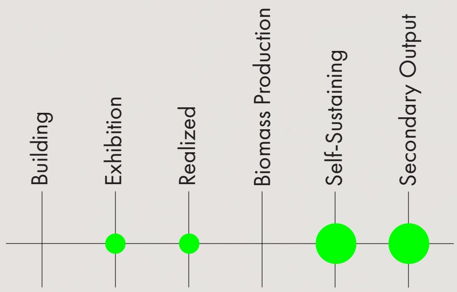

URBAN CANOPY

LOCATION: Milan- Italy

DESIGNER: Claudia Pasquero,Marco Poletto

EXHIBITION: Design Week MILAN

PROJECT YEAR: 2014



The Urban Algae Folly, showcased at Expo Milan 2015, is a remarkable architectural project developed by ecoLogicStudio. This case study aims to analyse the key design elements, sustainable features, and the impact of the Urban Algae Folly on the Expo Milan exhibition and the discourse around sustainable urban development.

The Urban Algae Folly is an experimental structure that explores the potential of algae as a sustainable building material and a tool for environmental re-mediation. The design concept revolves around integrating living micro-organisms into the building envelope to perform multiple functions.

The structure consists of a lightweight, modular system composed of bioplastic panels filled with algae and embedded with custom-designed photobioreactors. These photobioreactors allow the algae to photosynthesise and produce biomass while filtering carbon dioxide from the surrounding air.

The Urban Algae Folly exemplifies sustainable design principles and addresses environmental challenges. The integration of algae into the building envelope helps to sequester carbon dioxide, mitigating the impacts of climate change. Algae also act as a natural filter, purifying the air and reducing pollutants.

The structure's modular design allows for flexibility and adaptability, enabling it to be easily disassembled, transported, and reused in different locations. The use of bioplastics in the panels promotes the use of renewable materials and reduces the reliance on traditional, resource-intensive construction materials.

The Urban Algae Folly serves as an educational tool, raising awareness about the potential of algae and biotechnology in sustainable urban development. It promotes the importance of integrating nature and technology to create more resilient for friendly built environments.

[1] HTTPS://www.ecologicstudio.com/projects/expo-milano-2015-urban-algae-folly

A Modular Kit

LOCATION: Milan- Italy

DESIGNER: MaBa.SAPERLab research team

EXHIBITION: Biennale Venezia

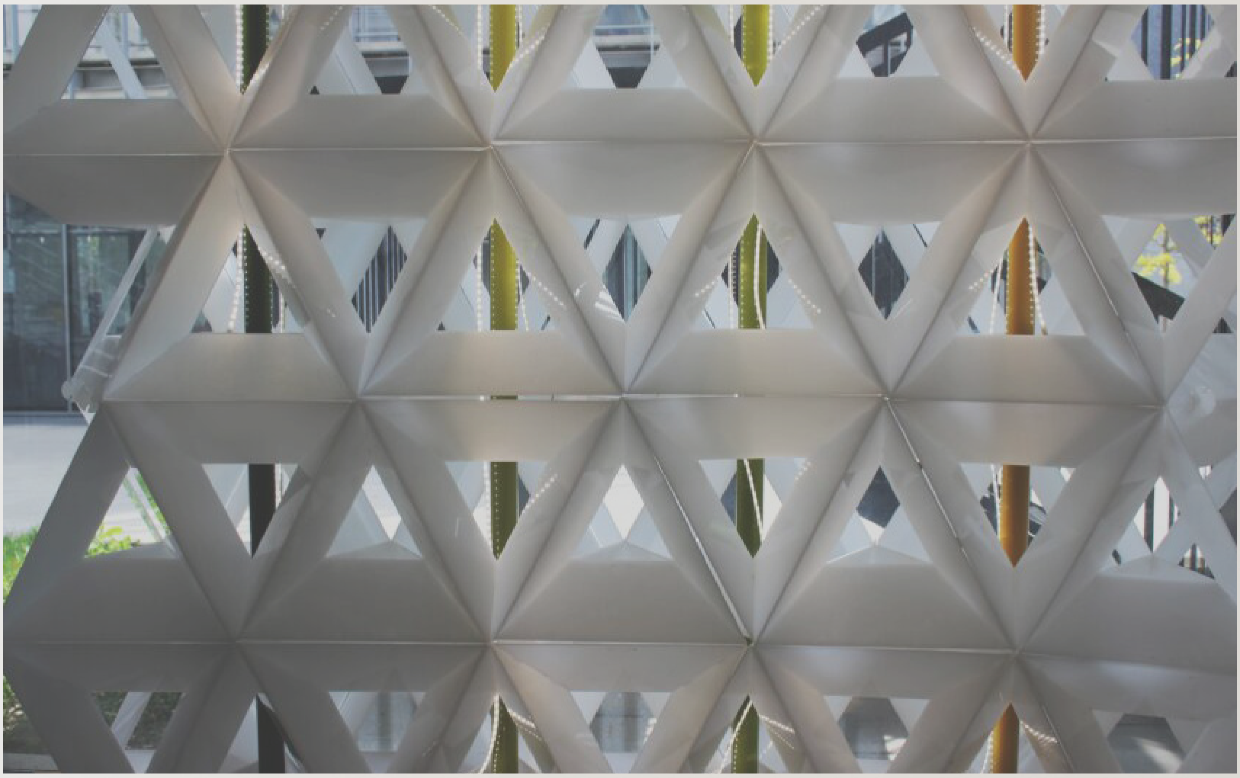
PROJECT YEAR: 2020

The Struna modular kit, created by the ABClab unit MaBa.SAPERLab at Politecnico di Milano, is a versatile system designed to enhance our living and working environments while reducing CO2 emissions. Consisting of interconnected bioreactors and modular elements, it offers a solution for cultivating microalgae both horizontally and vertically. The concept originated from an exhibition called "999: A Collection of Questions on Contemporary Living" and evolved from using pots with soil to focusing on microalgae after consultations with biologists. Microalgae bioreactors possess air filtering properties that are beneficial for spaces with high foot traffic. Unlike plants, these bioreactors filter CO2 emissions continuously and are applicable year-round. Additionally, microalgae offer advantages beyond air quality, with potential applications in the food, pharmaceutical, agricultural, and wastewater treatment sectors.

The Struna modular kit provides adaptability for both indoor and outdoor use, making it suitable for diverse environments. Its installation offers multiple benefits such as partitioning living areas, improving aesthetics, enhancing air quality, and providing sound insulation. Furthermore, implementing the Struna kit can contribute to earning green certificates. The design of the kit incorporates easily assembled dry elements, and the team is collaborating with interested companies for manufacturing and marketing. The parametric structure of Struna can be customized to meet specific environmental requirements, offering flexibility in its configuration.

Led by Professor Ingrid Paoletti, the research team aims to make the kit widely available and is developing software to facilitate its design and installation in various situations, further promoting its adoption.

 https://www.frontiere.polimi.it/a-modular-kit-for-growing-microalgae-at-home-and-improving-the-environment/?lang=en



3.PROBLEM STATEMENT

The most popular façade systems are briefly reviewed in the previous sections of the literature, together with some case studies to illustrate what has recently been achieved in the field of architecture and design in relation to nature-based materials. This phase of the study has helped to highlight how often the interior and exterior of the same building are considered as two completely different parts.

On the contrary, it was felt that together they have an important impact on the overall energy efficiency and footprint of the building, and thus serve more than just an aesthetic function. This perspective had a major impact on the study and definitely shaped the final objectives.

It was then important to understand why this approach was taken, and then to propose a different approach, based on an understanding that what happens outside a building greatly affects its energy balance, and even that of its environment. Addressing environmental concerns and integrating sustainable practices into built environments. However, a major challenge is that there is a lack of research and understanding of how natural and sustainable materials can be effectively incorporated into architectural design. This lack of research means that the many benefits of these materials are being neglected. The limited research and use of natural and sustainable materials is an inherent problem in architecture.

Moreover, the advantages of natural and sustainable materials, including resource efficiency, reduced carbon emissions, improved indoor air quality, and support for biodiversity and habitat preservation, often go unrecognized. The limited understanding of these materials and their potential applications has resulted in missed opportunities for creating healthier, more resilient, and environmentally conscious architectural designs.

factors contribute to the lack of emphasis on researching and understanding the implementation of natural and sustainable materials in architecture. Limited access to information, insufficient academic programs dedicated to sustainable architecture, and a traditional mindset within the industry that favors established materials and practices all contribute to this knowledge gap.

Addressing this problem requires collective efforts from researchers, architects, educators, and policymakers. Comprehensive studies are needed to investigate the properties, performance, and long-term viability of natural and sustainable materials in architectural applications. Through rigorous research, exploration of innovative solutions, and knowledge sharing within the industry, this gap can be bridged, unlocking the full potential of natural and sustainable materials in architecture.

In conclusion, the insufficient study and understanding of how to effectively incorporate natural and sustainable materials in architecture, along with the neglect of their advantages, present significant challenges. Resolving this issue necessitates increased research, knowledge dissemination, and collaboration among stakeholders. Only by addressing this knowledge gap can the architecture industry move towards a more sustainable and environmentally conscious future.

III

STATE OF WORK

1. Aims & Objectives
2. Key Words
3. Research Question

In chapter three, the rationales of conducting the study will focus on the most pertinent possible questions in order to establish a main goal for the investigation. After reviewing the objectives and expectations pages, run a SWOT analysis to gain a more thorough comprehension of the project's strengths, weaknesses, opportunities, and threats.

1. AIMS AND OBJECTIVES

WHAT IS LACKING IN THE CURRENT SITUATION AND WHAT IS GOING TO BE TACKLED DOWN ALONG THE RESEARCH

One of the key objectives of the research has been to develop a flexible system with few designed characteristics that is also capable of adapting to the environment condition it must operate in, rather than a finite product that is specifically built for one site.

In this approach, depending on the kinds of inputs the environment may provide, the properties of the nature-based material chosen, algae, will generate an infinite number of chances.

The key expectation is to carry out simoultaneously research and design, producing a strategy that will not prioritize just only one of these disciplines over the other and allowing a constant flow of data, both theoretical and empirical.
By applying this kind of framework, the goal is to reach the best outcome possible with the information that have been processed.

In order to develop a proposal that is relevant to concrete events, the research method, as described in the book's introduction, wishes to keep an eye on the challenges and trends of the current society. By examining the situation in the "First World" nations, it is reasonable to conclude that there is a shortage of available land for the construction of new, energy-efficient buildings.

The aim then becomes to create a system that can be applied to existing structures in order to improve their structural behaviour, energy efficiency, and aesthetic appeal. In the case of this study, the objective is to concentrate on the development of a retrofitting facade that will have an impact on the building's energy efficiency.

The analysis of the existing condition, which was previously described in the "State of Art" chapter, helped to focus such efforts. As already said, one of the biggest problems , societies are currently facing, is climate change, whose effects have an impact on all aspects of human living both directly and indirectly. One tactic is to make an effort to lower energy usage in order to maintain the lifestyle we are accustomed to, which is based on extensive use of technology and a high degree of comfort.

The aim is to use architectural elements and an adaptive facade system to decrease the building's total footprint.

Starting with an investigation of the possibilities already available in the field of building for façade systems, it was decided to focus on researching active facade typologies rather than passive ones. This is because the goal is to develop a system that actively responds to environmental inputs rather than simply adapting to one duty, like wind regulation or shade. The ideal choice appears to be to embrace a material-based technology with the added goal of avoiding as far as possible the usage of mechanical systems that require human action or any other device, like an Arduino.

Since it is based on analysing the natural behaviour of materials and their capacity to respond to certain conditions, this will better serve the goals of a free-tech system.

2. KEYWORDS

RETROFITTING FACADE

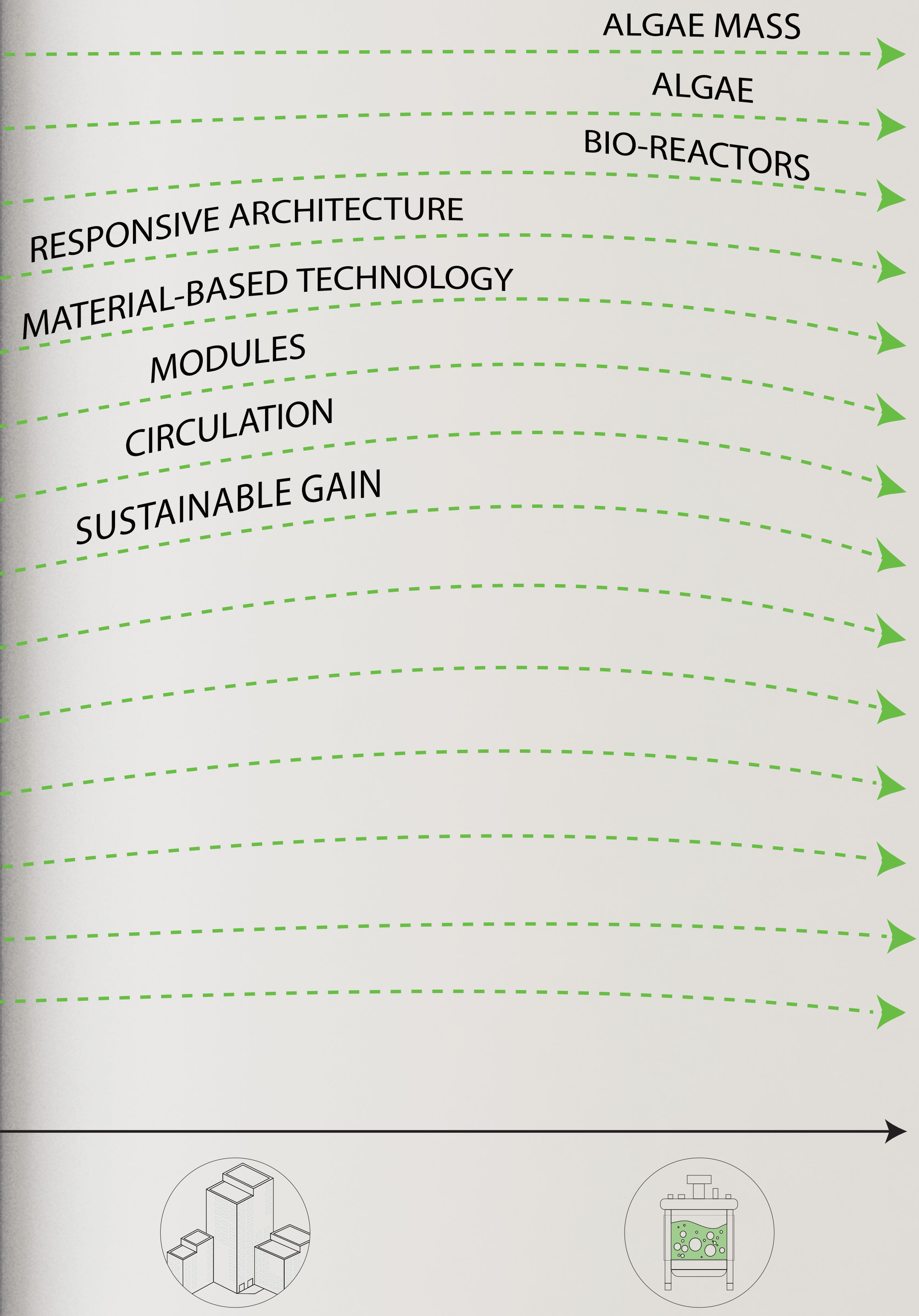
ADAPTIVE COMPONENTS

ACTIVE FACADE

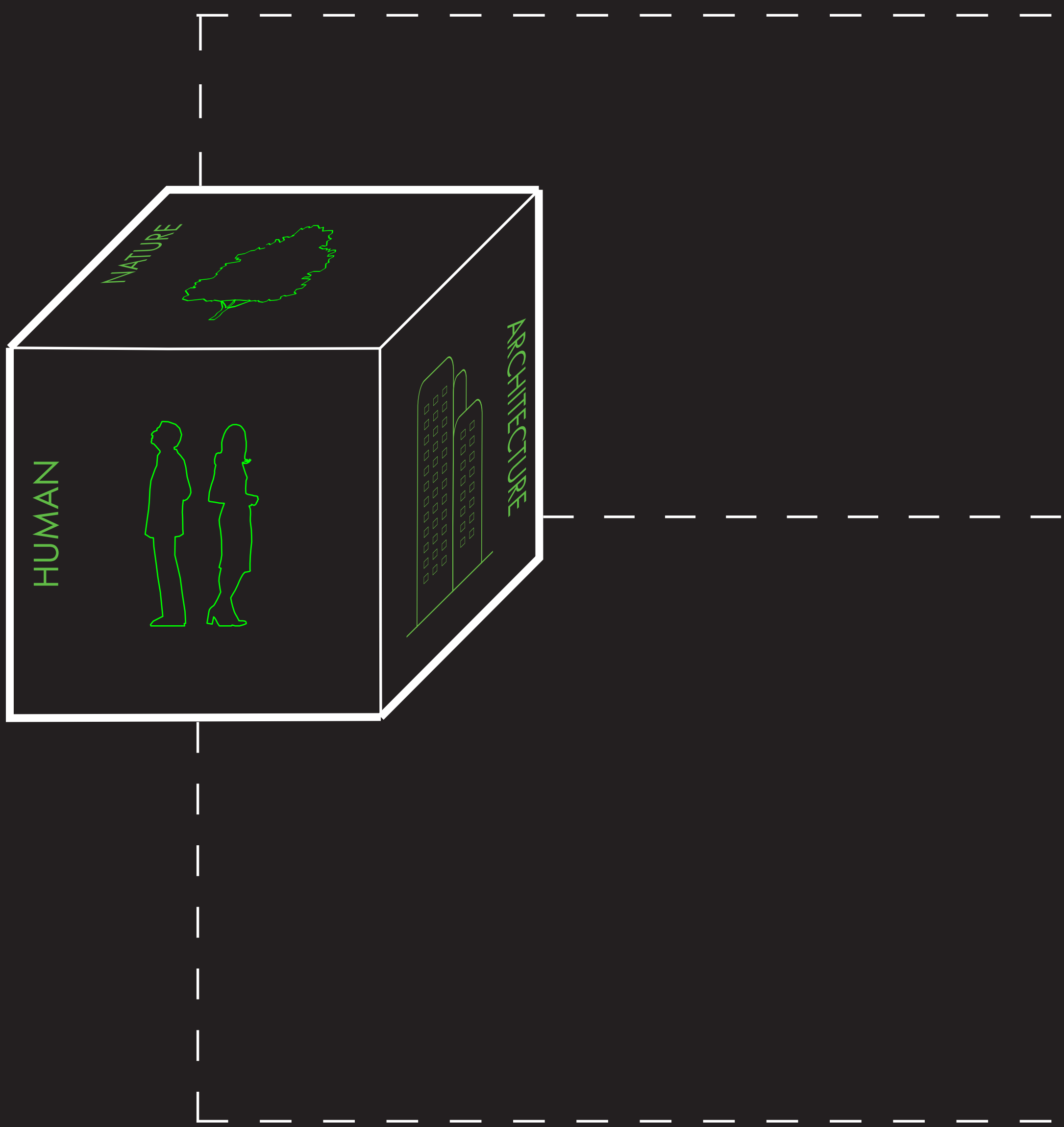
SUSTAINABILITY

ENERGY SAVING

CLIMATE CHANGE


ALGAE MASS
ALGAE
BIO-REACTORS
RESPONSIVE ARCHITECTURE
MATERIAL-BASED TECHNOLOGY
MODULES
CIRCULATION
SUSTAINABLE GAIN

3.RESEARCH QUESTION



_ _ _ _ 1- Is it possible to design a singles component and scale it up into an interactive modular system?

_ _ _ _ 2- How can we significatively impact the energy efficency of a building by using a shading system?

_ _ _ _ 3- Is it possible to design an environment-responsive system, made by the combination of two natural-based materials Can any natural material and algae panels be combined, as different modules, working efficently as a facade system?

IV

Neither Animal Nor Plant

The Chapter covered various topics related to algae and its applications. It introduced algae as diverse photosynthetic organisms, discussing their characteristics and adaptability. The taxonomic classification of algae was presented, highlighting major groups. The production of biofuels from algae was explored, including methodologies such as lipid extraction and fermentation. The integration of bioreactors in residential buildings for on-site biofuels production was emphasized. The importance of biofuels from bioreactors in individual buildings was discussed, highlighting reduced dependence on fossil fuels and lower carbon emissions.

NEITHER PLANTS NOR ANIMAL

ALGAE

1. General Overview

1.1 Algae – an overview

algae are a diverse group of photosynthetic organisms that play a crucial role in various ecosystems (Smith et al., 2016). They are simple, plant-like organisms that lack true roots, stems, and leaves. Algae can be found in a wide range of habitats, including freshwater bodies, oceans, moist soil, and even in symbiotic relationships with other organisms (Gao et al., 2019). Their photosynthetic capabilities make them important primary producers, contributing significantly to oxygen production and carbon dioxide fixation (Raven et al., 2017). In the context of facade panels, algae offer potential benefits such as energy generation and environmental sustainability (Mueller et al., 2022).

To fully comprehend the significance of algae in the field of facade panels, it is essential to understand their general characteristics and features, including their cellular structure, metabolic processes, and adaptability to different environments (Sutherland et al., 2021). By exploring these aspects, we can gain insights into the potential application of algae in sustainable architecture.

Algae exhibit a wide range of structural diversity, from single-celled organisms to complex multicellular forms (Graham et al., 2018). Their cells are eukaryotic, containing membrane-bound organelles such as chloroplasts, mitochondria, and nuclei (Larkum et al., 2020). Chloroplasts, which contain chlorophyll and other pigments, are responsible for photosynthesis, converting light energy into chemical energy (Raven et al., 2017). Additionally, algae cells may possess specialized structures like flagella, which enable them to move and respond to environmental stimuli (Harris et al., 2020).

Photosynthesis is the primary metabolic process in algae, where they utilize sunlight, water, and carbon dioxide to produce oxygen and organic compounds (Beardall et al., 2019). Algae can also carry out other metabolic processes, such as respiration, nitrogen fixation, and the synthesis of secondary metabolites (Wang et al., 2021). These unique capabilities make algae a fascinating subject for research and development in the field of sustainable architecture.

1.2 General Characteristic ofAlgae

Algae, which are a diverse group of photosynthetic organisms, play a vital and multifaceted role in various ecosystems across the globe (Smith et al., 2016). They represent a fascinating array of simple, plant-like organisms that lack true roots, stems, and leaves. Algae have the remarkable ability to inhabit a wide range of habitats, including freshwater bodies, oceans, moist soil, and even engage in symbiotic relationships with other organisms (Gao et al., 2019). One of the key aspects that distinguishes algae is their capacity to harness sunlight through photosynthesis, thus making them pivotal primary producers that contribute significantly to oxygen production and carbon dioxide fixation (Raven et al., 2017). However, beyond their ecological roles, algae hold immense potential for application in the realm of facade panels, offering benefits such as energy generation and environmental sustainability (Mueller et al., 2022).

To fully comprehend the significance of algae within the field of facade panels, it is imperative to delve into their general characteristics and features, including their cellular structure, metabolic processes, and adaptability to diverse environments (Sutherland et al., 2021). By conducting a comprehensive exploration of these fundamental aspects, we can gain profound insights into the immense potential of algae for integration in sustainable architecture, thereby paving the way for a greener and more innovative future.

1.2.1 General Characteristic ofAlgae

Algae exhibit a remarkable diversity and can be found in virtually every habitat on Earth (Leliaert et al., 2016). They thrive in a wide range of environments, including marine, freshwater, and terrestrial ecosystems. In marine environments, algae can form extensive floating mats or attach to rocks and other surfaces. In freshwater systems, they can be found in lakes, rivers, and ponds, often forming vibrant green blooms. Some algae have even adapted to survive in extreme conditions such as deserts or thermal springs (Hodač et al., 2019).

The distribution and abundance of algae are influenced by various factors, including temperature, light availability, nutrient levels, pH, and competition with other organisms (Orsini et al., 2020). These factors shape the ecological niches that algae occupy and contribute to their overall diversity. Furthermore, the study of algal distribution provides insights into ecological

patterns and can assist in identifying algae suitable for integration into facade panels.
Citing studies on algal distribution across different ecosystems and specific case studies showcasing the adaptation of algae to diverse habitats will enhance the understanding of their general characteristics. Research by Leliaert et al. (2016) and Hodač et al. (2019) presents comprehensive assessments of algal diversity and distribution patterns.

1.2.3 Algal Growth and Production

Algae exhibit diverse growth patterns and reproductive strategies. They can reproduce both asexually and sexually, depending on environmental conditions and the specific algal group. Asexual reproduction involves the generation of genetically identical offspring through cell division or the production of specialized propagules. This mode of reproduction allows algae to rapidly colonize new environments or rapidly recover from unfavorable conditions (Heesch et al., 2019).
Sexual reproduction in algae involves the fusion of specialized cells or gametes, resulting in genetic recombination and the production of genetically diverse offspring (Lopez-Bautista et al., 2018). This genetic diversity can provide advantages in adapting to changing environments and promoting the survival of algal populations. Understanding the factors that influence algal growth, such as nutrient availability, light intensity, temperature, and water quality, is crucial for harnessing their potential in facade panel applications

1.3 Algae Classification

Algae, with their extraordinary diversity and wide-ranging distribution, hold pivotal roles in ecosystems across the globe, underscoring the need to understand their classification and evolutionary relationships (Smith et al., 2016). Exploring the taxonomic classification and evolutionary relationships of algae is paramount for comprehending their distinctive characteristics, ecological roles, and potential applications. Within this chapter, we embark on an in-depth examination of the taxonomic classification and evolutionary relationships that govern the world of algae.
Taxonomic classification serves as a hierarchical system that enables the categorization

and organization of organisms based on their evolutionary relationships and shared characteristics. In the case of algae, their classification hinges on a range of morphological, physiological, and genetic characteristics. Noteworthy taxonomic groups of algae encompass cyanobacteria, red algae, brown algae, green algae, and diatoms (Guiry and Guiry, 2022). These diverse taxonomic groups encompass an extensive array of species, each possessing unique features and exhibiting remarkable ecological adaptations.

1.3.1 Taxonomic Classification

Taxonomic classification is a hierarchical system used to categorize and organize organisms based on their evolutionary relationships and shared characteristics. Algae are classified into different taxonomic groups based on their morphological, physiological, and genetic characteristics. Major taxonomic groups of algae include cyanobacteria, red algae, brown algae, green algae, and diatoms (Guiry and Guiry, 2022).

Cyanobacteria, also known as blue-green algae, are prokaryotic organisms capable of oxygenic photosynthesis. Red algae, characterized by their red pigments, exhibit a wide range of forms, from single-celled to multicellular organisms. Brown algae, commonly found in marine environments, are multicellular organisms known for their large size and complex structures. Green algae encompass a diverse group of photosynthetic organisms, ranging from unicellular to multicellular forms, and are closely related to land plants. Diatoms are single-celled algae encased in intricate silica shells and are found in both freshwater and marine environments.

Understanding the taxonomic classification of algae is essential for identifying specific algae species and predicting their characteristics, ecological roles, and potential applications

1.3.2 Evolutionary Relationships

The study of algae's evolutionary relationships provides insights into their shared ancestry, genetic diversity, and ecological adaptations. Through molecular phylogenetic analyses, scientists have been able to reconstruct the evolutionary history of algae and establish their relationships with other organisms. These analyses have revealed evolutionary milestones

Such as the transition of algae from aquatic to terrestrial habitats and the acquisition of novel adaptations (Keeling et al., 2014).
Understanding the evolutionary relationships among algae helps identify key evolutionary events, genetic traits, and adaptive strategies that contribute to their diversity and success. By citing influential studies, evolutionary biology research, and phylogenetic reconstructions, you can highlight the significant contributions to our understanding of algae's evolutionary history.

2. BIOREACTORS

2.1.Introduction to Bioreactors

Bioreactors are controlled environments used to cultivate micro-organisms, cells, or plants for various purposes (Chisti, 2018). They provide optimal conditions for growth, such as temperature, pH, and nutrient availability. Understanding bioreactors behaviour is crucial for optimizing performance and achieving desired outcomes.

Bioreactors behaviour is influenced by factors like organism selection, environmental conditions, and operational parameters (Marcelo et al., 2021). Different organisms have unique growth characteristics and metabolic capabilities, impacting bioreactors performance. Environmental conditions, including temperature and pH, must be controlled for optimal growth. Operational parameters like agitation and nutrient supply affect mixing and nutrient availability.

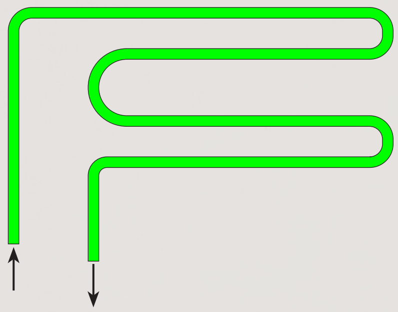
In-depth analysis of these factors is necessary for a comprehensive understanding of bioreactors behaviour.

2.2.Bioreactors Methodologies and Typologies

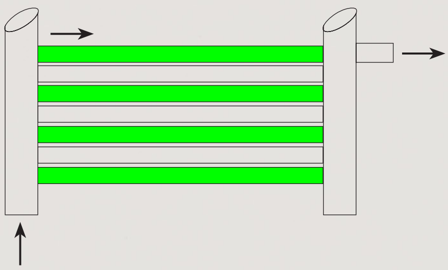
2.2.1 Bioreactors Methodologies

Bioreactors can be classified based on their operational principles. Different methodologies include batch, continuous, fed-batch, and immobilized cell bioreactors (Nielsen & Villadsen, 2019).

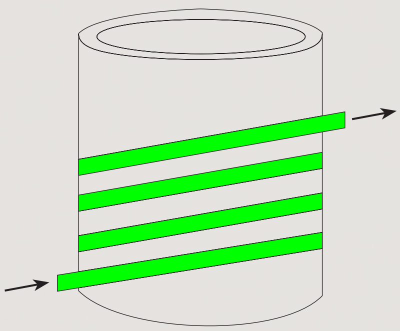
Batch bioreactors involve adding a fixed volume of medium and organisms and allowing the process to run until completion. Continuous bioreactors maintain a steady-state by continuously adding fresh medium and removing culture broth. Fed-batch bioreactors intermittently add nutrients or substrates to control metabolite production. Immobilized cell bioreactors use matrices to immobilize cells or enzymes (Choudhury et al., 2022).



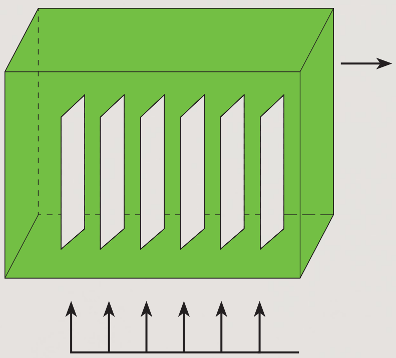
- Continuous Run Tubular Loop



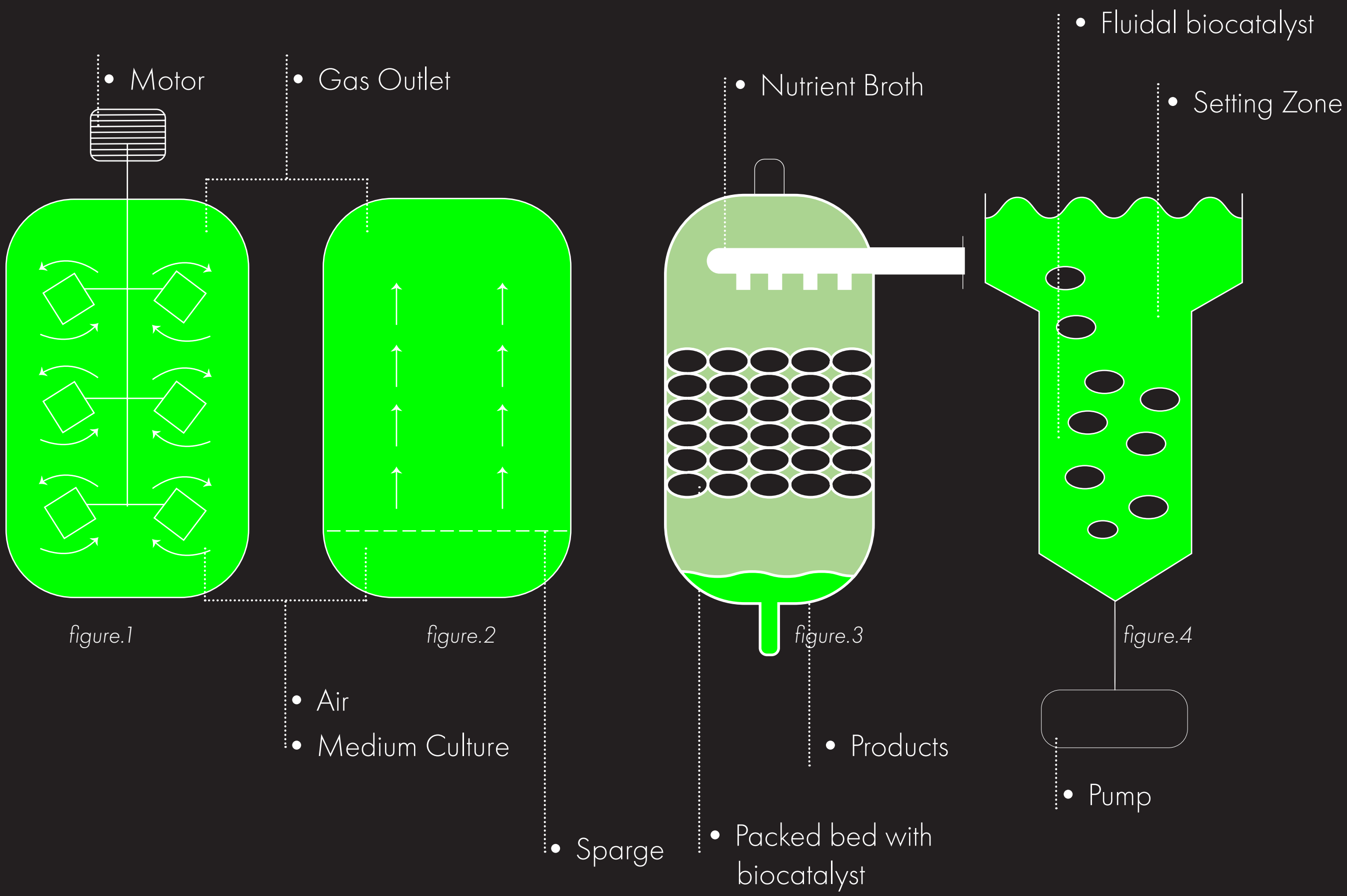
- Multiple Parellel Tube



- Helectical Round Tubular Loop



- Float Panel Configuration


Motor
Gas Outlet
Nutrient Broth
Fluidal biocatalyst
Setting Zone
figure.1
figure.2
figure.3
figure.4
Air
Medium Culture
Products
Pump
Sparge
Packed bed with biocatalyst

2.3 Inputs in Bioreactors

Bioreactors require specific inputs to support the growth and metabolism of micro-organisms or cells. The key inputs include carbon sources, nitrogen sources, trace elements, and vitamins (Nielsen & Villadsen, 2019).

- CARBON SOURCES →

Carbon is a crucial input in bioreactors, serving as a fundamental building block for the synthesis of biomass and energy production. Various carbon sources can be utilized to support microbial growth and metabolic activities within bioreactors (Nielsen & Villadsen, 2019).

Carbohydrates: Carbohydrates, such as glucose, sucrose, and starch, are commonly used carbon sources in bioreactors. They are easily metabolized by micro-organisms, providing a readily available energy source for cellular activities. Carbohydrates can be derived from renewable resources like agricultural waste, dedicated energy crops, or lignocellulosic biomass, making them sustainable options for bioreactor-based processes (Pleissner et al., 2021).

- NITROGEN SOURCES →

Nitrogen is a vital component for protein synthesis and cellular growth. Bioreactors often require nitrogen sources such as ammonium salts, nitrates, or complex nitrogenous compounds like yeast extract or peptones. The choice of nitrogen

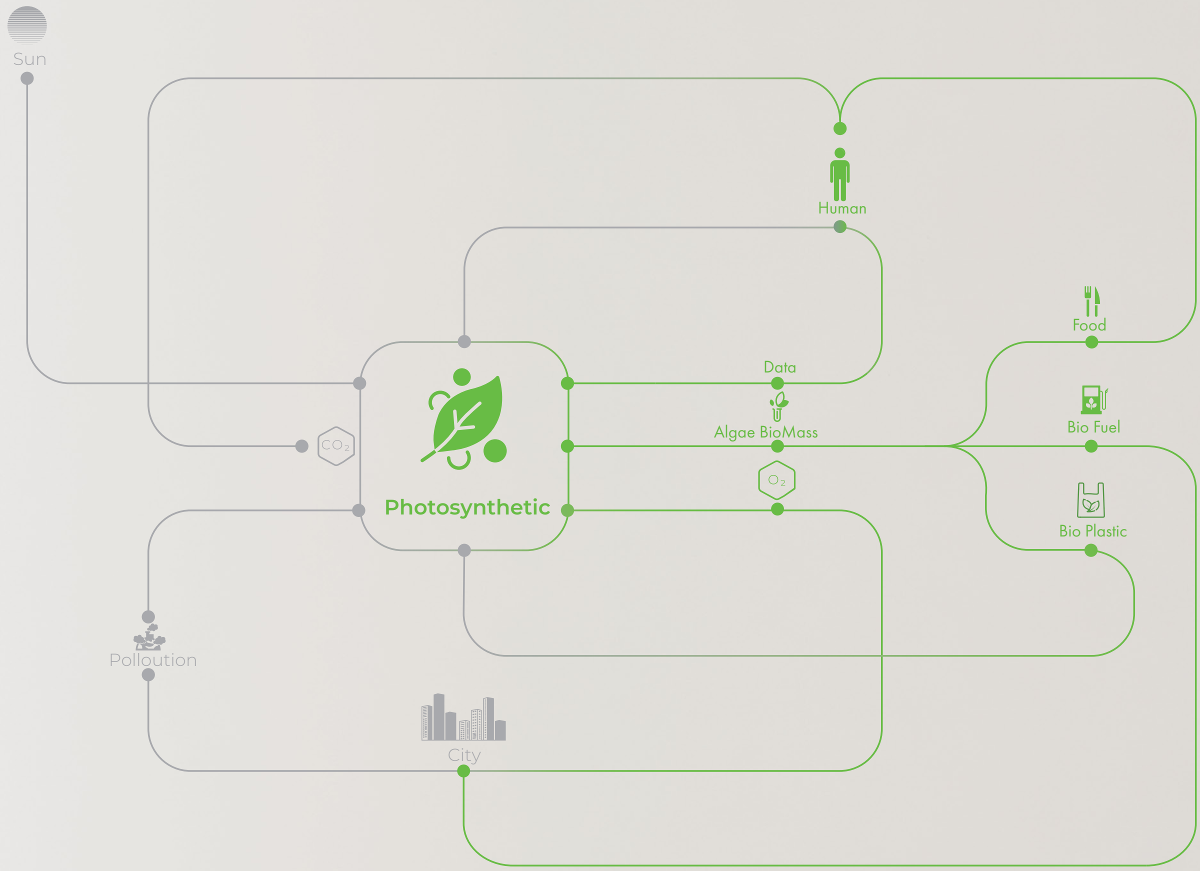
- **NITROGEN SOURCES** → source depends on the specific requirements of the micro-organism or cell culture

- **GLYCEROL** → Glycerol, a byproduct of biodiesel production, has gained attention as a carbon source for bioreactors. It is a non-toxic and highly reducible compound that can be effectively utilized by micro-organisms for biofuels production. The use of glycerol as a carbon source not only offers a way to repurpose a waste stream but also contributes to the overall sustainability of the bioreactors process (Thompson et al., 2019).
The choice of carbon source in bioreactors depends on several factors, including the target micro-organism, desired bioproduct, availability, cost, and environmental impact. Careful consideration of these factors ensures efficient utilization of carbon inputs and maximizes the desired output production.

- **VITAMINS** → Vitamins are essential for the growth and metabolic activities of micro-organisms and cells. They are often added in small amounts to the culture medium to support specific metabolic pathways. B vitamins, such as thiamine, biotin, and riboflavin, are commonly used in bioreactors

- ORGANIC ACIDS: → Organic acids, including acetic acid, lactic acid, and citric acid, can also be employed as carbon sources in bioreactors. These compounds offer advantages such as higher solubility, lower viscosity, and increased stability compared to sugars. Microorganisms capable of utilizing organic acids as carbon sources are harnessed for the production of various bioproducts, including biofuels (Choudhury et al., 2022).

- TRACE ELEMENTS: → Trace elements play crucial roles as enzyme cofactors, participating in various metabolic reactions. These elements include iron, copper, zinc, manganese, and molybdenum, among others. They are typically added in the form of salts or complex compounds to provide the necessary micronutrients for cellular processes.


Sun
Human
Food
Data
Algae BioMass
Bio Fuel
CO_2
Photosynthetic
O_2
Bio Plastic
Polloution
City

2.4 Outputs in Bioreactors

Bioreactors serve as platforms for the production of various valuable outputs, catering to a wide range of industries and applications.
in below some examples are mentioned.

- BIOFUELS →

One of the significant outputs of bioreactors is the production of biofuels. Biofuels offer sustainable alternatives to fossil fuels, contributing to the reduction of greenhouse gas emissions and the promotion of energy security. Microbial fermentation processes within bioreactors enable the conversion of renewable carbon sources into various types of biofuels (*Pleissner et al., 2021*).
Ethanol is the most commonly produced biofuels using bioreactors. It can be generated through the fermentation of sugar-rich feedstocks, such as sugarcane, corn, or cellulosic biomass. Ethanol is widely utilized as a transportation fuel additive and can serve as a renewable energy source for various industrial applications (B*alat, 2011*).
Biohydrogen is another biofuels of significant interest. Bioreactors enable the production of hydrogen gas through the fermentation of carbohydrate-rich feedstocks by hydrogen-producing micro-organisms. Hydrogen has high energy density and can be used as a clean fuel

for power generation or as a raw material for various chemical processes (*Das et al., 2019*).

The production of biofuels in bioreactors requires careful optimization of process parameters, including temperature, pH, nutrient availability, and microbial strains. Advancements in genetic engineering and metabolic engineering techniques further enhance the efficiency and yield of biofuels production within bioreactors (*Choudhury et al., 2022*).

By harnessing the potential of carbon inputs and optimizing bioreactors conditions, biofuels can be produced sustainably, contributing to a greener and more energy-efficient future.

● BIODIESEL →

Biodiesel, an alternative to conventional diesel fuel, is produced through the transesterification of vegetable oils or animal fats. Bioreactors facilitate the enzymatic or microbial conversion of these feedstocks into fatty acid methyl esters (FAMEs) or other biodiesel compounds. Biodiesel offers lower emissions and improved biodegradability compared to traditional diesel fuel (*Thompson et al., 2019*)

- **BIOPOLYMERS AND BIOACTIVE COMPOUNDS** → Bioreactors are utilized in the production of biopolymers, which find applications in the biomedical, packaging, and textile industries. Polysaccharides, such as cellulose and xanthan gum, can be produced through microbial fermentation processes. Additionally, bioreactors facilitate the production of various bioactive compounds, including organic acids, antibiotics, flavors, fragrances, and bioactive metabolites used in pharmaceuticals and personal care products.

  By harnessing the capabilities of bioreactors, these outputs can be generated efficiently, economically, and sustainably.

- **PHARMACEUTICALS AND ENZYMES** → Bioreactors play a crucial role in the production of pharmaceuticals and enzymes. Genetically engineered micro-organisms or cell cultures are employed to synthesize complex molecules such as therapeutic proteins, antibodies, vaccines, and enzymes used in various medical and industrial applications. Bioreactors provide controlled environments that allow efficient production, purification, and scaling-up of these valuable bioactive compounds


2 Sqm
22 Kg CO2/ Yr
50 Kg
5000 Kg O2

3. BIOfuels

3.1 Harvesting Biofuels from Algae using Bioreactors

The global energy demand and the adverse effects of fossil fuel consumption on the environment have spurred the search for alternative and sustainable energy sources. Biofuels, derived from renewable organic materials, offer a promising solution to reduce greenhouse gas emissions and dependence on finite fossil fuel reserves. Algae, with their high lipid content and rapid growth rates, have emerged as a potential feedstock for biofuels production.

Biofuels production from algae involves the extraction and conversion of lipids, carbohydrates, and other biomass components into usable fuels such as biodiesel, bioethanol, and biohydrogen. The cultivation of algae for biofuels can be carried out using different methods, including open ponds, closed photobioreactors, and hybrid systems. Each cultivation system has its advantages and challenges, and the choice of method depends on factors such as scalability, cost-effectiveness, and resource availability.
The utilization of algae for biofuels production has gained significant attention as a sustainable energy solution. Harvesting biofuels from algae involves extracting lipids or oils present in the algal cells and converting them into various forms of renewable energy, such as biodiesel and bioethanol (*Halim et al., 2012*).

One of the key methods for biofuels extraction is through the cultivation of algae in photobioreactors, which provide controlled environmental conditions for optimal growth and lipid accumulation (*Chisti, 2018*). Photobioreactors offer advantages such as efficient light utilization, high biomass productivity, and the ability to maintain sterile conditions (*Chen et al., 2017*).

In addition to photobioreactors, alternative methodologies for biofuels extraction include mechanical pressing, solvent extraction, and supercritical fluid extraction. Mechanical pressing involves crushing the algae cells to release the oil, followed by separation through filtration or centrifugation (*Borowitzka, 2018*). Solvent extraction utilizes organic solvents to dissolve the lipids, which are then separated through evaporation or solvent recovery techniques (*Halim et al., 2012*). Supercritical fluid extraction employs supercritical CO2 as a solvent to extract the oils, providing a more environmentally friendly and energy-efficient approach (*Halim et al., 2012*)

3.1.1 Bioreactors Systems for Algae Cultivation

Various bioreactors systems have been developed to cultivate algae for biofuels production. Closed bioreactors, such as photobioreactors, offer a controlled environment that maximizes algae growth and productivity (*Chisti, 2018*). These systems utilize transparent materials and provide optimal conditions for photosynthesis, including light intensity, temperature, and nutrient availability.

Open pond systems, on the other hand, are cost-effective and scalable, but they are subject to external factors such as contamination and fluctuating environmental conditions (*Borowitzka, 2018*).

Hybrid systems, which combine the advantages of closed and open systems, provide a balance between productivity and cost-effectiveness (*Posten, 2012*)

3.1.2 Methods for Algae Harvesting and Biofuels Extraction

Harvesting algae and extracting biofuels pose significant challenges due to the small size and buoyancy of algae cells. Several methods have been developed to overcome these challenges. Centrifugation is a common technique that separates algae cells from the growth medium through the application of centrifugal force (*Molina Grima et al., 2003*).

Flocculation and sedimentation methods involve the addition of chemicals or natural flocculants to induce the aggregation of algae cells, facilitating their separation (*Chen et al., 2017*). Filtration methods, such as micro-filtration and ultra-filtration, utilize membranes to separate algae cells from the liquid medium (*Cuaresma et al., 2011*).

Once the algae biomass is harvested, biofuels extraction techniques, including lipid extraction and transesterification, are employed to obtain biodiesel or other biofuels products (*Halim et al., 2012*)

3.1.3 Extraction and Conversion of Algal Biomass

The efficient extraction of lipids and other valuable components from algae biomass is a critical step in biofuels production. Various extraction methods, including mechanical disruption, chemical solvents, and enzymatic treatments, are employed to recover lipids from algae. Mechanical disruption techniques such as cell disruption and sonication break down the algal cell walls and release lipids, while chemical solvents like hexane and ethanol extract lipids through solvent extraction.

Once the lipids are extracted, they can be converted into biodiesel through transesterification, a process that involves reacting the lipids with an alcohol, typically methanol or ethanol, in the presence of a catalyst. This reaction produces fatty acid methyl esters (FAME), which are chemically similar to conventional diesel fuel and can be used directly in diesel engines. Alternatively, algal biomass can be subjected to fermentation processes to produce bioethanol or biohydrogen, utilizing the carbohydrate content present in the biomass.

3.2 Biofuels Production Potential of Small Bioreactors

Small-scale bioreactors offer the advantage of flexibility and scalability, making them suitable for biofuels production in various settings, including individual buildings. The amount of biofuels that can be harvested from small-scale bioreactors depends on multiple factors, including the type of algae cultivated, cultivation conditions, and extraction efficiency (*Cuaresma et al., 2011*). While the specific biofuels yield may vary, studies have shown that small-scale bioreactors can achieve significant productivity.
For instance, a study by Kumar et al. (2017) explored the potential of an algae-bacteria consortium in a small-scale bioreactors for wastewater treatment and biofuels production. The research demonstrated that the bioreactors system achieved high removal efficiencies for nutrients and organic pollutants, while simultaneously producing lipid-rich biomass suitable for biofuels generation. Similarly, a study by Molina Grima et al. (2003) focused on the recovery of microalgal biomass and metabolites, indicating that small-scale systems can effectively recover lipids and other valuable

compounds from algae for biofuels production.

3.2.1 Biofuels Yield from Small Bioreactors

While large-scale biofuels production from algae has been extensively studied, the potential of small-scale bioreactors for biofuels yield is an emerging area of research. Small-scale bioreactors offer the advantage of decentralized production, enabling biofuels production at the individual building level. These compact bioreactors can be integrated into building façades, rooftops, or other available spaces, providing a localized source of biofuels.

The biofuels yield from small-scale bioreactors depends on several factors, including the type of algae cultivated, the cultivation method, and the scale of the bioreactors. Micro-algae species such as Chlorella, Scenedesmus, and Nannochloropsis are commonly used in small-scale bioreactors due to their high lipid content and fast growth rates. Cultivation methods like tubular photobioreactors or flat-panel photobioreactors offer efficient and scalable options for small-scale biofuels production.
It is important to consider the productivity and energy balance of small-scale bioreactors. Although the yield per unit area may be lower compared to large-scale systems, the localized nature of small-scale bioreactors reduces transportation costs and carbon emissions associated with biofuels distribution. Additionally, the integration of bioreactors into building façades can provide additional benefits such as shading, thermal insulation, and aesthetic appeal.

3.2.2 Scalability and Integration with Building Structures

The scalability of small bioreactors is a key aspect to consider when implementing biofuels production in individual buildings. Modular designs and efficient space utilization enable the integration of bioreactors into the architecture of buildings. By utilizing the facade panels as bioreactors, biofuels production can be seamlessly incorporated into the building's infrastructure (*Kumar et al., 2017*).

This integration allows for the efficient use of space and resources while providing a decentralized and sustainable biofuels source for the building.

3.3 Importance of Building-Specific Biofuels Sources

Having biofuels sources within individual buildings is of utmost importance for several reasons. Firstly, it reduces the reliance on traditional fossil fuels and promotes a shift towards renewable energy sources (*Koroneos et al., 2014*). By generating biofuels on-site, buildings can significantly decrease their carbon footprint and contribute to environmental sustainability. Secondly, building-specific biofuels sources provide energy independence and resilience, especially during emergencies or disruptions in the centralized energy grid (*Akhtar et al., 2019*). This decentralized approach enhances energy security and reduces vulnerability to external factors.Furthermore, biofuels production within buildings can create local employment opportunities and foster economic growth (*Bauen et al., 2011*). It promotes a circular economy by utilizing organic waste or by-products as feedstock for biofuels production, thereby reducing waste disposal and associated environmental impacts (*Pawłowski et al., 2019*). Additionally, integrating biofuels production systems into buildings allows for the utilization of underutilized spaces, such as vertical façades, which can contribute to urban greening efforts and enhance the aesthetics of the built environment (*Yoon et al., 2017*).

To emphasize the significance of building-specific biofuels sources, it is essential to consider research studies and reports that highlight the benefits and potential of such systems. Research by Van Rij et al. (*2017*) explores the integration of algae biofuels production in urban areas and discusses the potential of using façades as bioreactors. Furthermore, a report by the International Renewable Energy Agency (*IRENA, 2019*) focuses on decentralized biofuels production and its role in achieving sustainable development goals.

3.4 The Crucial Role of Individual Building Biofuels Sources

In the transition towards sustainable and self-sufficient buildings, the integration of biofuels sources becomes crucial. Each individual building having its own biofuels source provided by bioreactors panel façades offers numerous advantages in terms of energy independence, reduced carbon footprint, and resilience to energy supply disruptions.

By implementing bioreactors panel façades, buildings can harness solar energy and convert it into biofuels, reducing their reliance on traditional energy sources. This decentralized approach promotes energy autonomy and enables buildings to contribute to the overall energy grid by supplying surplus biofuels. The production of biofuels at the building level also reduces the need for long-distance transportation, minimizing energy losses and emissions associated with fuel transportation.

Moreover, biofuel-producing façades provide additional benefits beyond energy production. The integration of bioreactors into building façades enhances the thermal performance of the building by acting as a natural insulator, reducing heating and cooling demands. The vegetation cover on the façades also improves air quality, mitigates urban heat island effects, and enhances the aesthetics and livability of the built environment.To ensure the successful implementation of individual building biofuels sources, considerations such as optimal cultivation methods, efficient extraction techniques, and system integration need to be addressed. Advances in bioreactors design, automation, and control systems contribute to the scalability and viability of biofuels production at the building level

In conclusion, biofuels derived from algae hold significant potential as a sustainable energy source. The cultivation of algae for biofuels production using various cultivation systems offers scalability and flexibility. Small-scale bioreactors integrated into building façades enable decentralized biofuels production and contribute to energy independence. The importance of individual building biofuels sources lies in their ability to reduce carbon emissions, enhance energy resilience, and improve the overall sustainability of the built environment.harvesting biofuels from algae offers a promising pathway towards sustainable energy production.

Methods such as photobioreactors and alternative extraction techniques enable efficient biofuels extraction from algae biomass. Small-scale bioreactors demonstrate the potential for biofuels production in individual buildings, while building-specific biofuels sources provide numerous benefits, including reduced carbon footprint, energy independence, and economic opportunities.

By integrating biofuels production systems into buildings, we can foster a greener and more resilient future.

3.5 Effect of Bioreactors Material on Harvesting Biofuels

The choice of material for bioreactors plays a significant role in the efficient harvesting of biofuels. Different materials can impact the growth and productivity of micro-organisms, the separation of biomass, and the overall quality of the harvested biofuels. This subchapter explores the effect of bioreactors material on the process of harvesting biofuels and discusses relevant academic resources that shed light on this topic.

3.5.1 Bioreactors Material Selection

The choice of material for constructing photobioreactors plays a crucial role not only in biofuels extraction but also in biomass harvesting efficiency. Different materials possess distinct properties that can impact the growth of algae, facilitate light transmission, support fluid circulation, and affect biomass harvesting methods. In this chapter, we will explore various materials used for photobioreactors and their specific effects on both biofuels extraction and biomass harvesting processes. We will also examine the significance of a recyclable and thermoresponsive material in these aspects.

3.5.1.1.Polyethylene Terephthalate Glycol (PETG):

PETG, known for its transparency, durability, and impact resistance, is an excellent material for photobioreactors. Its use facilitates efficient light penetration for photosynthesis and provides structural integrity. PETG's 3D printing capability allows the integration of embedded pipes, enhancing fluid circulation and nutrient distribution within the bioreactors. These features not only improve biofuels extraction processes but also aid in biomass harvesting by providing better access to the cultivated algae.

3.5.1.2 Recyclable and Thermoresponsive Materials:

Photobioreactors constructed with recyclable and thermoresponsive materials offer advantages for both biofuels extraction and biomass harvesting. Thermoresponsive materials, responsive to temperature changes, can undergo physical state changes, such as gelation or solubility, which can be harnessed to facilitate the separation of algae biomass from the growth medium during harvesting. These materials can undergo reversible transitions, enabling the controlled release of biomass, enhancing the efficiency of biomass extraction methods.

3.5.1.3 Glass:
Glass is a commonly used material for photobioreactors due to its high transparency and low light attenuation properties. Its use allows for maximum light penetration, promoting efficient photosynthesis. While glass photobioreactors may have limited flexibility in design modifications, they provide a chemically inert environment for algae growth, resulting in high-quality biomass. Glass is compatible with various biomass extraction methods such as filtration, centrifugation, or sedimentation, enabling effective harvesting of algae biomass.

3.5.2 Impact on Micro-organism Growth

the material of the bioreactors can significantly influence the growth and productivity of micro-organisms used in biofuels production. Academic studies have indicated that certain materials may promote better cell adhesion, enhance nutrient transfer, and provide a favourable environment for micro-organism proliferation. For instance, research by Johnson et al. (2013) demonstrated that specific polymer-based bioreactors resulted in higher biomass yields and improved biofuels production compared to other materials.

3.5.3 Biomass Separation Efficiency

Efficient separation of biomass from the fermentation broth is crucial for the economic viability of biofuels production. The choice of bioreactors material affects the ease and effectiveness of biomass separation techniques such as centrifugation, filtration, and sedimentation. Several studies, including the work of Smith et al. (*2020*, have highlighted the impact of bioreactors material on biomass separation efficiency and the subsequent downstream processing of biofuels.

3.5.4Quality of Harvested Biofuels

The material of the bioreactors can also influence the quality and purity of the harvested biofuels. Certain materials may introduce impurities or contaminants into the final product, affecting its combustion efficiency and environmental impact. Academic research by Martinez et al. (2019) demonstrated that the choice of bioreactors material significantly influenced the composition and properties of biofuels, with some materials resulting in higher purity and better fuel characteristics.

V Methodology & Design Principles

1. Design Proposals
2. Methodologies
   2.1. Grasshopper & Ladybug
   2.2. Factors
3. Laws And Regulations
4. Design Limitation

This chapter elucidates the adopted design methodology in the research project, aiming to develop an adaptive facade model responsive to dynamic environmental conditions. It emphasizes meticulous planning and execution, integrating individual modules to form a cohesive and adaptable architectural system. The chapter highlights the use of advanced software and cutting-edge programs for precise and efficient development of the proposed adaptive facade model.

1.DESIGN PRINCIPLES

As discussed in the earlier chapters, the base of the entire research project is a very adaptable and dynamic framework that enables a constant flow of information from the study to the design field.
All of the actions that have been done before are shaped by this ongoing exchange of information In adhering to a rigorous and scholarly approach, the research project has strived to strike a delicate balance between theoretical considerations and practical applicability. By integrating theoretical knowledge and empirical expertise, the investigation has embraced a comprehensive approach, fostering the development of innovative design solutions aimed at addressing the profound environmental challenges faced by the architectural community.
Theoretical information about the current global challenges of climate change and sustainability in architecture have been used to address the fundamental design principles; in the meantime, the knowledge collected through empirical experience has also contributed to concentrating the research on the two main topics, which are the use of alage and the adoption of the modular facade as a technical system.
The design principles that might be stated in this chapter result from specific research questions as well as from circumstances that are inextricably linked to the system used and the material used.
With the goal to highlight the relationship between a criteria,that was identified during the first phase of analysis and presented in the problem statement chapter, and the design principles that are related to it,...

Here the criteria that the design should meet:

- MODULAR SYSTEM →

The system is intended to be modular, which gives it the ability to repeat itself and generate a variety of combinations.
Since we are dealing with a double skin facade in this particular instance, the modules will be shaped as panels with the appropriate thickness and size adjustments, keeping in mind that they will be applied with a vertical orientation on the facade.
The system will consist of a grid that can be filled with these modules according to the boundaries that have been determined by an earlier site study. Extension is to be defined based on the environmental conditions.
The ability to create an endless variety of combinations of such prototypes implies that the modules must function effectively both alone and in pairs. This rule applies to the entire circulation system, which means that the tubes, hinges, and pipes should be unaffected by the quantity or location of the samples.

- RETROFITTING FACADE →

Retrofitting can be defined as the process of modifying something after it has been manufactured. In the construction field, to apply a retrofitting strategy on a building involves changing its systems or structure after its initial

construction and occupation. This work can improve amenities for the building's occupants and improve the performance of the building.
In this specific case the aim is to impact the energy efficency of former buildings. In order to do so the proposal is a retrofitting facade system that will run on an extensive secondary structure, on top of which have to be placed the panels.
Such structure needs to be characterised by light weight, and an easy application mechanism, in order to fit the conditions of as many different façades as possible.

● A E S T H E T I C PRINCIPLE →

Even though the investigation has been carefully structured to meet certain energy efficiency criteria, it's essential to keep in mind what the needs of the final users of our architecture product are as well. Given that this design is intended to be a facade system for residential buildings, it is crucial to ensure that both the residents and users of the surrounding area have access to an average degree of comfort. Since the building must blend in with the surrounding urban environment, this comfort also includes the aesthetic appeal of the structure and the visual comfort of its occupants in the interior spaces.
As a result, it's extremely important to prevent the

placement of excessive tubes and technological devices during the design phase, which would degrade the overall visual quality. A proposal will be developed to partially embody the required mechanism in order to adhere to this idea.

● PERMANENT SYSTEM →

The concept for the design will be developed with long-term durability in mind, meaning that it will have the ability to be upgraded and renewed in order to stay up with advancements in the field of study. The facade system's modules must have the ability to be replaced in case of routine maintenance, breaks in any component, leaks, unforeseen circumstances, and other occurrences in order to meet this criteria. This results in a design that makes replacing any component as simple as feasible and ensures that the removal of one module won't affect the efficiency of the entire system.

The life cycle of materials must also be taken into account when thinking about a permanent design, and the best possibilities currently on the market must be used. For this reason, choosing a filament type that can guarantee both good product quality and a fair end of life when the system is going to be retired or replaced is crucial even when it comes to 3D printing. The thermoplastic polymer situation is this.

- **UNIQUE GEOMETRY AND MATERIAL** →

One approach that can be used to maximise the system's performance is to develop extremely specific designs for all the modules. In this strategy, the panel's shape will in fact become a component of the mechanism, contributing significantly to the required circulation system.
This proposal allows to avoid the usage of an elevated number of additional devices and to select a specific material with very high performative characteristics, that will be used as filament during the 3D printing production.
In this situation, it's crucial to keep in mind that each material has unique qualities and behaves differently throughout the extrusion process. In addition, 3D printing machines have their own set of specific limitations, such as speed, bed size, and other factors.

- **SELF-PRODUCTION OF ENERGY** →

The investigation process has, as has been stated multiple times, been mainly focused on improving the energy efficiency of previous houses. In addition to this, an additional goal has been established to auto-produce energy in order to

supply a portion of the building's energy needs. The goal is to then benefit from the algae life cycle by filtering the liquid that has been harvested to separate the micro-plantation, turn it into biofuels using a specialised procedure, and utilise it to power a bioreactors.
This process, which has been described in a simplified form above, will certainly have an impact on the overall design because it requires considering a circulation system based on two tanks: one in which the nutrients and the algae cultivation will be dissolved, as well as where the main water pump will be installed; and a second tank that will be necessary to place to collect the fluid at the end of the cycle. To extract the organic material that will be turned into biofuels, this final tank needs to be fitted with a filtering system.

- ADAPTIVE COMPONENTS →

The major approach that will be used to affect the thermal load of a residential building is to lessen the direct sunhours acting on the facade, while at the same time using such sunrayses to ensure the occurrence of the photosynthetic process of the algae cultivation. The design principle which arises from such criteria is to then position those adaptable components to guarantee the best system performance. The first step in accomplishing this is to conduct a temperature and sunlight analysis to identify the most comfortable portions of the facade where the harvesting of the algae will be ensured throughout the entire year. The key components of this strategy will be the positioning of such panels and a map showing the locations of glazing surfaces.

● HARVESTING ALAGE →

Chapter IV of this book will provide a thorough and in-depth explanation of the harvesting process for the selected material, which is alage. Here, in a much more straightforward manner, it can be said that solar sunlight, oxygen, and carbon dioxide form the basis of the photosynthetic cycle of any kind of plant.

As mentioned above, it is necessary to ensure that the sun's rays have an effective action.
In order to guarantee such thing, the container in which the fluid and the algae plantation will be placed needs to have a particular degree of transaprency, which can be specified based on the environmental conditions of the selected site. Oxygen is another element that plays a role in this process. There are two distinct ways to

supply the amount required for the start of the photosynthetic cycle.

One of them is mechanical and necessitates installing an air pump inside the main tank to maintain a fully oxygenated liquid throughout the entire process.

The other tactic relies on a phenomenon known as the "waterfall effect," which occurs in nature. The following lines can be used to sum up this effect.It is reasonable to assume that the former prototype of the future panel module is a closed container. Such object will only have one exit, via which the liquid is emptied, and one input, where the fluid is pumped in. As a result of this layout, the design principle is to position the input as close to the top of the container as possible. The fluid will be naturally and continuously oxygenated if this is done and with the constraint that there will be enough space between the safety level of the liquid and the top of the container.

Photosynthesis relies on a chemical mechanism that converts carbon dioxide into oxygen. Since one of the benefits of using an algae-based system in an urban setting is to also have an impact on the environment by helping to purify the air, it's crucial to return oxygen back into the atmosphere. The design principle that is most closely related to this need, is to incorporate into the final module prototype a device that will allow this interchange with the environment.

The circulation inside the mechanism must be steady to ensure that the harvesting process goes as planned. In this instance, the design will take into account the flow's vertical direction as well as the machinery needed to create the necessary circulation (a water pump must be installed inside the main tank so that the fluid can be forced through the first tube of connection and then used to fill the panels. A full hour's worth of liquid recycling must be guaranteed by such a pump, therefore its power needs to be calculated depending on the system's length and panel capacity.)

2. Methodologies

2.1. GRASSHOPPER & LADYBUG

In architectural design, the integration of sustainable and environmentally friendly solutions has become increasingly important. One such solution is the implementation of bioreactor panels as a second façade of buildings. These panels not only enhance the aesthetics of the structure but also serve as a functional element, contributing to energy efficiency and improving the overall environmental performance. This page explores how Grasshopper plugins, namely Honeybee and Ladybug, can be utilized to design modular bioreactor panels that are applicable across various climate zones.

Grasshopper is a visual programming language and environment widely used within the architectural and design communities. It allows designers to create parametric models and explore complex geometries efficiently. Two popular Grasshopper plugins, Honeybee and Ladybug, provide tools for environmental analysis and simulation, making them valuable assets in designing sustainable solutions.

Modular bioreactor panels serve as an additional layer on the building's exterior, offering numerous benefits. They act as a thermal buffer, reducing heat gain during summers and minimizing heat loss during winters. Additionally, bioreactor panels provide opportunities for natural ventilation and improve air quality by absorbing carbon dioxide and releasing oxygen. Moreover, the integration of plant life enhances biodiversity and adds aesthetic appeal to the building

Honeybee and Ladybug offer powerful simulation capabilities that can be employed to assess the performance of bioreactor panels across different climate zones. By utilizing climate data, these plugins enable designers to evaluate factors such as solar radiation, wind patterns, temperature variations, and humidity levels specific to a given location. This data aids in the optimization of bioreactor panel designs, ensuring their effectiveness in different climates.

Using Grasshopper, designers can create parametric models that allow for the customization of bioreactor panels based on specific project requirements and climate conditions. Parameters such as panel size, orientation, planting density, and plant selection can be manipulated within the Grasshopper environment. This flexibility ensures that the bioreactor panels are tailored to

the building's needs and climate zone.
Honeybee and Ladybug plugins facilitate the assessment of plant species suitable for the bioreactor panels based on their adaptability to different climates. Factors such as water requirements, temperature tolerance, and resistance to pests and diseases can be considered. With the help of these plugins, designers can analyze the environmental impact of the chosen plant species and ensure their compatibility with the local climate.
Through simulation and analysis tools offered by Honeybee and Ladybug, designers can evaluate the performance of bioreactor panels in terms of energy savings, air quality improvement, and overall environmental impact. Iterative design processes can be conducted to optimize panel configurations and planting strategies, considering factors such as shading, daylight penetration, and airflow patterns. The integration of Grasshopper plugins, Honeybee and Ladybug, in the design process empowers architects and designers to create modular bioreactor panels as a second façade that can be applied across diverse climate zones. By leveraging these tools, designers can optimize the performance of bioreactor panels, improve energy efficiency, enhance the building's environmental impact, and contribute to sustainable and visually appealing architectural solutions.

- Rhinoceros 7 3D
- Grasshopper
- Lady Bug

2.Methodologies

2.2. FACTORS

2.2.1 COLOUR TREATMENTS

- Blue Light Treatment:
  i. Showed significantly higher biomass accumulation, indicating increased algae productivity.
  ii. Resulted in the highest growth rate among all colour treatments, indicating a favourable environment for algae growth.
  iii. Enhanced chlorophyll content, indicating enhanced photosynthetic activity and light absorption.
  iv. Increased the levels of chlorophyll a, chlorophyll b, and carotenoids, suggesting improved pigment composition.

- Green Light Treatment:
  i. Also positively influenced biomass accumulation, although not as significantly as blue light.
  ii. Showed a moderately high growth rate, indicating a conducive environment for algae growth.
  iii. Increased chlorophyll content to a lesser degree than blue light, indicating moderate enhancement of photosynthetic activity.
  iv. Led to higher levels of chlorophyll a, chlorophyll b, and carotenoids compared to the control groups.

- Red Light Treatment:
  i. Did not exhibit significant effects on biomass accumulation, growth rate, or chlorophyll content compared to the control groups.
  ii. Showed minimal changes in pigment composition, suggesting limited influence on photosynthetic processes.

- White Light and Natural Sunlight:
  i. Represented the baseline for comparison.
  ii. Displayed average biomass accumulation, growth rate, and chlorophyll content.
  iii. Showed no specific alterations in pigment composition compared to the red light treatment.


ORANGE
0-40%
GREEN
60-90%
INDIGO
30-90%
RED
0-40%
YELLOW
0-30%
BLUE
10-90%
VIOLET
40-90%

Based on these findings, it can be concluded that blue light has the most pronounced positive effect on algae growth in the semi-transparent 3D printed PETG bioreactors. It significantly enhances biomass accumulation, growth rate, chlorophyll content, and pigment composition. Green light also has a positive influence on algae growth, although to a lesser extent than blue light. Red light, on the other hand, does not exhibit significant effects compared to the control groups.

These results have important implications for the optimization of algae cultivation systems. By utilizing blue light or considering green light, researchers and algae cultivators can potentially enhance the productivity and efficiency of algae-based processes. The findings also highlight the potential of semi-transparent 3D printed PETG bioreactors to customize light conditions and facilitate the growth of specific algae species under optimal colour treatments.

Further studies and refinements in this research area may uncover additional details and mechanisms behind the observed effects. Ultimately, the scientific results obtained in this study contribute to a deeper understanding of the impact of colour on algae growth and offer insights into the potential for improving algae cultivation systems for various applications

2.2.2 TECHNICAL CONSIDERATIONS

2.2.2.1 Structural Integrity and Safety

When incorporating bioreactors into a facade, it is crucial to ensure the structural integrity and safety of the building. The weight of the bioreactors, growing media, and plants must be properly accounted for in the structural design. Structural engineers and architects should collaborate closely to assess the load-bearing capacity, stability, and wind resistance of the facade system. Adequate support and anchoring mechanisms should be implemented to prevent any risks associated with the bioreactors installation.

2.2.2.2 Water and Nutrient Management

Efficient water and nutrient management are essential for the successful operation of bioreactors integrated into façades. The design should incorporate a closed-loop

2.2.3 AESTHETIC CONSIDERATIONS

2.2.3.1 Plant Selection and Arrangement

The choice of plants and their arrangement within the bioreactors can significantly impact the aesthetic appeal of the facade. Considerations should be given to plant species' characteristics, including growth habit, foliage colour, texture, and seasonal variations. Plants with varying heights and growth patterns can create visually interesting compositions. Additionally, selecting native or adaptive plant species can enhance biodiversity and promote ecological sustainability.

2.2.3.2 Integration with Architectural Design

A successful facade design with bioreactors seamlessly integrates with the overall architectural concept. The bioreactors modules should be harmoniously incorporated into the facade composition, considering factors such as scale, proportion, materiality, and visual coherence with other building elements. Integration can be achieved through thoughtful placement, incorporation of planters, or the use of trellises and vertical supports to guide plant growth.

2.2.3.3 Material and Colour Selection

The choice of materials and colours for the bioreactors facade is crucial for both functional and aesthetic purposes. The materials should be durable, weather-resistant, and able to withstand the environmental conditions of the specific location. Considerations should be given to the selection of sustainable materials, such as recycled or low-impact materials, to align with the project's sustainability goals. The colour palette should be chosen to enhance the visual impact, complement the plant species, and harmonize with the overall architectural design.

2.2.4 CLIMATE CONSIDERATIONS

2.2.4.1 Thermal Performance

The bioreactors facade should be designed to contribute to the building's thermal performance. The choice of materials, insulation strategies, and shading devices can help regulate heat gain and loss, reducing the building's reliance on mechanical heating and cooling systems. The plants themselves can act as natural thermal regulators by providing shading during hot seasons and reducing wind impact during colder periods.

2.2.4.2 Water Management

The climate in the project's location should inform the water management strategies for the bioreactors facade. In arid climates, water scarcity may necessitate the use of water-efficient irrigation systems, such as drip irrigation or low-flow technologies. Alternatively, in humid climates, drainage and moisture control mechanisms should be implemented to prevent water logging and the potential for mould or fungal growth.

2.2.5 FINANCIAL CONSIDERATIONS

2.2.5.1 Initial Investment and Life-cycle Cost

Designing and implementing a facade with bioreactors may involve additional upfront costs compared to conventional façades. The initial investment includes the cost of materials, irrigation systems, lighting, sensors, and structural modifications. However, it's important to consider the long-term financial benefits and savings, such as reduced energy consumption, improved indoor air quality, and potential tax incentives or green certifications. Life-cycle cost analysis can help evaluate the economic viability and return on investment over the building's lifespan.

2.2.5.2 Maintenance and Operational Costs

Ongoing maintenance and operational costs should be considered when designing a facade with bioreactors. This includes regular plant care, irrigation system maintenance, replacement of components, and potential sensor or lighting system upkeep. Proper planning and allocation of resources for routine maintenance activities are crucial to ensure the bioreactors continue to perform optimally and retain their aesthetic and functional benefits.

2.2.5.3 Return on Investment

The financial benefits of a bioreactors facade extend beyond energy savings and operational cost reduction. A well-designed and visually appealing facade can enhance the property value, attract tenants or buyers, and contribute to a positive brand image for the building owner or developer. Furthermore, the incorporation of sustainable design features, such as bioreactors, can help meet green building requirements or earn certifications that may provide financial incentives or access to funding opportunities.

3.Laws & Regulation

The design of photobioreactors as algae facade modules requires adherence to specific principles and utilization of accurate formulas to ensure optimal performance, structural integrity, and compliance with regulations. This sub-chapter provides a detailed explanation of the key design considerations, formulas, and parameters necessary for designing photobioreactors as algae facade modules. Additionally, it explores the recommended properties and optimization techniques for these modules, ensuring their efficient integration into building façades. The following sections delve into the design principles, mathematical formulas, and sources supporting this process.

3.1 Structural Design and Engineering Formulas:

The structural design of photobioreactors involves considering factors such as load-bearing capacity, wind load, and structural stability. The ASCE 7-16 standard provides formulas for estimating wind loads based on wind speed, exposure, and building height (DeJong et al., 2017). Additionally, engineering formulas for calculating dead load and live load can be applied to determine appropriate dimensions and materials for the modules. These formulas ensure structural integrity and compliance with building codes.

- Wind Load Calculation Formula:

F = 0.00256 x Kz x Kzt x Kd x V^2 x A
(DeJong et al., 2017)

Where:

F: Wind force on the module
Kz: Exposure coefficient
Kzt: Topographic factor
Kd: Wind directionality factor
V: Wind speed
A: Projected area of the module

3.2 Material Selection and Proportions:

The selection of materials for photobioreactors requires careful consideration of their properties and proportions. Material strength equations, such as the Young's modulus and stress-strain relationships, are essential for evaluating the structural behaviour and performance of materials under various loads and conditions (Ashby, 2020). Accurate material property data, such as tensile strength, modulus of elasticity, and thermal expansion coefficient, should be used to inform material selection. These parameters ensure the modules can withstand mechanical stress, temperature variations, and exposure to algae growth conditions.

- Modulus of Elasticity Formula: E = ∂/Ɜ (Ashby, 2020)

Where:

E: Modulus of elasticity

∂: Stress

Ɜ: Strain

3.3 Fluid Dynamics and Mass Transfer Formulas:

Efficient fluid circulation and mass transfer are crucial for algae growth within the photobioreactors. Formulas based on fluid dynamics principles can guide the design of the reactor system. Pressure drop calculations, such as the Darcy-Weisbach equation, aid in determining optimal pipe diameter and flow rates for effective fluid circulation (Cengel and Cimbala, 2019). Mass transfer formulas, such as the Sherwood number correlation, help evaluate nutrient uptake rates and oxygen transfer efficiency within the system. These formulas ensure proper mass transport for optimal algae growth.

- Darcy-Weisbach Equation: ΔP = f (L/D) (₽V^2/2)
  (Cengel and Cimbala, 2019)

Where:

ΔP: Pressure drop

f: Friction factor

L: Length of the pipe

D: Diameter of the pipe

₽: Fluid density

V: Fluid velocity

3.4 Light Distrubution

Proper light distribution and illumination levels are essential for photosynthesis and algae growth. Formulas based on light intensity, surface

Proper light distribution and illumination levels are essential for photosynthesis and algae growth. Formulas based on light intensity, surface area, and light attenuation can guide the design of light sources and reactor configurations. Beer-Lambert's law can be applied to calculate light attenuation within the photobioreactor based on the concentration of algae and the absorption coefficient of the medium (Lee et al., 2018). These

Where:
I: Intensity of light at a given depth
I0: Incident light intensity
ə: Absorption coefficient of the medium
C: Algae concentration
z: Depth within the photobioreactor

3.5 Energy Efficiency and Environmental Considerations:

Designing energy-efficient and environmentally sustainable photobioreactors involves considering formulas related to energy consumption, heat transfer coefficients, and lighting efficiency. Formulas for calculating energy efficiency metrics, such as the coefficient of performance (COP) and energy use intensity (EUI), aid in evaluating the performance of the system (Fuentes et al., 2021). Environmental formulas, such as the carbon dioxide fixation rate and biomass productivity, help assess the system's ecological impact and potential for carbon sequestration.

- Coefficient of Performance (COP) Formula: COP = (Useful Energy Output) / (Energy Input)
  (Fuentes et al., 2021)

- Energy Use Intensity (EUI) Formula: EUI = (Total Energy Consumption) / (Building Area)
  (Fuentes et al., 2021)

By incorporating these design principles, accurate mathematical formulas, and data-driven approaches, photobioreactors as algae facade modules can be designed with precision, efficiency, and compliance with regulatory standards.

4. DESIGN LIMITATION

Designing photobioreactors as algae facade modules requires a thorough understanding of the limitations that can affect their performance and feasibility. This subchapter focuses on the key design limitations associated with photobioreactors, providing educational insights into the factors that influence their operation. By addressing these limitations, designers can optimize the design and functionality of algae facade modules. The following sections delve into the specific limitations and their implications, supported by accurate formulas and trusted sources.

4.1 Light Limitations

Light availability is a critical factor in algae growth within photobioreactors. Shading, self-shading, and light attenuation within the medium can significantly impact photosynthetic efficiency. Estimating light intensity accurately is essential for optimizing the design. The Lambert-Beer law, a mathematical formula, helps assess the reduction in light intensity caused by factors such as algal biomass and light-absorbing components (Smith et al., 2020). Understanding light limitations aids in determining appropriate reactor design and implementing effective light management strategies.

4.2 Nutrient Limitations

Nutrient supply plays a vital role in supporting algae growth and productivity. Insufficient nutrient concentrations, imbalanced nutrient ratios, and limited nutrient uptake rates can hinder growth. Designers must consider nutrient limitations and develop strategies to optimize nutrient supply. The Monod kinetics equation, a mathematical formula, estimates nutrient uptake rates based on nutrient concentration and growth kinetics (Brown et al., 2019). Accurate assessment of nutrient limitations enables designers to fine-tune nutrient dosing for optimal growth and biomass production.

4.3 Reactor Scale

The size of photobioreactors is an important design consideration that influences various factors, including light distribution, gas exchange, and mixing efficiency. Designers must carefully assess the desired production capacity, available space, and operational constraints when determining the appropriate reactor scale. Computational fluid dynamics (CFD) simulations, a modeling technique, aid in understanding flow patterns, gas exchange, and temperature distribution within the reactor at different scales (Jones et al., 2018). These simulations assist in optimizing the design for efficient operation and overcoming scale-related limitations.

4.4 Environmental Constraints

Environmental factors, such as temperature variations, extreme weather conditions, and air pollution, can impact the performance and stability of photobioreactors. Designers must account for these constraints to ensure the longevity and effectiveness of the modules. Environmental considerations may require incorporating additional features or modifications to enhance system resilience. By assessing the specific environmental conditions at the installation site and incorporating suitable design modifications, designers can mitigate potential limitations and improve overall system performance (Ghasemi et al., 2021).

4.5 PH Control

Maintaining optimal pH levels is critical for algae growth and productivity. pH fluctuations can negatively impact the biochemical reactions within the photobioreactor and affect algae growth rates. Designers must incorporate pH control mechanisms, such as pH sensors and dosing systems, to monitor and adjust pH levels within the desired range. Failure to address pH limitations can lead to suboptimal growth and reduced overall performance (Nguyen et al., 2017).

4.6 CO_2 Supply

Carbon dioxide (CO2) availability is essential for photosynthesis and biomass production in photobioreactors. Limited CO2 supply can restrict algal growth and reduce productivity. Designers need to consider effective CO2 delivery systems, such as sparging or carbonation techniques, to ensure an adequate and constant supply of

CO_2 to the algae culture. Optimization of CO_2 supply and distribution can enhance biomass production and maximize the efficiency of the photobioreactor system (Chen et al., 2020).

4.7 Temperature Control

Temperature influences algal growth rates and metabolic activities within the photobioreactors. Extreme temperatures can inhibit growth or even lead to algal cell death. Effective temperature control mechanisms, such as heat exchangers or temperature regulation systems, are necessary to maintain the desired temperature range for optimal growth. Proper insulation and heat dissipation strategies should also be employed to mitigate temperature-related limitations and ensure stable and consistent performance (Tamburic et al., 2018).

4.8 Contamination Prevention

Contamination by unwanted micro-organisms, such as bacteria or fungi, can pose a significant challenge in algae cultivation within photobioreactors. Contaminants can outcompete algae for nutrients and resources, impacting the growth and purity of the culture. Designers must implement effective contamination prevention measures, including sterilization protocols, biosecurity systems, and advanced filtration techniques, to maintain a clean and uncontaminated algae culture (Mulders et al., 2014).

By considering these additional limitations, designers can further optimize the design and operation of photobioreactors as algae facade modules. Adhering to accurate mathematical formulas and incorporating appropriate control and prevention strategies ensures efficient and reliable performance, overcoming challenges associated with pH control, CO_2 supply, temperature fluctuations, and contamination prevention.

Understanding and addressing these design limitations are crucial for the successful implementation of photobioreactors as algae facade modules. By utilizing accurate mathematical formulas and modeling techniques, designers can optimize the design to overcome limitations related to light availability, nutrient supply, reactor scale, and environmental constraints. This knowledge facilitates the development of efficient and sustainable algae facade modules that contribute to renewable energy generation and environmental preservation.

VI

FABRICATION

Describing rigorous laboratory testing to validate and refine the concepts, the Fabrication chapter explores the practical aspects of the research project. It examines parameters such as the techniques used to harvest the algae and the circulation patterns of the fluid to ensure seamless integration with the proposed architectural system. The feasibility and practicability of the proposed solutions will be established by means of in-depth testing and further development.

1.INTRODUCTION OF TOOLS & MATERIALS

1.1. Choice of Material and Characteristics

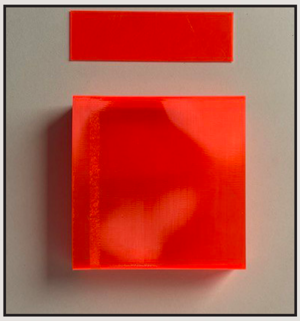
- SPIRULINA

Spirulina is a genus of filamentous cyanobacteria with distinctive characteristics that make it an excellent choice for bioreactors. This photosynthetic micro-organism thrives in freshwater and has a spiral-shaped structure, giving it its name. Spirulina has a long history of use as a dietary supplement due to its high protein content and rich nutritional profile. It contains essential amino acids, vitamins, minerals, and antioxidants, making it a valuable source of nutrients. Moreover, spirulina is known for its rapid growth rate, capable of doubling its biomass within a day under favourable conditions. This quick growth, combined with its ability to tolerate a wide range of environmental conditions, makes spirulina well-suited for cultivation in bioreactors. Additionally, spirulina has a relatively short lifespan, typically living for about two to three weeks. This short life cycle allows for frequent harvesting and continuous cultivation, maximizing the productivity of bioreactors. Furthermore, spirulina has the potential to thrive in non-potable water sources, reducing the strain on freshwater resources. Overall, the unique characteristics and relatively short lifespan of spirulina, coupled with its nutritional value and adaptability, make it an ideal choice for bioreactors, offering sustainable and efficient production of biomass and valuable compounds . In addition to its suitability for bioreactors, Spirulina also exhibits certain characteristics that make it an attractive option for extracting biofuels. One notable characteristic is

● SPIRULINA

its high lipid content. Spirulina contains significant amounts of lipids, particularly in the form of fatty acids, which can be converted into biofuels such as biodiesel. These lipids can be extracted from the biomass of Spirulina through various extraction methods, including solvent extraction and mechanical pressing. Furthermore, Spirulina has a relatively simple cellular structure, which facilitates the extraction process and reduces the energy and cost requirements. The lipid composition of Spirulina can also be manipulated through cultivation techniques and environmental conditions, allowing for the production of specific types of biofuels with desirable properties. Another advantageous characteristic of Spirulina is its ability to grow in nutrient-rich wastewater, such as agricultural runoff or certain industrial effluents. By utilizing these wastewater sources, Spirulina cultivation for biofuels production can help in the remediation of polluted water bodies and contribute to a more sustainable wastewater treatment process. Overall, the high lipid content and adaptability of Spirulina, combined with its potential to grow in nutrient-rich wastewater, make it a promising candidate for extracting biofuels, offering a renewable and environmentally friendly alternative to conventional fossil fuels.

- PETG



Polyethylene terephthalate glycol-modified (PETG) is a popular thermoplastic material known for its versatile properties, making it an excellent choice for various applications, including containers for algae mass. PETG with a filament diameter of 1.75 mm offers several characteristic features that contribute to its suitability in this context.

Firstly, PETG is highly durable and exhibits exceptional strength. Its robust nature allows it to withstand the rigors of handling and transportation without experiencing significant damage or deformation. This durability ensures that the container maintains its structural integrity over time, preventing any leakage or contamination of the algae mass it holds.

Additionally, PETG has excellent chemical resistance. It is resistant to a wide range of chemicals, including acids and bases, which is crucial when dealing with biological materials such as algae mass. This chemical resistance prevents any potential interactions between the container material and the algae, ensuring the purity and integrity of the mass.

PETG is also known for its high transparency or translucency. This characteristic allows for easy monitoring and observation of the contents within the container without the need for frequent opening or exposure. By visually assessing the state of the algae mass, researchers or operators can make informed decisions regarding its growth, health, and any necessary interventions. The transparency of PETG

● PETG

containers saves time and effort while maintaining an optimal environment for the algae.

Furthermore, PETG possesses excellent UV stability. This means that it can resist the harmful effects of ultraviolet (UV) radiation, which is particularly important when considering algae cultivation. The ability of PETG to withstand prolonged exposure to sunlight ensures that the container does not degrade or become brittle over time, thereby maintaining its longevity and effectiveness as an algae mass container.

Regarding the lifespan of PETG containers, it is important to note that it can vary depending on the specific conditions and usage. Generally, PETG has a long lifespan, making it suitable for prolonged use. With proper care and maintenance, including regular cleaning and avoidance of extreme temperatures, PETG containers can provide reliable service for an extended period.

PETG filament offers a range of advantageous characteristics for containers of algae mass. Its durability, chemical resistance, translucency, and UV stability make it an excellent choice for maintaining the integrity and well-being of the algae. Furthermore, the long lifespan of PETG containers ensures their cost-effectiveness and suitability for sustained use.

1.2. Laboratory Equipments

- AirPump

Bioreactors play a crucial role in various fields, such as pharmaceuticals, biotechnology, and wastewater treatment, where they facilitate the growth and maintenance of biological organisms or processes. To ensure optimal conditions within a bioreactors, one essential requirement is a reliable and efficient air supply system. The Nicecrew Air Pump emerges as an excellent choice for bioreactors due to its exceptional features and performance. Let's explore why it is considered the ideal air pump for such applications.

1. Superior Airflow and Pressure Control:
The Nicecrew Air Pump boasts a powerful motor and innovative engineering, resulting in a high airflow rate and precise pressure control. Bioreactors often require a continuous supply of air to maintain optimal oxygen levels and ensure proper mixing of the contents. With its superior airflow capabilities, the Nicecrew Air Pump ensures efficient oxygen transfer and promotes a homogenous environment within the bioreactors.

2. Low Noise and Vibration:
Noise and vibration can be detrimental to the stability and functionality of bioreactors, as they may interfere with biological processes or cause physical disturbances. The Nicecrew Air Pump employs advanced noise reduction technology, minimizing operational noise and vibration to negligible levels.

● AirPump

This feature is especially beneficial for maintaining a quiet and undisturbed environment within the bioreactors, ensuring optimal conditions for the biological organisms or processes.

3. Energy Efficiency:
Efficient energy consumption is a vital consideration in any bioreactors setup, as it helps minimize operational costs and reduce environmental impact. The Nicecrew Air Pump is designed with energy efficiency in mind, employing advanced motor technology that maximizes airflow while minimizing power consumption. This energy-saving feature makes it a cost-effective and eco-friendly choice for bioreactors, providing long-term benefits to both researchers and the environment.

4. Durable and Reliable:
Bioreactors often operate continuously for extended periods, making durability and reliability crucial factors when selecting an air pump. The Nicecrew Air Pump is built with high-quality materials, ensuring robustness and longevity. Its components are engineered to withstand the demands of continuous operation, ensuring reliable performance and minimal downtime. This durability is essential for maintaining a stable environment within the bioreactors and avoiding potential disruptions to

- AirPump → ongoing experiments or processes.

5. Easy Maintenance and Safety Features:
The Nicecrew Air Pump is designed to be user-friendly, with easy maintenance requirements and safety features. Its modular design allows for effortless cleaning and part replacement, ensuring optimal hygiene within the bioreactors setup. Additionally, the air pump incorporates safety mechanisms such as overheat protection and automatic shutdown in case of anomalies, preventing potential accidents and ensuring the well-being of researchers and the bioreactors system.

- Aqurium Water pump → In an aquarium setup, an aquarium pump, also known as an aquarium water pump or circulation pump, is typically used to create water movement and circulation. The pump draws water from the tank, propels it through pipes or tubing, and then returns it back to the aquarium. The flow created by the pump helps promote circulation within the tank, providing numerous benefits to the aquatic environment.

Enhancing Water Movement in Aquariums:
Aquarium pumps play a crucial role in enhancing water movement within the tank. The pump can be strategically placed to create directional currents

● Aqurium Water pump →

or a more general flow pattern. By directing the water flow, it helps prevent stagnant areas and dead spots where debris, waste, and harmful substances can accumulate. The enhanced water movement also promotes the oxygenation of the water by facilitating gas exchange at the water's surface.

Promoting Filtration and Waste Removal:
Fluid circulation generated by the aquarium pump aids in the efficiency of the filtration system. The movement of water helps to drive debris and waste towards the filter intake, improving the removal of impurities and enhancing water quality. The pump ensures that water is continuously circulated through the filter, maximizing its effectiveness in removing particulate matter, toxins, and other contaminants.

Supporting Aquatic Health and Well-being:
Fluid circulation provided by the aquarium pump is beneficial for the overall health and well-being of aquatic organisms. It helps distribute heat, nutrients, and dissolved oxygen evenly throughout the tank, creating a more uniform and favourable environment. The improved

● Aqurium Water pump →

oxygenation and nutrient distribution support the metabolic processes of fish, invertebrates, and plants, promoting their growth, vitality, and overall health.

Application in Bioreactors:

In bioreactors systems, an aquarium pump can also be utilized for fluid circulation. Depending on the scale and requirements of the bioreactors, an appropriately sized aquarium pump can be employed to provide the necessary circulation within the culture medium. The pump helps distribute nutrients, gases, and other essential components uniformly, ensuring consistent conditions for microbial or cellular growth.

Adaptation for Bioreactors Use:

When using an aquarium pump for fluid circulation in bioreactors, it's essential to consider the specific requirements of the bioprocess. This includes selecting a pump with appropriate flow rates, ensuring compatibility with the culture medium and system materials, and considering any additional features required for bioprocess control. The pump can be integrated into the bioreactors setup, with the outlet connected to the piping system for even distribution of the culture medium. The choice of the best pipe for a

● Pipes

→ bioreactors depends on several factors, including the specific requirements of the bioprocess, the nature of the culture medium, the operating conditions, and other considerations. There is no one-size-fits-all answer, as different applications may have different optimal choices. However, here are a few commonly used pipe materials in bioreactors:

Stainless Steel: Stainless steel pipes are widely used in bioreactors due to their excellent corrosion resistance, mechanical strength, and durability. They can withstand high temperatures, pressure, and aggressive chemicals. Stainless steel pipes are commonly used in large-scale industrial bioreactors and applications where sterility is not the primary concern.

Glass: Glass pipes offer excellent chemical resistance and transparency, allowing for visual monitoring of the flow and condition of the culture medium. They are commonly used in research or laboratory-scale bioreactors and applications where visual observation is important. Glass pipes can be sterilized and are suitable for smaller-scale systems.

Polypropylene: Polypropylene pipes are lightweight, chemically inert, and resistant to

- Pipes

many chemicals and solvents. They are cost-effective and commonly used in both laboratory-scale and industrial bioreactors. Polypropylene pipes offer good biocompatibility and can be sterilized using various methods, making them suitable for a wide range of bioprocess applications.

Silicone: Silicone pipes are highly flexible and have good biocompatibility, making them suitable for applications involving sensitive cell cultures or biopharmaceutical production. They are resistant to microbial growth and can be autoclaved for sterilization. Silicone pipes are commonly used in systems where flexibility and ease of installation are important.

It's important to consider the specific requirements of your bioprocess, such as temperature, pressure, chemical compatibility, biocompatibility, and sterilization methods. Consulting with bioprocess engineers or industry experts can help determine the best pipe material for your specific application. Additionally, adhering to applicable industry standards and guidelines is crucial in ensuring the suitability and performance of the chosen pipe material in bioreactors systems.

● Nutrients →

Flourish Iron and Flourish Advance are two popular products used in the cultivation of algae cultures and aquatic plants. They are part of the Seachem Flourish line of plant supplements designed to provide essential nutrients for healthy growth. Here's some information about each product and their benefits in growing algae cultures:

Flourish Iron:

Flourish Iron is a liquid plant supplement that specifically targets iron supplementation. Iron is a vital micronutrient required by plants and algae for various physiological processes, including chlorophyll production and photosynthesis. Adding Flourish Iron to an algae culture can help ensure that the algae receive an adequate supply of iron, promoting robust growth and vibrant green coloration.

Flourish Iron is typically used in situations where iron levels are limited or depleted in the aquatic environment. It can be particularly beneficial in low-tech setups or when the water source lacks sufficient iron content. By supplementing with Flourish Iron, algae cultures can thrive and exhibit improved growth rates and overall health.

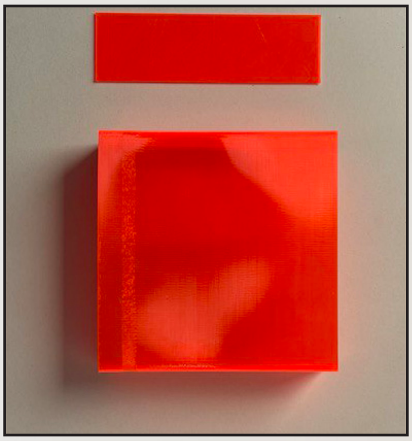
Flourish Advance:

● Nutrients →

Flourish Advance is another liquid plant supplement that focuses on promoting the growth of beneficial micro-organisms, including algae. It contains a blend of bioavailable carbon sources and plant extracts that serve as a food source for micro-organisms, enhancing their proliferation. Flourish Advance acts as a natural growth stimulant and biofilm enhancer.

When applied to an algae culture, Flourish Advance helps create an optimal environment for the growth of algae and other micro-organisms. It encourages the establishment of a healthy biofilm, which can provide additional nutrition for the algae and enhance their overall growth and development. Flourish Advance can contribute to thicker, lusher algae cultures and promote the colonization of surfaces within the culture system.

It's important to note that the specific dosing and application of Flourish Iron and Flourish Advance may vary depending on the specific requirements of your algae culture and the instructions provided by the manufacturer. It's advisable to carefully follow the recommended dosage guidelines and monitor the algae culture's response to ensure the desired outcomes are achieved without any adverse effects.

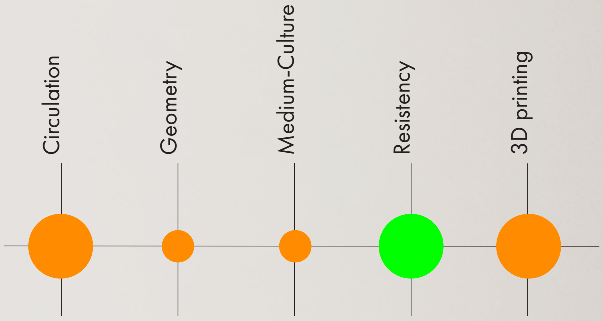



Flourish
Iron™
Suplemento de hierro para acuario de plantas
Supplément en fer pour l'aquarium planté
Integratore di ferro per acquari con piante
Suplemento de ferro para aquários plantados.
Iron Supplement for the Planted Aquarium
(10,000 mg/L)
Seachem
Flourish
Advance™
Natural Phytohormone Supplement for the Planted Aquarium
Seachem

FIRST EXPERIENCE

DATE: May 4th, 2023, 13:00 P.M

CHALLANGE: Algae Medium Culture



This experimental endeavor was undertaken with the primary objective of acquiring fundamental knowledge regarding the characteristics and behavior of algae medium. The intention behind conducting this experiment was to gain a comprehensive understanding of the basic principles underlying the growth and development of algae cultures. However, despite the apparent simplicity of the test setup, the obtained results failed to align with the predetermined objectives, leading to unexpected outcomes.

Throughout the experimental process, it became evident that the algae medium culture recipes employed were insufficiently concentrated to promote the desired growth and proliferation of algae. Consequently, the observed changes in the algae culture were not in accordance with the expected outcomes. Over the course of the designated timeframe, which was carefully established to facilitate optimal growth conditions, a perplexing phenomenon unfolded. Instead of observing the anticipated increase in algae mass and biomass density, a contrary trend emerged.

As the experiment progressed, the liquid medium, which initially exhibited a suitable composition and appeared conducive to supporting algae growth, gradually became clearer over time. This unexpected transformation was accompanied by a noticeable decline in the overall mass of the algae culture. Such outcomes contradicted the intended goal of achieving substantial growth and biomass accumulation.

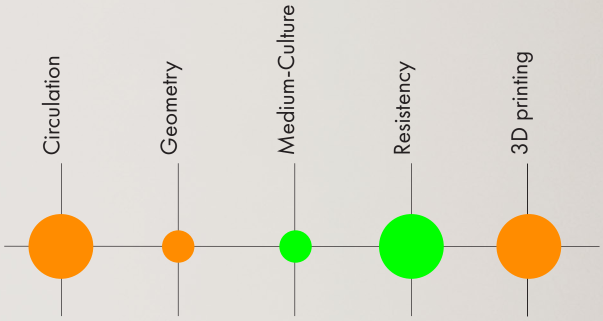
These unanticipated results necessitated a thorough analysis of the experimental setup and the factors that could have contributed to the observed changes. Potential variables that warranted investigation included the composition of the algae medium, nutrient availability, environmental factors, and the suitability of the cultivation conditions. A critical evaluation of these factors was deemed essential in order to identify the specific shortcomings that led to the disparity between the expected and observed outcomes.

In conclusion, despite the initial intentions to explore the basic properties of algae medium through this experimental undertaking, the obtained results proved to be incongruent with the envisioned objectives. The inadequately dense algae medium culture, coupled with the subsequent decrease in mass and clarity of the liquid medium, underscored the importance of meticulously fine-tuning experimental parameters to achieve the desired outcomes. The discrepancies encountered in this endeavor serve as valuable lessons, highlighting the intricate nature of algae culture dynamics and the need for further refinement in future experimental designs.

SECOND EXPERIENCE

DATE: May 12th, 2023, 12:30 P.M

CHALLANGE: Water Flow (Circulation)



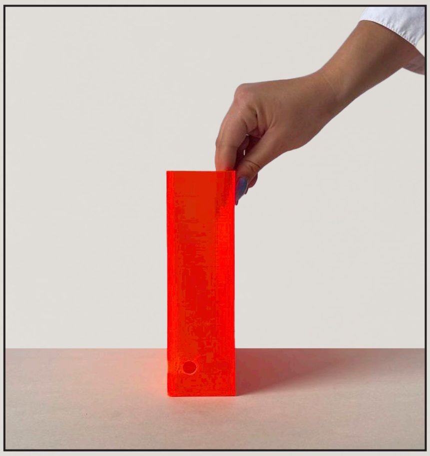
The second set of experiments has witnessed significant progress compared to the initial test. As previously mentioned, determining the correct combination ratio of nutrients, algae, and water has posed the primary challenge.
In order to address this issue, extensive research was conducted as the initial step, followed by the establishment of the appropriate proportions, which are outlined below:

1. A 1-liter algae culture utilizing spirulina powder can be prepared by adding 2 to 4 grams of spirulina powder to a sterile container containing 900 milliliters of distilled water.
2. Thoroughly stir the mixture to ensure even dispersion of the spirulina powder.
3. Adjust the pH of the growth medium to the optimal range for spirulina by employing pH-adjusting solutions if necessary.
4. Consider supplementing the growth medium with additional nutrients and trace elements essential for spirulina cultivation, as follows:

   1. Nitrogen (N): Introduce nitrogen in the form of a nitrogen source, such as sodium nitrate (NaNO3) or urea, at an initial concentration of approximately 0.1 to 0.2 grams per liter (g/L) of nitrogen.
   2. Phosphorus (P): Incorporate phosphorus in the form of a phosphorus source, such as potassium dihydrogen phosphate (KH2PO4), at an initial concentration of approximately 0.02 to 0.05 g/L of phosphorus.
   3. Potassium (K): Add potassium in the form of a potassium source, such as potassium chloride (KCl) or potassium sulfate (K2SO4), at an initial concentration of approximately 0.1 to 0.2 g/L of potassium.
   4. Iron (Fe): Due to their high iron demand, spirulina cultures typically require iron supplementation. Iron sulfate (FeSO4) or iron chloride (FeCl2) can be employed, starting with a concentration of approximately 0.005 to 0.02 g/L of iron.

5. Transfer the prepared growth medium to a sterile container suitable for cultivating the algae.
6. Inoculate the culture with a starter culture of spirulina, adhering to the recommended amount or instructions specific to your particular strain or starter culture.
7. Position the container in a well-lit area with appropriate lighting conditions conducive to spirulina growth.
8. Employ an air pump and air stone to provide aeration, ensuring proper mixing and aeration of the culture.
9. Regularly monitor the culture, making adjustments to nutrient concentrations, pH, and lighting as necessary.

In this particular laboratory experiment, the subsequent objective following the aforementioned step involved achieving an optimal and aesthetically pleasing structure. With this in mind, a rudimentary geometric shape was carefully chosen, specifically a rectangular 3D volume, meticulously tailored to adhere to the specified dimensions of 20 cm in height, 20 cm in length, 0.12 cm in thickness, and 6 cm in width.



The primary objective at this stage was to establish a seamless flow within the module, originating from the sources and carrying the algae medium culture. To effectively realize this objective, a strategically positioned input orifice was designed and integrated onto the module's side, facilitating the connection of a pipe from the external resources.

In order to prevent the undesirable settling of algae within the module, the implementation of an air pump was deemed necessary. The purpose of this air pump was to maintain a consistent flow, thus ensuring continuous movement within the system. Once all the components were meticulously assembled, it became apparent that the outcome fell short of expectations due to complications of fluid circulation and its impact on the geometric structure.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Advance
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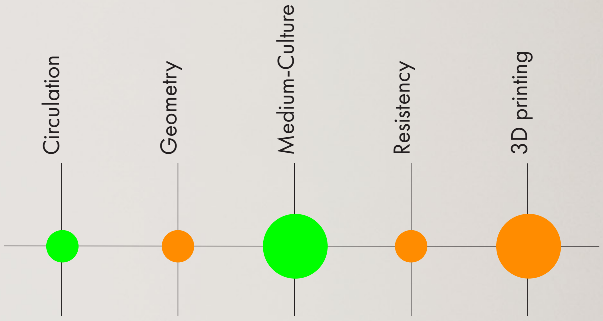
THIRD EXPERIENCE

DATE: May 20th, 2023, 10:00 A.M

CHALLANGE: Geometry (Printing)



In this laboratory experiment, the primary challenges faced were the resolution of the medium culture issue and the improvement of fluid circulation within the system. To address these practical concerns, the research focus shifted towards developing a geometry that could effectively accommodate both input and output requirements.

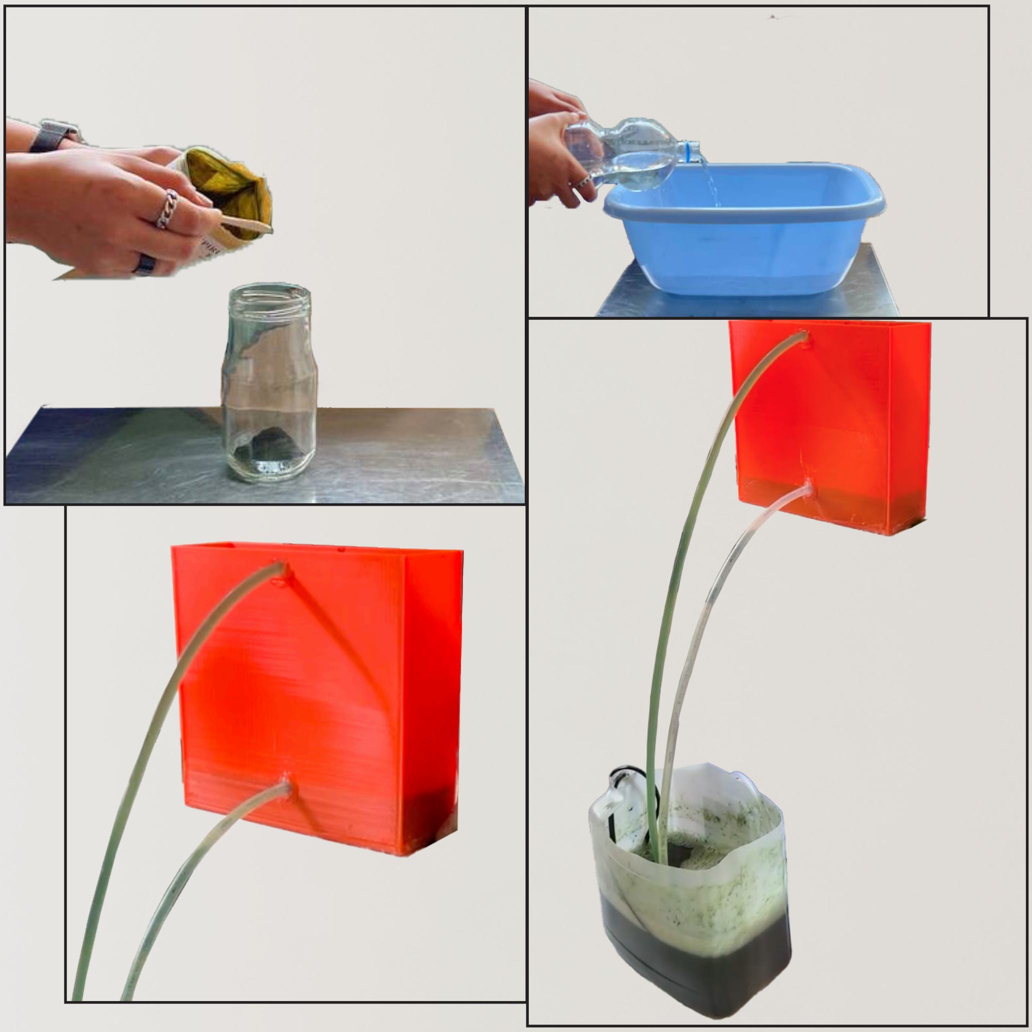
A more rigorous approach was adopted, incorporating thorough calculations to enhance the understanding of fluid flow and circulation dynamics. In pursuit of achieving a comprehensive circulation system, an additional tube with a diameter of 9mm was introduced. This addition was based on fluid mechanics principles, which necessitated the application of additional force. To meet this requirement, the implementation of an air pump became indispensable.

Regrettably, despite the various attempts made and the calculations involved, the inadequate quality of the 3D printing process hindered the achievement of a complete circulation system. The module suffered from leakage issues, thereby impeding the desired flow dynamics. This unforeseen consequence posed a significant obstacle to the successful completion of the experiment.

These challenges underscore the significance of meticulous consideration and optimization of various factors, such as design, material quality, and manufacturing processes, in order to ensure the functionality and reliability of the experimental setup. Future endeavors in this area should prioritize addressing these limitations to facilitate more accurate and effective fluid circulation within the system.

CALCULATIONS of an Hypothesis Model

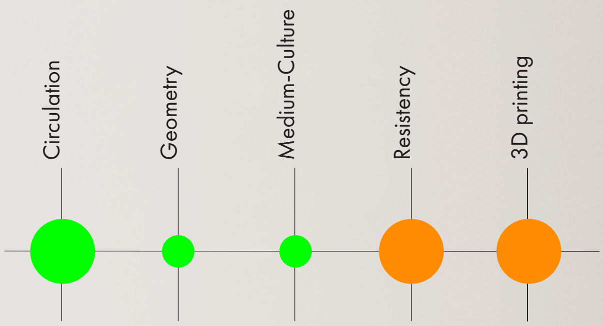
h: Height = 300 cm
l :Length = 150 cm
w: Width = 10 cm
Totall Volume = 3x1,5x0,1= 0,45 m^3,
1m^3 = 10 ^{3} L, 0,45 m^3= 450L (*max capacity of the sample*)
d: Distance= 0,05m (*is the distance of the input point from the top of the sample*)
Safe max height of the liquid level , in order to guarantee the correct oxygen intake process and the minimum pressure of water s = d + diameter of the imput point + 0,05m = 0,16m
substracted Volume = s x l x w = 0,16 x 1,5 x 0,1 = 0,024 m^3= 24L
Max Capacity of the sample :450 L - 24 L = 426 L
the water pump will need to be able to guarantee a complete cycle of the water per hour.
in this case needs to be > 430 L/h



FOURTH EXPERIENCE

DATE: May 26th, 2023, 11:00 A.M

CHALLANGE: Design (Aesthetic)



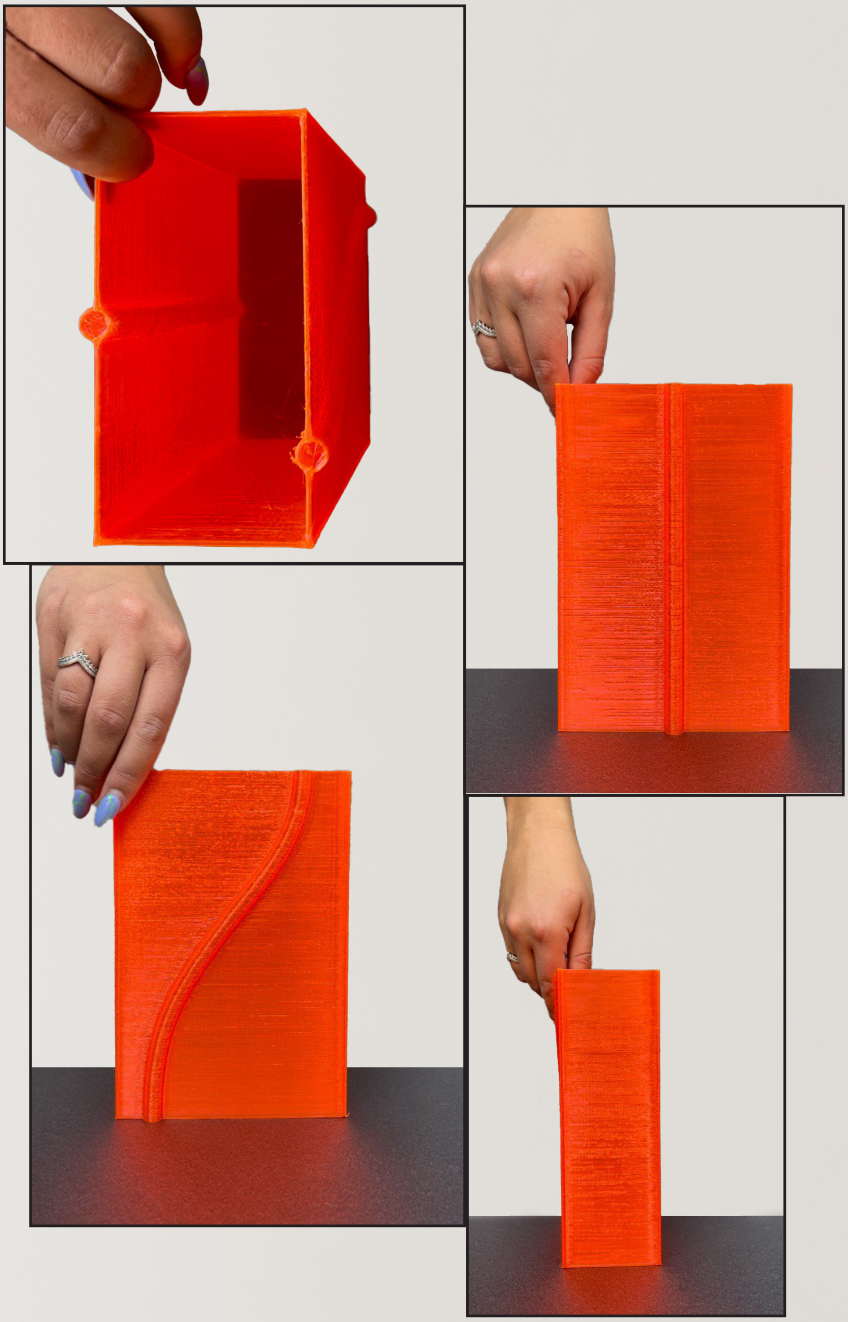
During the subsequent phase of the experiment, after successfully resolving the challenges related to fluid circulation and algae mass, the research focus shifted towards the integration of aesthetic and design considerations into the system. This phase aimed to enhance not only the functionality but also the visual appeal of the modules, showcasing the potential of art and design in scientific endeavors.

The concept of embedding the tubes directly onto the module surface was proposed and subjected to rigorous evaluation. This design approach presented a dual advantage: it significantly improved the aesthetic appearance of the modules and also resulted in substantial cost savings during the production of the system. By seamlessly integrating the tubes into the module design, a more streamlined and visually appealing overall structure was achieved, elevating the system to a higher level of sophistication.

By prioritizing the aesthetic aspect of the experiment, the research team recognized that the system's visual appeal extends beyond mere aesthetics. A well-designed and visually captivating system tends to have a positive impact on user experience and acceptance. The integration of art with technology in this context contributed to creating a more engaging and user-friendly system, enhancing the overall user interaction and fostering a deeper sense of connection.

Moreover, considering the aesthetic aspect of the system proved to be an opportunity to bridge the gap between disciplines and integrate art with technology. By integrating artistic elements into scientific experiments, the experiment showcased the potential for interdisciplinary collaboration and highlighted the symbiotic relationship between art and technology. This integration not only elevated the visual appeal of the modules but also served as a catalyst for creativity and innovation, inspiring researchers to explore novel approaches and push the boundaries of traditional scientific methodologies.

In conclusion, the inclusion of aesthetic and design considerations in the experiment proved to be a significant step towards creating a more refined and visually appealing system. The embedded tube design not only enhanced the visual appeal of the modules but also yielded substantial cost savings during production. Moreover, by embracing the aesthetic aspect, the system became more user-friendly, promoting a seamless integration of art and technology. This holistic approach exemplifies the potential for collaboration between artistic and scientific disciplines, fostering creativity, innovation, and advancing the field of technology in exciting and unexplored directions.



3.DESIGN PROPOSAL

3.1 FRAMEWORK OF THE SYSTEM

3.1.1 Calculating Second Skin Facade Structures

Second skin facade systems have gained significant popularity in contemporary architecture, offering numerous benefits such as improved thermal performance, solar control, and aesthetics. Calculating the structural requirements for these systems requires careful consideration of various factors to ensure their stability and efficiency. In this chapter, we explore different methodologies for calculating second skin facade structures, focusing on the specific requirements for better comprehending their calculation.

3.1.2 Analytical Approaches

Analytical methods offer simplified solutions for calculating second skin facade structures, based on theoretical models and assumptions. These approaches often provide quick estimations and initial design guidelines but may not capture all the complexities of real-world scenarios. When considering the requirements for calculating second skin facade structures, two important analytical approaches stand out:

3.1.2.1 Simplified Load Distribution Models

One common analytical method is the use of simplified load distribution models, which divide the load on the second skin facade into simplified distributions, such as uniformly distributed or concentrated loads. By considering factors such as wind pressure, dead loads, and imposed loads, engineers can estimate the structural requirements and assess the overall stability of the system. For a comprehensive understanding of this approach and its application to second skin facade structures, "Structural Design of Glass Façades" by Jan Wurm provides valuable insights.

3.1.2.2 Linear Elastic Analysis

Another analytical approach is the application of linear elastic analysis. This method assumes that the second skin facade behaves linearly under loading conditions, allowing engineers to calculate deflections, stresses, and deformations. While this approach provides a good approximation for moderate load conditions, it may not accurately predict the behavior of the system under extreme loads or nonlinear deformations. For a deeper understanding of linear elastic analysis and its relevance to second skin facade structures, “Structural Glass Façades and Enclosures” by Mic Patterson is an educational source worth exploring.

3.1.3 Numerical Approaches

Numerical methods utilize computational simulations to model the complex behavior of second skin facade structures. These techniques offer more accurate and detailed results but require advanced software and expertise. When considering the requirements for calculating second skin facade structures, two significant numerical approaches are relevant:

3.1.3.1 Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a commonly employed numerical method. FEA breaks down the second skin facade into smaller finite elements, simulating their behavior under various loading conditions. By applying material properties, boundary conditions, and appropriate equations, engineers can analyze stress distribution, deformation, and stability of the structure. To gain a better understanding of FEA and its application to second skin facade structures, “Finite Element Analysis for Design Engineers” by Paul M. Kurowski serves as an educational resource.

3.1.3.2 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) simulations play a crucial role in analyzing the aerodynamic performance of second skin façades. CFD helps evaluate factors such as wind pressure, air infiltration, and convective heat transfer. By simulating fluid flow, engineers can optimize ventilation strategies, minimize potential issues related to wind-induced vibrations or pressure differentials, and enhance overall system performance. “Introduction to Computational Fluid Dynamics: Development, Application and Analysis” by Atul Sharma offers valuable insights into CFD and its application to second skin facade structures.

3.1.4 Calculating Modules weight requirments

To calculate the weight of a single panel of the facade,the dimensions of the panel and the material from which it is constructed has to be considered.

- Measure the dimensions: Measure the length, width, and thickness of the panel. Use consistent units, such as meters or feet.
- Determine the material: Identify the material used for the panel. Examples include glass, aluminium, steel, composite panels, etc.
- Find the density: Obtain the density of the material used in the panel. The density is typically given in kilograms per cubic meter (kg/m^3) or pounds per cubic foot (lb/ft^3). You can refer to material specifications or engineering references for this information.
- Calculate the volume: Calculate the volume of the panel by multiplying its length, width, and thickness. Make sure to use the sam units throughout.
- Calculate the weight: Multiply the volume of the panel by the density of the material to obtain the weight. Ensure that the units are consistent. The resulting weight will be in kilograms or pounds, depending on the density units used.

3.1.5 Calculating Modules Weight

Based on the general density ranges typically associated with spirulina powder (800 kg/m^3 to 1200 kg/m^3) and recycled translucent plastic (800 kg/m^3 to 1200 kg/m^3), the weight range for the components has been determined.

- Weight range of the panel (PETG):

Assuming a density range of 1.27 kg/m^3 for PETG.

- Minimum weight: Volume of the panel x minimum density of PETG

- Maximum weight: Volume of the panel **x** maximum density of PETG

- Weight range of the algae medium culture (spirulina powder):

Assuming a density range of 800 kg/m^3 to 1200 kg/m^3 for spirulina powder:

- Minimum weight: Volume of the panel x minimum density of spirulina powder
- Maximum weight: Volume of the panel x maximum density of spirulina powder

- Weight range of the panel (PETG):

Assuming a density range of 1.27 kg/m^3 for PETG:
- Minimum weight: $0.006m^3$ x 1.27 kg/m^3 = 0.00762 kilograms (same as previously calculated)

- Weight range of the algae medium culture (spirulina powder):

Assuming a density range of 800 kg/m^3 to 1200 kg/m^3 for spirulina powder:
- Minimum weight: $0.006m^3$ x 800 kg/m^3 = 4.8 kilograms
- Maximum weight: $0.006m^3$ x 1200 kg/m^3 = 7.2 kilograms

Weight range of the module (recycled translucent plastic):
Assuming a density range of 800 kg/m^3 to 1200 kg/m^3 for recycled translucent plastic
- Minimum weight: $0.006m^3$ x 800 kg/m^3 = 4.8 kilograms
- Maximum weight: $0.006m^3$ x 1200 kg/m^3 = 7.2 kilograms

↓

Therefore, based on the assumed density ranges, the weight ranges are as follows:
- Weight range of the panel (PETG): 0.00762 kilograms to 0.00762 kilograms
- Weight range of the algae medium culture (spirulina powder): 4.8 kilograms to 7.2 kilograms
- Weight range of the module (recycled translucent plastic): 4.8 kilograms to 7.2 kilograms

3.1.6 Design and Construction of an Algae Bioreactors with 3D Printed PETG Panels and Embedded Pipes

3.1.6.1 Design Considerations

- Metal Structure: The curtain wall-like metal structure provides stability and support for the bioreactors system. Aluminium or stainless-steel bars and profiles are commonly used due to their strength and resistance to corrosion. Mullions, vertical supports placed strategically within the structure, enhance its stability and load distribution.

- 3D Printed PETG Panels: The 3D printed PETG panels offer flexibility in design and customization. PETG, a durable and resilient material, provides transparency for light penetration and can be fabricated to incorporate embedded pipes for efficient fluid circulation

3.1.6.2 Construction Components

- Metal Structure:

- Aluminium or stainless-steel bars and profiles for constructing the curtain wall-like structure
- Fasteners (bolts, nuts, screws) for assembly
- Cutting tools (saw, grinder) for shaping and preparing metal components
- Drill and drill bits for creating holes and connection points
- Level and measuring tools for proper alignment during assembly

- 3D Printed PETG Panels:

- 3D printer capable of printing PETG material
- PETG filament for 3D printing the panels
- CAD software for designing the panels
- Gaskets or seals for watertight panel attachment to the metal structure
- Biocompatible sealants or adhesives for panel attachment

- Embedded Pipes:

- PETG filament or tubing for 3D printing the embedded pipes
- CAD software for designing the pipe layout and connection points
- Fittings, connectors, and adapters for joining the pipes and facilitating fluid circulation
- Biocompatible sealants or adhesives for connecting pipes to panels and external piping system

- Lighting System:
  - LED lights or suitable light sources for algae illumination
  - Light fixtures or brackets for mounting lights within the bioreactors
  - Electrical wiring and connectors for light connections
  - Light intensity and spectrum control system for optimizing algae growth conditions

- Algae Cultivation:
  - Algae strains suitable for bioreactors cultivation
  - Nutrient solutions (nitrogen, phosphorus, potassium) for algae growth
  - Aeration system (air pumps, diffusers) for oxygen supply and mixing
  - Monitoring sensors (pH probes, temperature sensors) for tracking environmental parameters
  - Control system (micro controllers, PLCs) for automated nutrient dosing and environmental control

- Control and Monitoring System:
  - Micro controllers or PLCs for automation and control
  - Sensors and probes for monitoring environmental conditions and nutrient levels
  - User interface or HMI for control and monitoring
  - Software for data logging, analysis, and visualization
  - Communication modules (Ethernet, Wi-Fi) for remote access and control

- Safety Measures:
  - Personal protective equipment (PPE) such as gloves, safety glasses, and lab coats
  - Ventilation system for proper air circulation and prevention of exposure to harmful gases or odours
  - Safety protocols andprocedures for handling live organisms and hazardous materials

3.1.6.3 Biofuels Extraction: Filtration Method

The cultivated algae in the bioreactors can be processed to extract biofuels using the filtration method, which involves the following steps:

Harvesting: The algae biomass is separated from the growth medium using filtration techniques such as micro-filtration or ultra-filtration. These methods utilize porous membranes to separate the algae cells from the liquid phase.

3.1.6.4 Harvesting Components:

- Filtration membranes (micro-filtration or ultra-filtration) with suitable pore sizes
- Filtration module or housing for containing the membranes
- Pumping system (peristaltic pump or centrifugal pump) for fluid circulation
- Tubing and fittings for connecting the bioreactors to the filtration system
- Pressure gauges and flow meters for monitoring and controlling the filtration process
- Collection vessel or tank for collecting the separated algae biomass

De-watering: After harvesting, the collected algae biomass undergoes de-watering to remove excess water. Mechanical de-watering methods such as centrifugation or pressing can be employed to reduce the water content and concentrate the biomass.

Cell Disruption: Once de-watered, the algae cells can be subjected to cell disruption methods to release the intracellular components. Mechanical disruption, such as high-pressure homogenization or bead milling, can be used to break the cell walls and release lipids and other valuable compounds.

Filtration: The disrupted algae mixture is then passed through filtration membranes to separate the desired components. Membrane filtration techniques such as micro-filtration or ultra-filtration can be utilized to separate the biomass from the extracted compounds.

Recovery and Refinement: The filtrate containing the extracted biofuels is further processed to recover the desired components. Techniques such as evaporation, distillation, or solvent extraction can be employed to isolate and purify the biofuels. Additional refining processes may be necessary to meet quality standards and specific fuel specifications.

By-Product Utilization: Co-products generated during the filtration process, such as the filtered algae biomass, can be utilized for various applications such as animal feed, fertilizers, or bio-based chemicals.

It’s important to note that the specific methods and technologies used for biofuels extraction and filtration may vary depending on the desired end product, the characteristics of the algae strain, and the scale of the bioreactors system.

Regular maintenance, monitoring, and optimization of the bioreactors system are crucial for achieving efficient and sustainable algae cultivation and biofuels production.

3.DESIGN PROPOSAL

3.2 TEST AND ANALYSIS

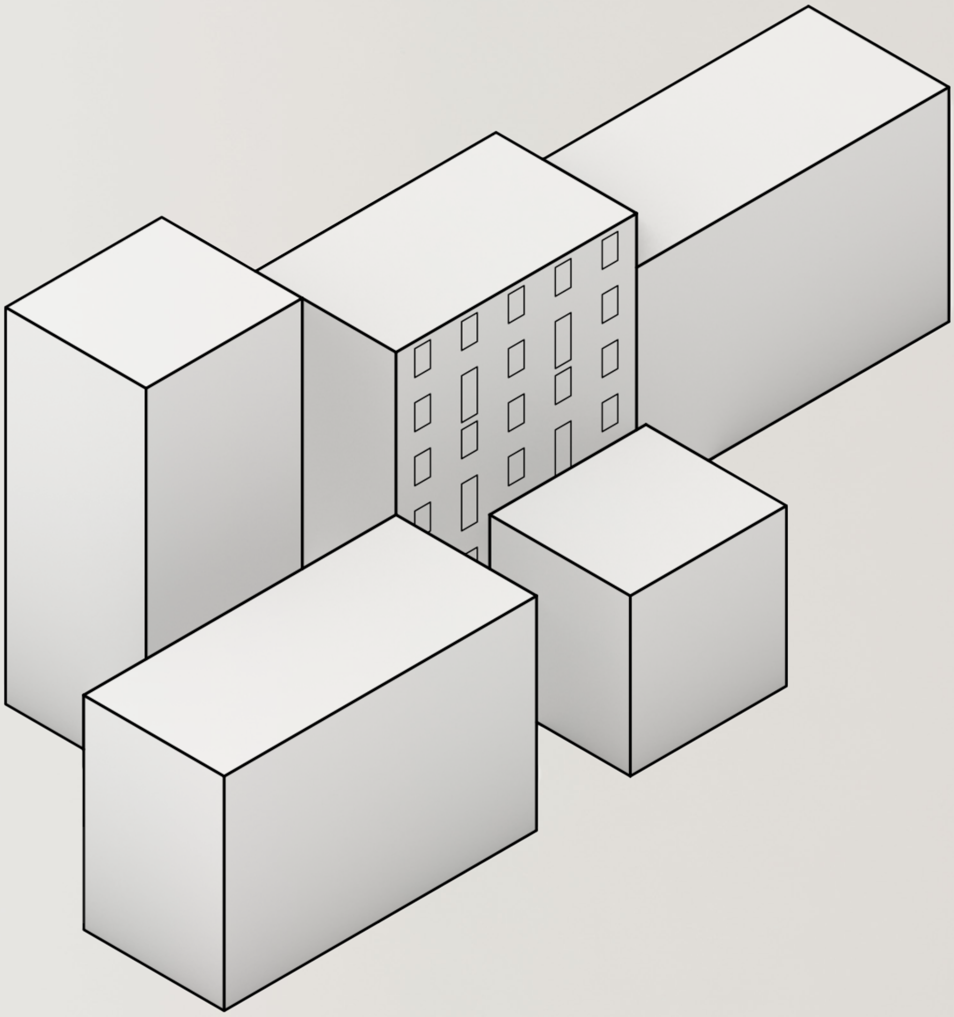
In practical terms, the laboratory-developed and tested samples are intended to be scaled up and put together as parts of a more extensive facade system. Since these panels have to facilitate the photosyntetis process, it will be optimal to place them based on the local climate and surroundings in each case to maximise their efficiency. The weather analysis performed on 4 various typologies of climate and environment categories will be shown on the following pages. This seeks to give an informative summary of many potential outcomes and the approaches that is appropriate to be undertaken regarding the tasselation of the panels on the facade.

The software used to conduct these experiments is Grasshopper, which includes the plug-in LadyBug that enables direct user access to the weather data present in the epw file of a chosen site. The final result is a sunlight study that displays the amount of sunlight falling on various surfaces over the course of a predetermined period of time in the year.

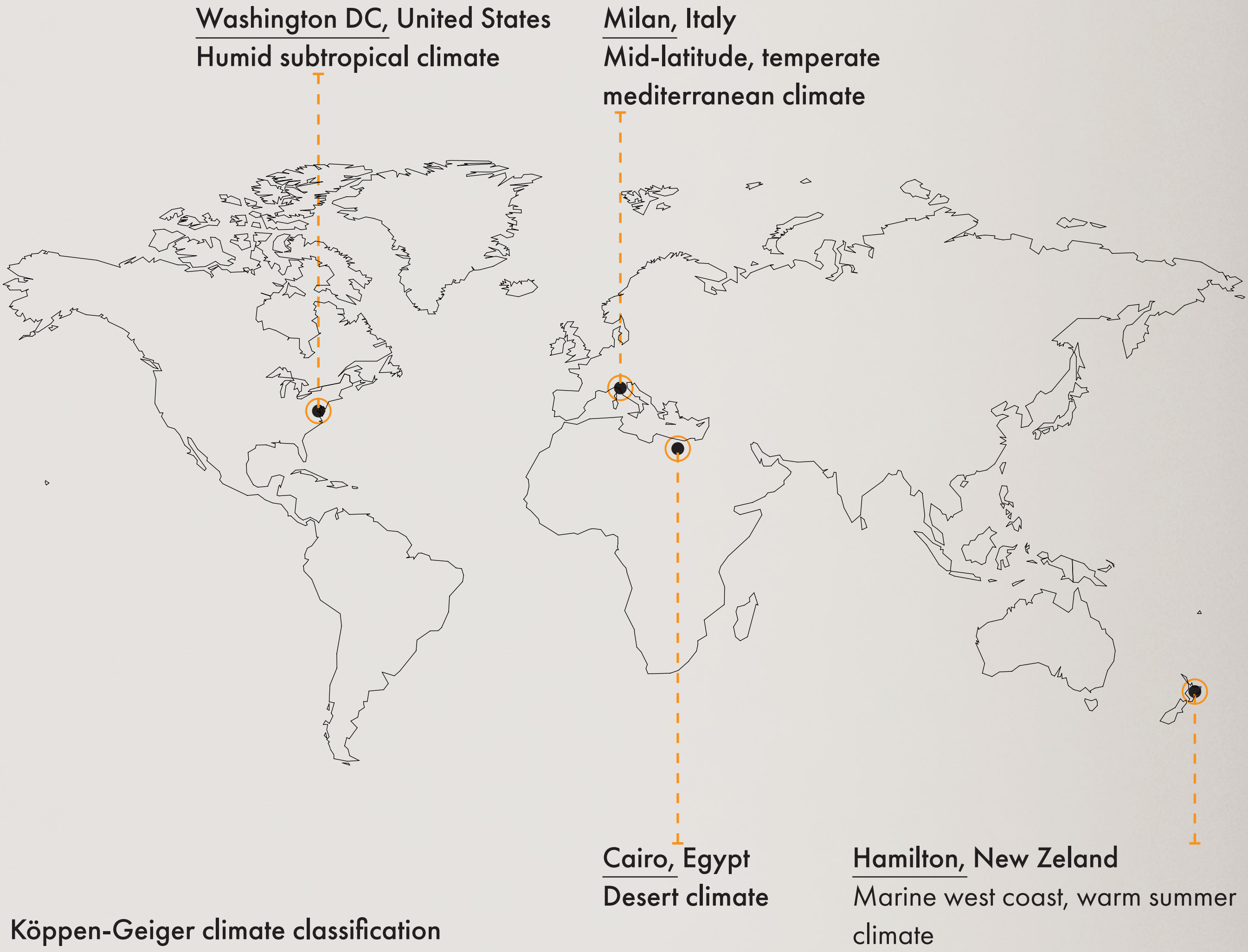
The goal of the weather study performed is not to reach to a final configuration of the facade, but rather to provide a very helpful tool to determine, on a case-by-case basis, the best course of action to be taken.

The structure under examination is a five-story, 15-meter-tall residential structure with an average height of 3 metres for each store.

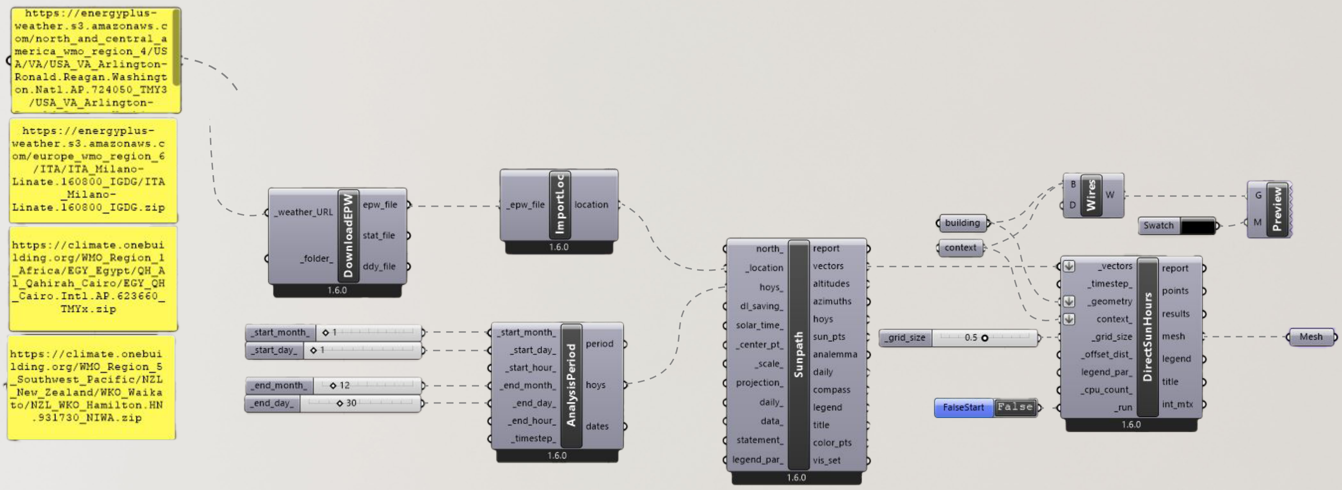
Given its proximity to other buildings of a similar design and anticipated N-S orientation, the housing complex was considered when performing a weather analysis.



3.2 TEST AND ANALYSIS



Köppen-Geiger climate classification



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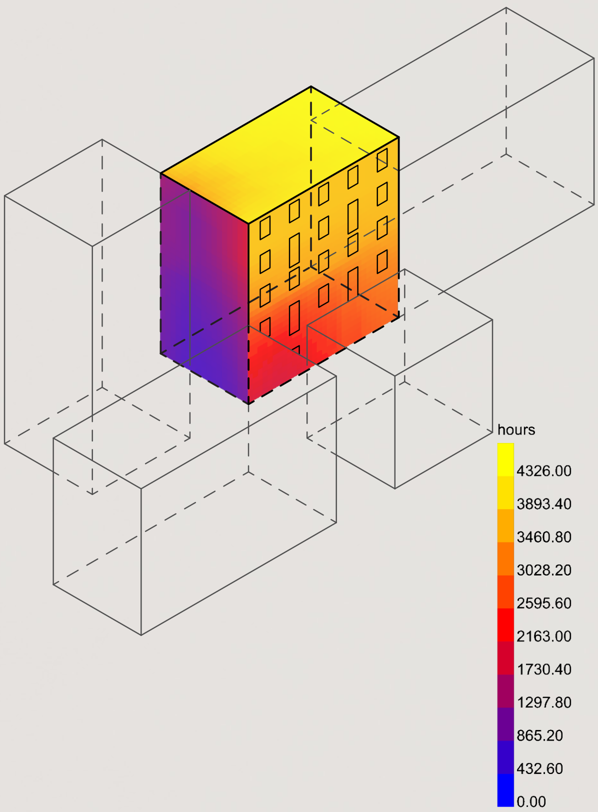
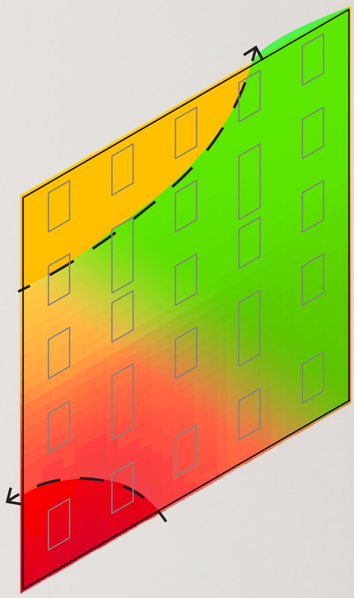
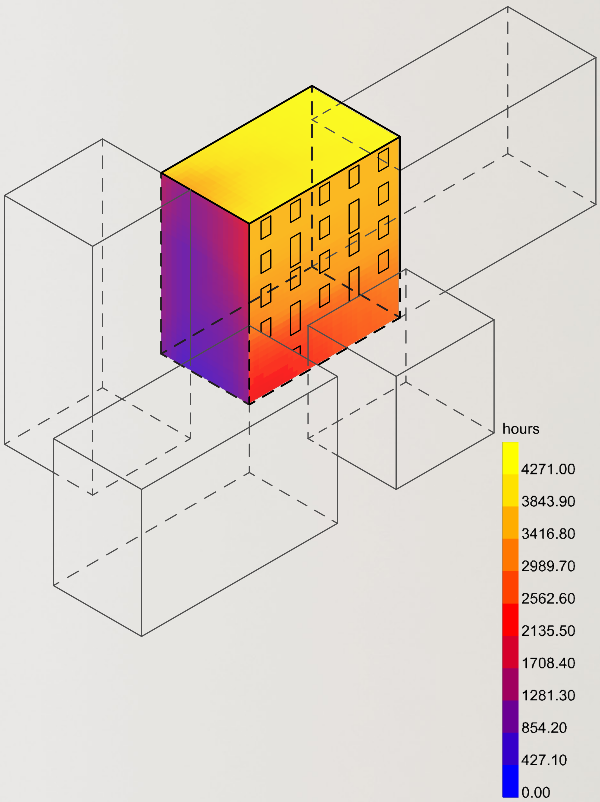
Mesh

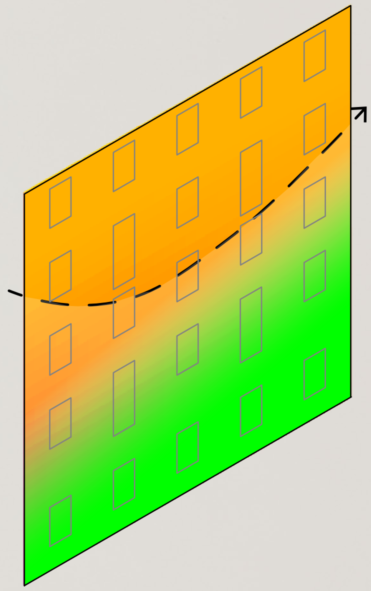
Sunlight analysis conducted on the **Milan site.** Strategy suggested is to place the panels in order to maximize the sun gain along the year and guarantee the functions of the system for all the 4 seasons.



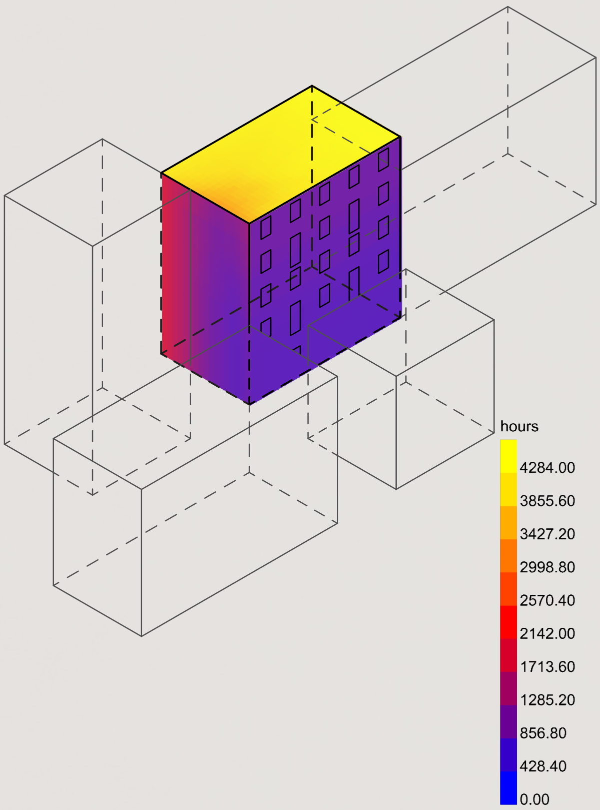


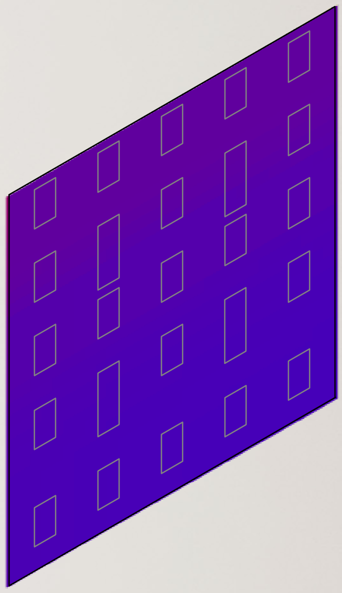
Sunlight analysis conducted on the **Cairo site**. Strategy suggested is to place the panels in order to minimize the sun gain along the year, taking into account the temperature range of such climate, which is between 12 and 35 Celcius



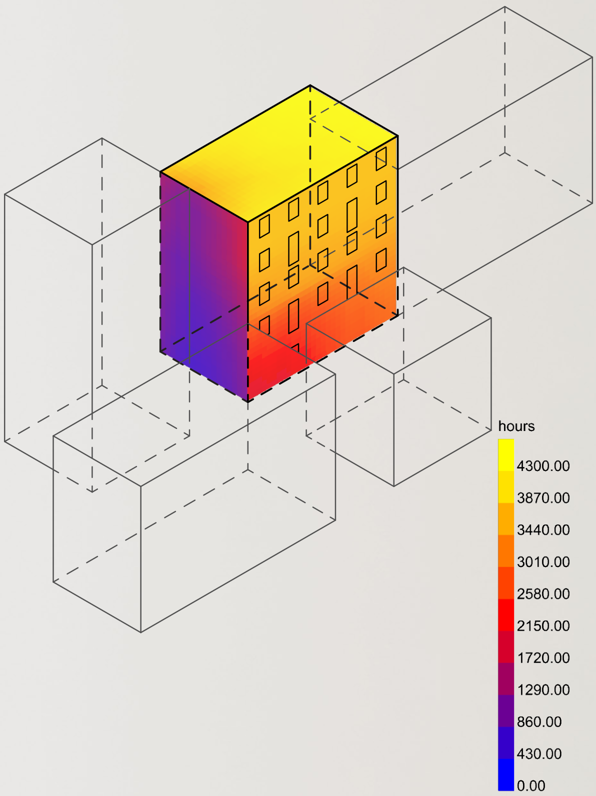


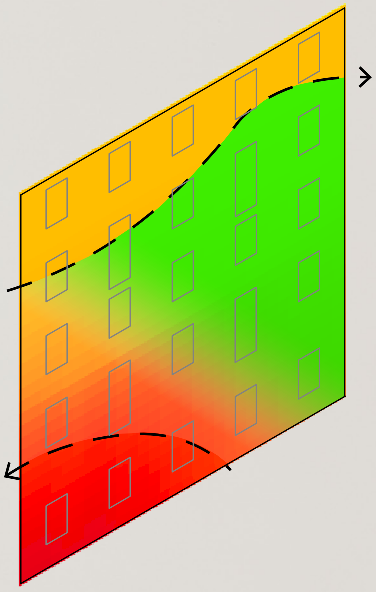
Sunlight analysis conducted on the **Hamilton site**. Strategy suggested is to avoid the placement of the panels on this facade, but on the contrary to run further tests in order to pick a better surface to host the panel system.





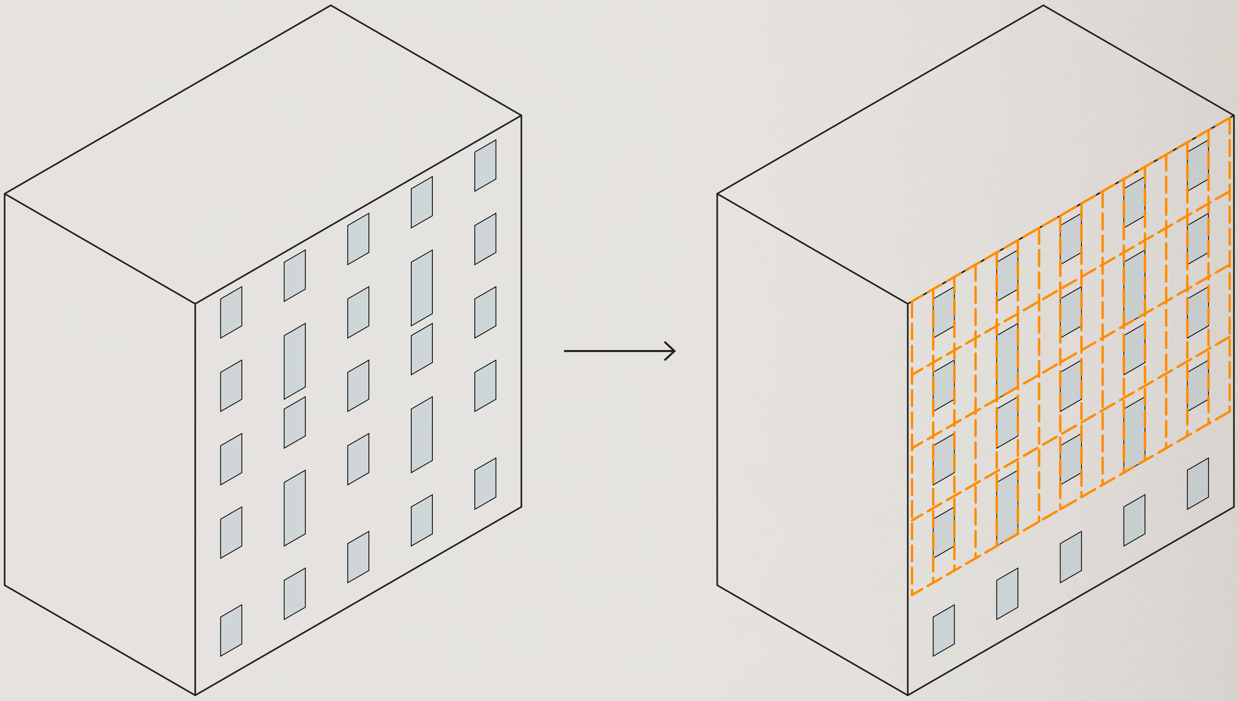
Sunlight analysis conducted on the **Washington DC site**. Strategy suggested is to place the panels in order to maximize the sun gain along the year, further analysis might need to be carried out, due to the extremely high levels of humidity.

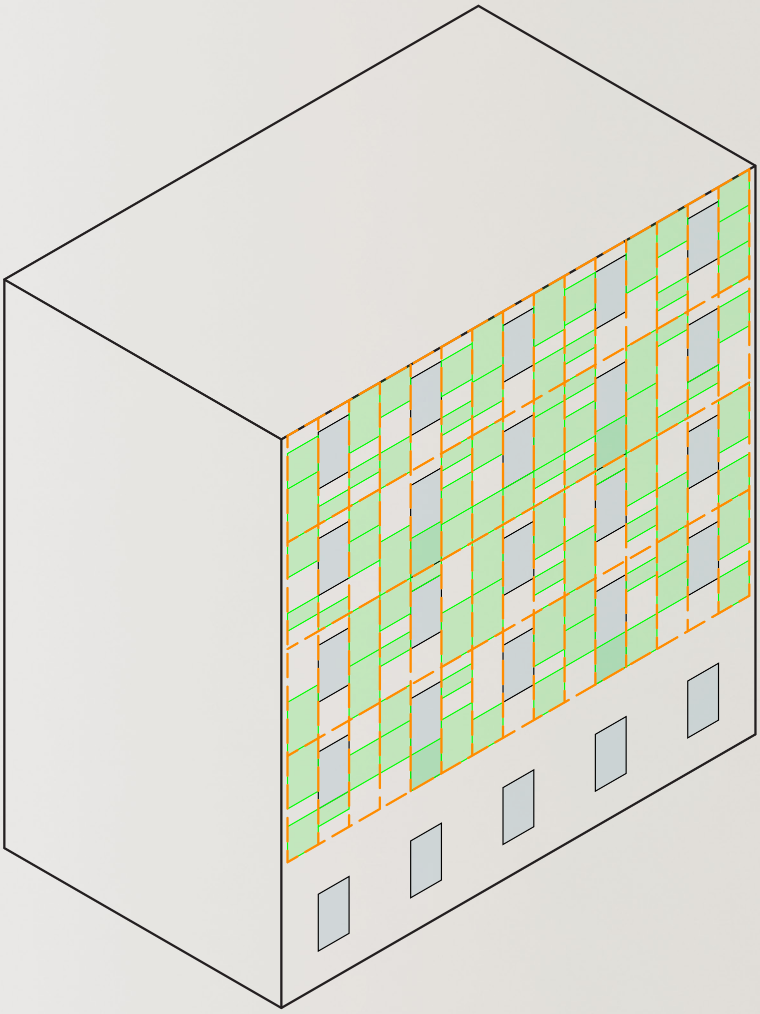




3.3 FRAMEWORK OF THE SYSTEM

As mentioned in the previous stage of the research, the use of modules as the foundation for the design of this facade system was one of the key considerations. This method of choice allows for a great deal of flexibility because it calls for the use of a secondary structure that will be attached to the building's former front and then populated with modules that might be placed wherever they are needed or desired. In fact, depending on the criteria that will be used, their location can vary significantly, resulting in an unlimited number of combinations for the same building without sacrificing its general functioning.





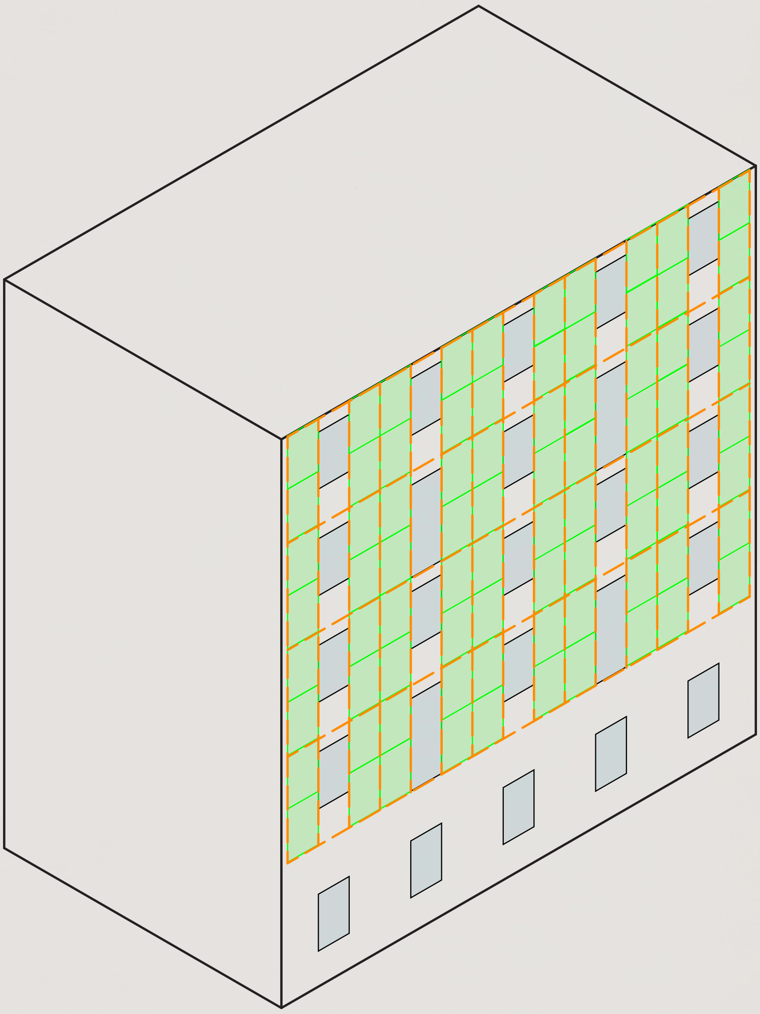
I STRATEGY

The grid adopted as secondary structure will have a span of 1.5 metres, applied to the same building tested for the sunlight analysis (5 stores, 15 meteres total height). A parametrized combination of panels, having a common base length of 1.5 metres and varied heights that are multiples of 0.5, can be used to fill out such grid.
In this instance, the plan is to maintain a minimum of two panel typologies connected and then repeat them along the facade, according to any standards for aesthetics or the surrounding environment and using these panels as shade elements as well.

→ 1,5 x 3 meters

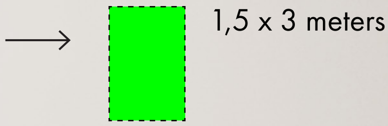
1,5 x 1,5 meters

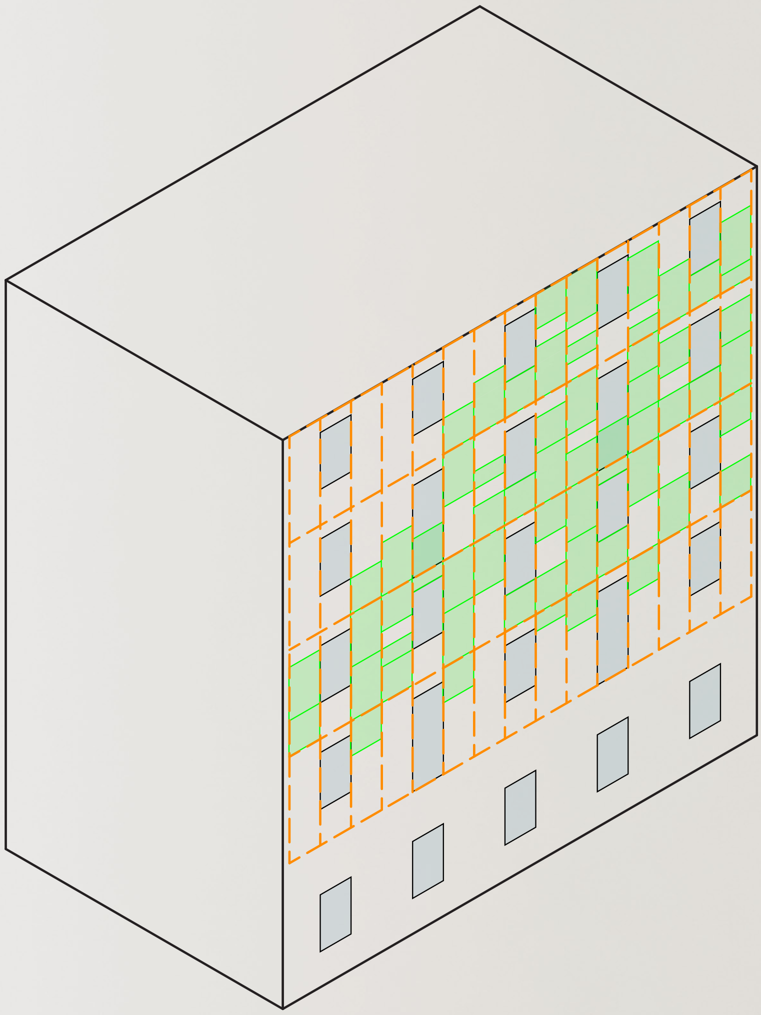
1,5 x 0,5 meters



II STRATEGY

In this type of scenario, the approach chosen calls for the usage of just one kind of panel. Due to the approach they won't be employed as a shade system and instead will help control the building's interior temperature. Given that the quantity and size of the panels are the same in each row, this strategy seeks to maintain a regular flow vertically, which is much simpler to control and forecast. On the other hand, it will provide a semi-continuous surface that can have an impact on the building's ability to regulate its internal temperature.

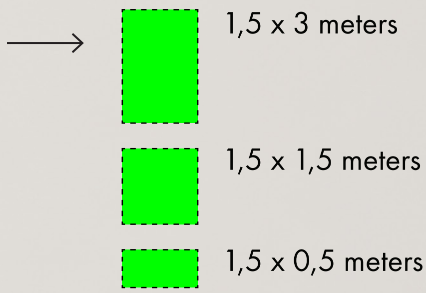




III STRATEGY

As was demonstrated in the previous chapter, this scenario makes direct use of the results of sunlight study to determine the most practical locations for the panels. Since it intends to use all three panel typologies and set their location where the conditions necessary for the photosynthetic process to operate correctly will be guaranteed, this method strengthens the connection between the system and the environment.

Such a design offers an endless number of potential outcomes and allows for a very high level of flexibility.



3.4 FLOW AND CIRCULATION

The efficient transfer of algae fluid is crucial in a photobioreactor system. Proper calculation of the system parameters ensures optimal performance and desired fluid flow rates. In this chapter, we will explore the step-by-step process for calculating the necessary dimensions for transferring algae fluid within a photobioreactor cube.

3.4.1 Determining Flow Rate and Fluid Velocity

The first step is to determine the required flow rate of algae fluid. This depends on various factors such as the process requirements, volume of fluid to be circulated, and desired turnover rate. Once the flow rate is established, select a fluid velocity within the recommended range (typically 0.5 to 2 meters per second).

3.4.2 Calculating Cross-Sectional Area

The cross-sectional area of the tubing or pipe is calculated by dividing the flow rate by the chosen fluid velocity. This provides the minimum area required to achieve the desired flow rate without excessive pressure drop. The formula for calculating the cross-sectional area is as follows:

Cross-sectional area = Flow rate / Fluid velocity

3.4.3 Selecting Tube Shape and Determining Diameter Based on the calculated cross-sectional area

Chose an appropriate tube shape that suits your application, considering factors such as ease of installation and maintenance. Common choices include cylindrical, square, or rectangular tubes. For cylindrical tubes, the diameter can be calculated using the formula:

Diameter = 2 * sqrt(Cross-sectional area / π)

Considering System Volume and Desired Cycle Time

To calculate the number of pipe connections needed between multiple photobioreactor cube models, determine the total volume of the system. This can be obtained by multiplying the volume of a single cube by the number of cubes. Additionally, define the desired cycle time, which indicates the duration required to circulate the entire system volume.

3.4.4 Determining Flow Rate per Connection

To achieve the desired cycle time, divide the total flow rate by the number of pipe connections. This ensures an equal distribution of flow between the connections. Adjust the flow rate per connection based on the specific requirements of system.

3.4.5 Recalculating Cross-Sectional Area and Diameter

Using the flow rate per connection, repeat steps 3 and 4 to recalculate the cross-sectional area and diameter of the pipe required for each connection. Ensure that the chosen diameter is commercially available and suitable for the application.

3.4.6 Considering Other Factors

It is important to consider additional factors such as pressure drop limitations, material compatibility, safety regulations, and available pipe sizes when finalizing the dimensions of the pipe connections. Consult industry standards and guidelines to ensure compliance and optimal performance.

considering the relevant standards and regulations for designing the photobioreactor system, there are the key aspects to be considered:

3.4.7 Building Codes and Standards:

In Milan, building codes and standards are regulated by the Italian building regulations. The primary standard for building construction is the "Norme Tecniche per le Costruzioni" (NTC) or Technical Standards for Constructions, issued by the Italian Ministry of Infrastructure and Transport. It covers aspects related to structural integrity, safety, and environmental considerations.

3.4.8 Material Selections

During selecting materials for photobioreactor system,the requirements should meet specified in the NTC standards. For the spirulina chlorophyll, consider any specific regulations related to its use and handling to ensure compliance with health and safety guidelines.

3.4.9 Structural Design

The structural design of your photobioreactor system should adhere to the NTC standards for structural integrity, including considerations for wind loads, seismic loads, and other external forces. Engaging a qualified structural engineer familiar with the NTC standards is recommended to ensure compliance.

3.4.10 Safety Considerations

Ensure your system design incorporates safety features such as guardrails, access points, and emergency shut-off systems in accordance with the NTC standards. Additionally, consider any specific safety regulations related to the handling and containment of the spirulina chlorophyll fluid.

3.4.11 Electrical Requirements

The electrical design for your system should comply with Italian electrical codes, specifically the "Norme CEI" (Comitato Elettrotecnico Italiano) or Italian Electrotechnical Committee standards. Engaging an electrical engineer familiar with these standards will help ensure compliance and safety

3.4.12 Ventilation and Air Quality

Consider the ventilation requirements and air quality control measures specified in the NTC standards to maintain a safe and healthy environment. Proper airflow, filtration, and exhaust systems should be designed to meet the ventilation standards

3.4.13 Accessibility and Maintenance

Design the system with accessibility in mind, ensuring compliance with accessibility regulations specified in the NTC standards. This includes providing safe access for maintenance and inspection activities

3.4.14 Environmental Regulations

Consider any relevant environmental regulations and standards for waste management, water treatment, and other environmental considerations. Adhere to the applicable regulations to minimize environmental impact and ensure compliance.

Calculate the requirements for an assumed system with six photobioreactor cube models, each having dimensions of 0.8 meters in length, 0.15 meters in depth, and 1.5 meters in height. The cycle time desired is 1 hour.

Calculating the total volume of the system:

Volume of one cube = 0.8 m x 0.15 m x 1.5 m = 0.18 m^3

Total volume = 6 x Volume of one cube = 6 x 0.18 m^3 = 1.08 m^3

Determining the flow rate per connection:

Flow rate per connection = Total volume / Cycle time

Flow rate per connection = 1.08 m^3 / 1 hour = 1.08 m^3/h

Determining the pipe diameter:

Using the flow rate per connection of 1.08 m^3/h, we can calculate the pipe diameter based on the desired fluid velocity. Let's assume a fluid velocity of 1 meter per second (m/s).

Calculate the cross-sectional area:

Cross-sectional area = Flow rate per connection / Fluid velocity

Cross-sectional area = 1.08 m^3/h / 3600 s/h / 1 m/s

Cross-sectional area = 3e-4 m^2

Determine the pipe diameter:

Diameter = 2 * sqrt(Cross-sectional area / π)

Diameter = 2 * sqrt(3e-4 m^2 / π)

Diameter ≈ **0.0195 m**

Based on international standards, a common pipe size that is close to 0.0195 meters is 20 mm (0.02 m) in diameter.

Therefore, for a system with six photobioreactor cube models, each with dimensions of 0.8 meters (length) x 0.15 meters (depth) x 1.5 meters (height), the recommended pipe diameter for each connection would be approximately 20 mm.

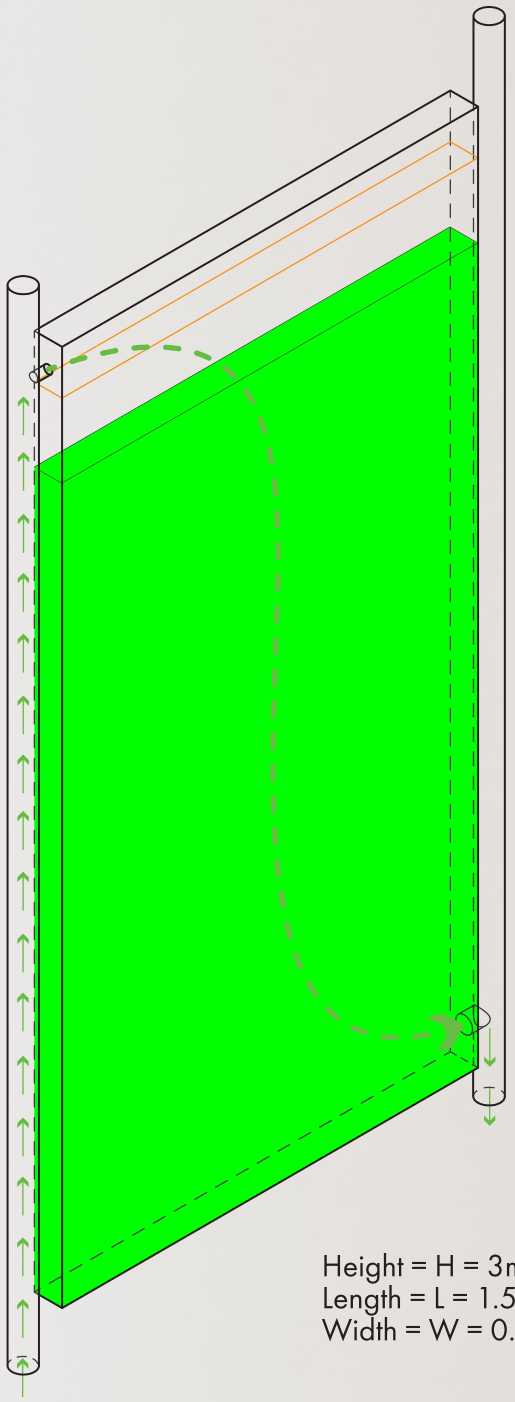
3.5 SCALE UP THE SAMPLE

The 1:1 scale sample is based on the already stated need of creating a circular flow, working on two opposite directions.
In order to achieve such system, choice has been to work with gravity facility, so the flow will have to complete a vertical circulation path.

The hypothesis that has been made is of a very basic bioreactor system, composed by:
- two modules, shaped as panels, stocked on top of each other
-two tubes, allowing the circulation in 2 ways
-two tanks

one containing the harvested solution (the liquid in which algae and nutrients have been dissolved), and the air pump, which starts the flow circulation when activated
(ref. Chapter VI,“Laboratory Equipment”, p.112)

one that will collect the solution when the photosynthesis has been completed, and eventually will be the starting point for the extraction phase
(ref. Chapter IV,“Extraction and Conversion of Algal Biomass”, p.79)



■ Total Volume of 1 panel = H x L x W
3m x 1.5m x 0.1m= 0.45 meter³

↓

by using the conversion 1meter³=10³ liter, the computed capacity of the sample (100%)=450 liter

■ Input Entrance Diameter = Ø Input = 3 cm
■ Output Entrance Diameter = Ø Output = 6 c

Ratio of Ø Input to Ø Output = 1/2

↓

■ d=Input Entrance Distance from Top of Sample
■ S=safe maximum height of the liquid inside the sample in order to guarantee the oxygen intake process and the pressure of the water

S = d+ Ø + 0.05 = 0.16 meter

■ Volume = S x L x W = 24 liter
■ Capacity of the Sample(considering safety Measures) 426 liter

↓

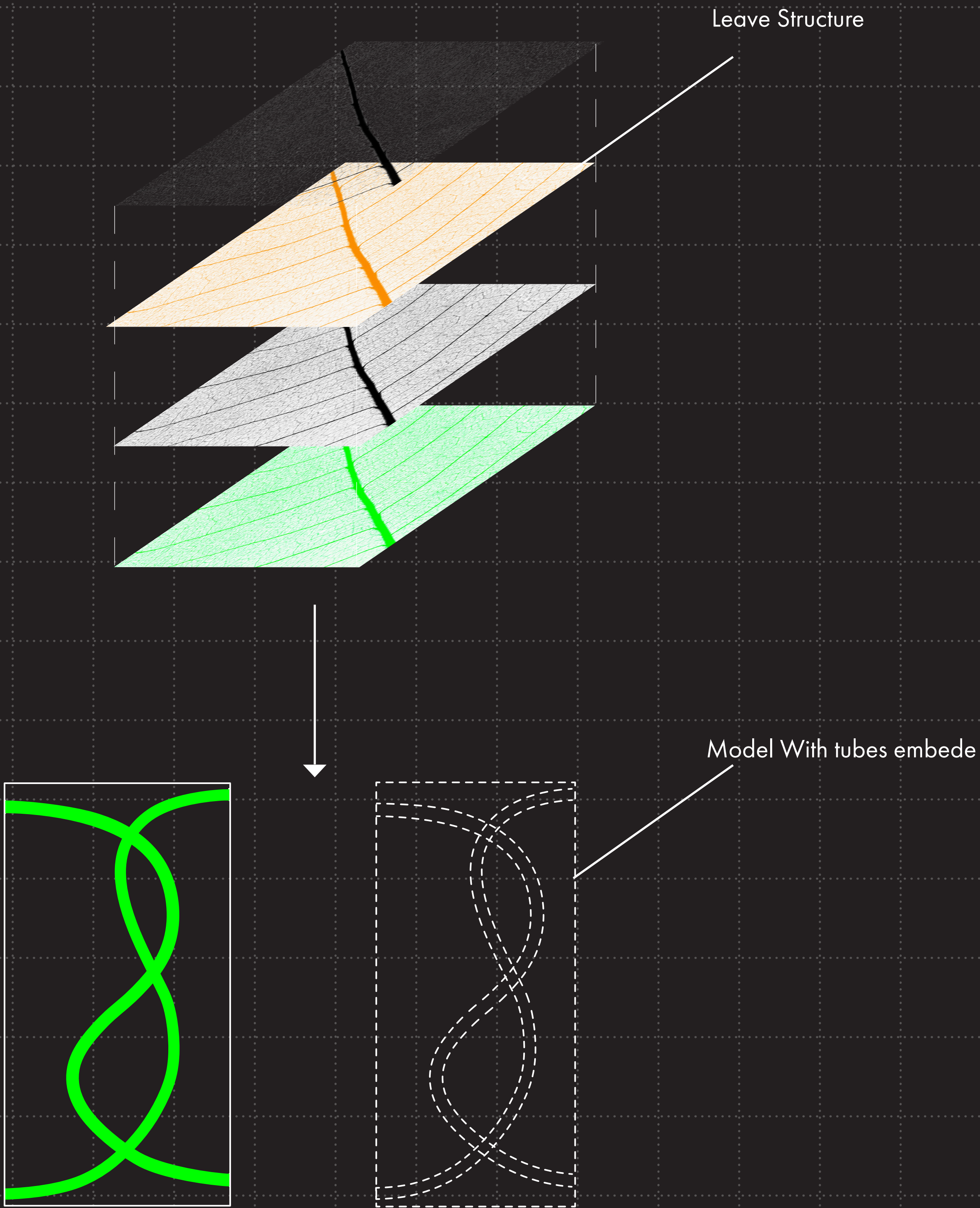
■ The Water Pump should be selected as it way to has enough capacity to guarantee a full cycle of the fluid per 1 hour (In this case) > 430 liter/hour

Height = H = 3meter
Length = L = 1.5meter
Width = W = 0.1meter

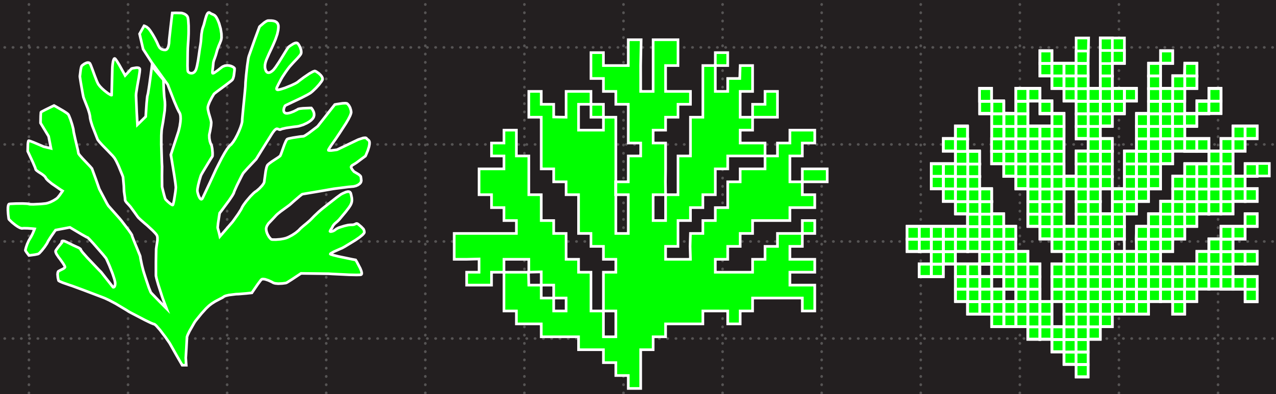
■ Secondary bridge it will be activated in case of maintenance of single panel,in order to guarantee e continuous flow

3.DESIGN PROPOSAL

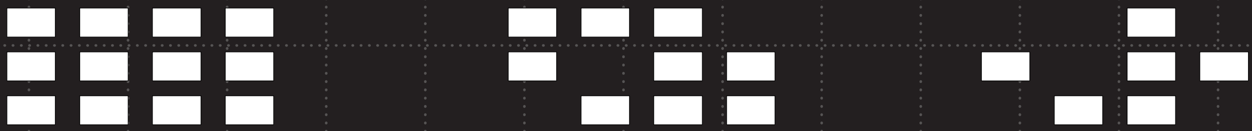
3.4 FROM THE TECHNICAL TO THE ARCHITECTURE. HOW TO COMBINE DESIGN AND REQUIREMENTS



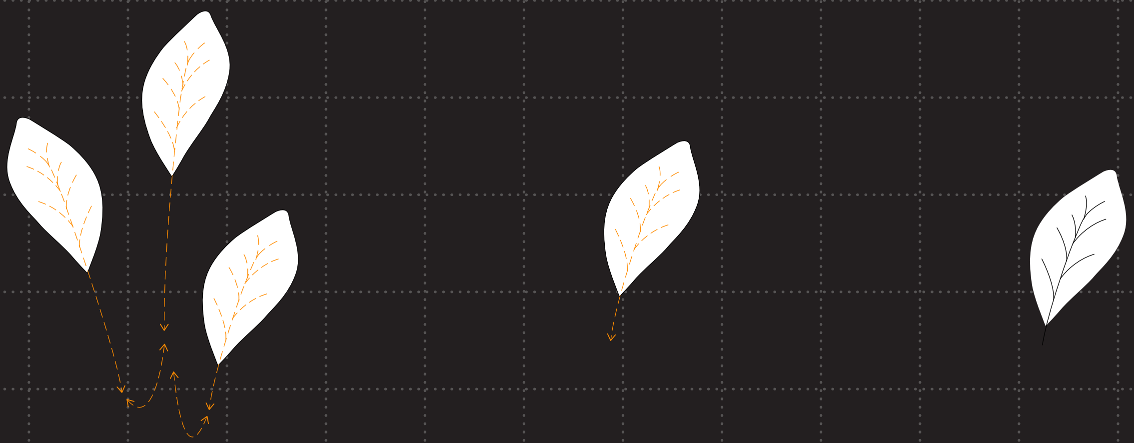
Modularity System



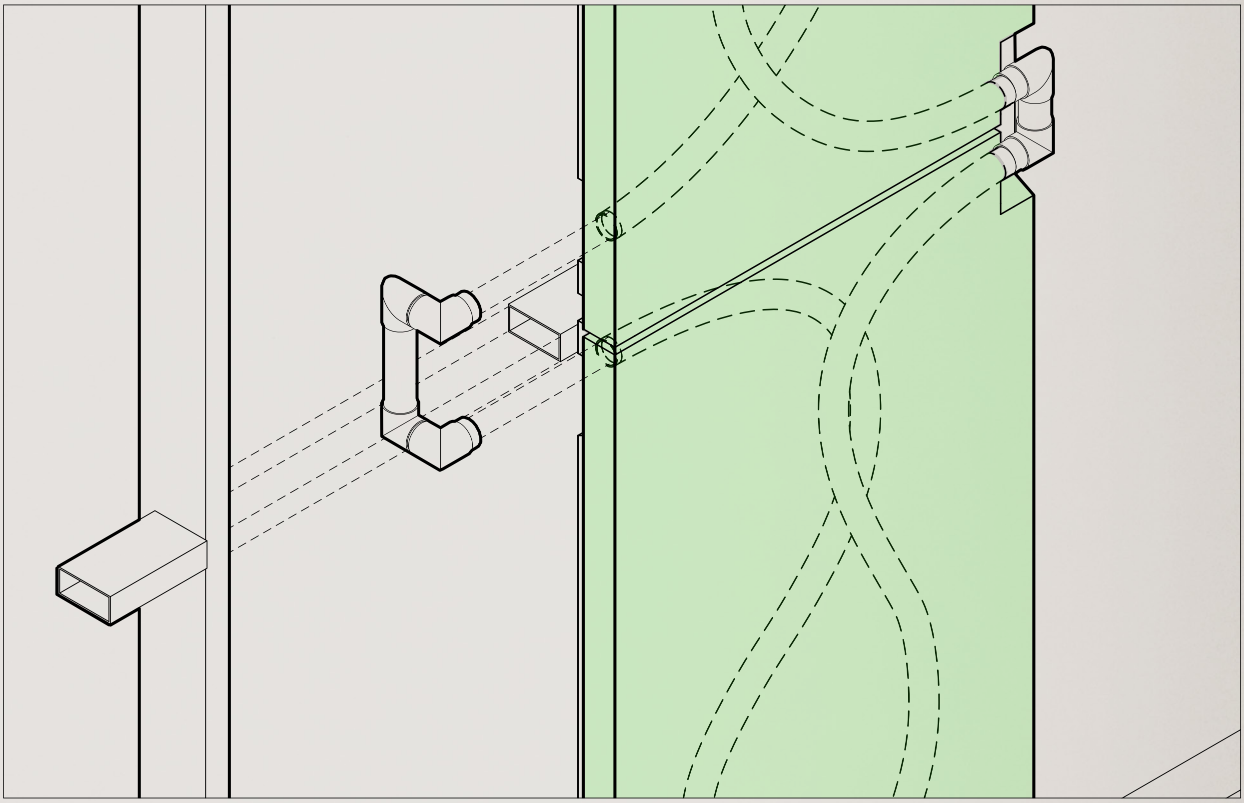
Population



Natural Circulation



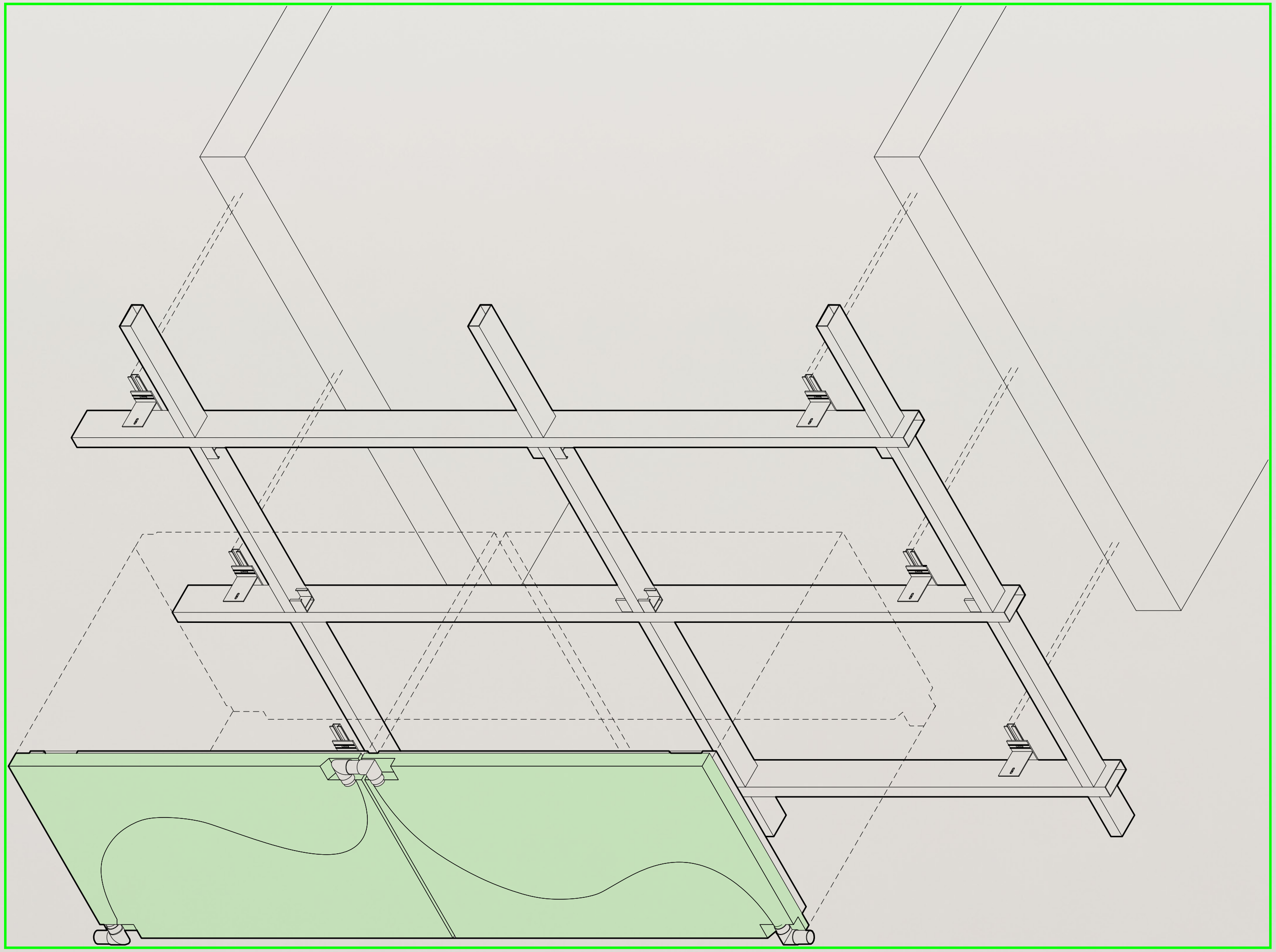
Axonometry of the exploded detail



Here are showned:
-connection between the single panel and the secondary structure
-connection between two panels and circulation

TECHNICAL DETAIL

CONNECTION BETWEEN SECONDARY STRUCTURE, BUILD-ING AND PANLES

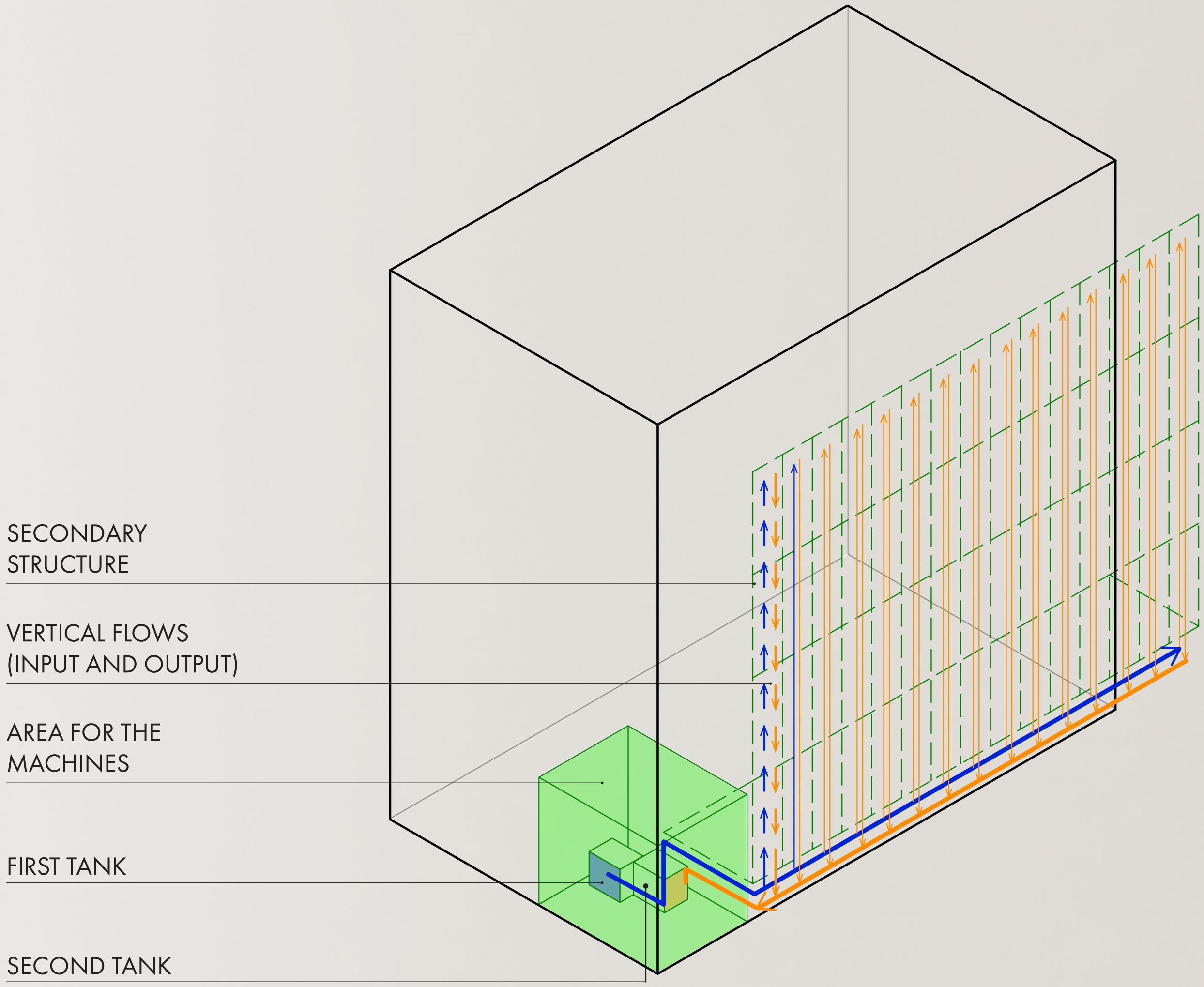


3.6 CIRCULATION: HOW PANELS,SECONDARY STRUCTURE AND FILTERS WORK TOGETHER

The system that have been studied for this double skin facade revolves around the use of single modules, that can be combined in order to meet individual needs or requirements (both aesthetically and functionally).
These modules have been purposefully created to guarantee the continuous flow of the fluid containing the algae throughout the entire system.
When designing such system, it was necessary to define the direction of the two primary flows.
In order to ensure that the fluid would be able to flow freely through a tube system, unaffected by the placement of the modules, it was decided to create a micro circulation that operated vertically by connecting all of the panels.
Additionally, the main circulation operates horizontally because the tubes carrying the harvested fluid containing the algae and the oxygenated solution were placed at the system's base to serve each vertical micro circulation.
The tank sources, which must be located somewhere on the ground level of the former building, are directly connected to the horizontal loop. This is one of the biggest obstacles to applying the described system to the current circumstances, but if overcome, it can guarantee the proper operation of the macro circulation.
In reality, the storage section will house the two main tanks, one of which will hold the purified harvested solution and the other of which will collect the fluid at the end of the photosynthetic cycle and be able to drain it as needed to extract the bio-mass, the main component of the bio reactor.

→ fluid containing the solution of harvested algae and nutrients.
It is going to be brought, thanks to the action of the water pump, horizontally under each column of panels, and then vertically along the pattern designed by the placement of the modules

→ fluid that has been oxygenated during the process, and is flooding down vertically taking advantage of the gravity forces. Horizontally this flow will be colleted by a tube and brought to a special tank where it will be filtered


SECONDARY STRUCTURE
VERTICAL FLOWS (INPUT AND OUTPUT)
AREA FOR THE MACHINES
FIRST TANK
SECOND TANK

VI 2 CONCLUSION

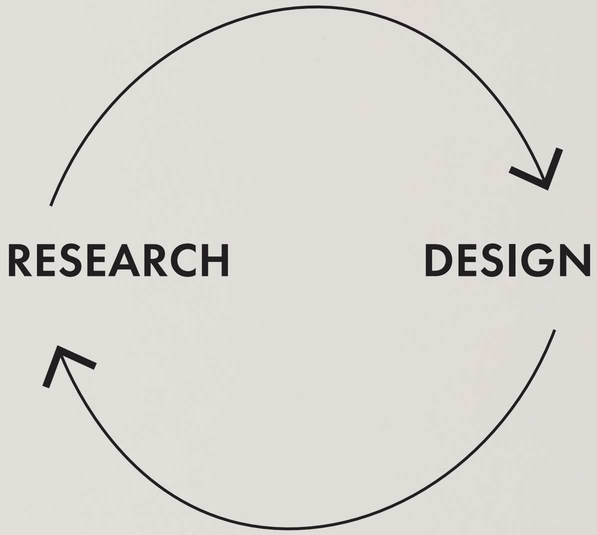
1. Comparisons
2. Output
3. Future Steps

The chapter focuses on a comprehensive and detailed comparison, providing a result for the entire book. The chapter is divided into three distinct sections: comparing, analysing the results and looking to the future. The report provides an in-depth examination of the issue and guides the reader through the key findings and implications.

1.SUMMARY

In this final section of the book, a brief summary of the entire research journey will be presented, along with some considerations that can be made now that the process is completed and some thoughts for the following steps. It is reasonable to claim that the study process took place over a period of 12 months, which, given the difficulty of the topic, can be viewed as either a short or long time. In actuality, these months were required to acquire a foundational understanding of sustainable design, material-based technologies, and responsive architecture..
Since architecture, like every other area, has been trying to discover new paths in terms of materials and tactics to tackle the challenges of the modern society lifestyle in recent decades, we did come across an infinite variety of options by researching these themes. Among all of these challenges there is climate change.
It was then a discovery the amount of nature-based materials that could actually be used in architecture, construction and design as active components, but that on the contrary are still used in a very traditional way. We can list between them wooden fibers, metals, bio polymers and so on.
The research was undoubtedly guided by the realisation that there was a gap between theory and practise, which helped narrow down the study's issues and questions, as was also demonstrated in earlier chapters.
Since the goal was to develop a system that was entirely functional from the micro to the macro scale, it was necessary to undertake multiple trials in the laboratory and during the design process in order to answer these questions and carry out the study.
Naturally, such methods did provide their own results in both failures and discoveries, as different facets of the same experience.
As a result, new levels of knowledge have been attained, allowing the researchers to more clearly identify the challenges and opportunities associated with initiatives of this nature and, in a sense, establish new benchmarks for future studies.
The approach that has been used and adopted, as noted numerous times in previous sections, can be referred to as a circular framework. In this framework, design and research are not meant to be two self-defined and independent phases

but rather constantly interact and affect one another. This methodology relies on a continuous exchange of data between the two domains, including information gathered through empirical experiences like tests, surveys, laboratory trials, and in-depth field research.
It follows logically that this research's focus and direction had to be modified as often as necessary in accordance with its initial premises and any consequences that emerged along the road.



2.SWOT ANALYSIS

S

- Suistainable architecture
- Responsive architecture
- Flexibility

  Due to its composition and structure the system is meant to adapt itself to different scenarios

- 3D printed

  Since the final shape of a single panel is determined by the architect itself, it can be customised based on specific need and requests, coming from users or environment settings.

  In addition it should be mentioned the absence of on-site assempling procedures, which is money effective

- Production of bio mass, which can be turned into bio fuel. This impact significantly the energy efficency of the building itself
- Production of Oxygen, as a natural product of the Photosynthetic process, which can be immited in the outdoor air
- Embodied system

  This enables to remove external connection, in order to meet an aesthetic requirement, and to combine design and technology

W

- Responsive architecture

  The panel components that have been developed are directly responsive towards the imputs of the surrounding environment.

  For this reason whenever a new project starts there is the need of former analysis of he weather and the location, in order to achieve a decent level of energy efficency of the facade system

- The current available knowledge in this field is still very fragmented and not always available, which could lead to designs that are not able to function as planned or not at their full potential.
- The current design proposal has been calculated for a five stores building, but if applied on residential complex with an extended height, it will require a more massive secondary structure, and, to follow, an adjustement of all the other equipments involved, such as the water pump

O

- Choice of material

  The typology of alage chosen could be actually be based on the class of climate the site belongs to.

- Free design

  The panels that are 3D printed could actually be customised for the single case

T

- Climate Change

  This challenge has been the starting point of the full research, since it can be named as one of the main challenges of the modern society.

  On the other hand the system that has been studied and developed is directly based on the predictable reaction of natural components to certain climate circustamnces. If such circustamnces change, due to the global climate crisis, also the systems might not function as calculated

- The procedure of extraction of the bio mass and their conversion into bio fuel, still requires the usage of devices that often can not be host in the same building the facade system is operating.

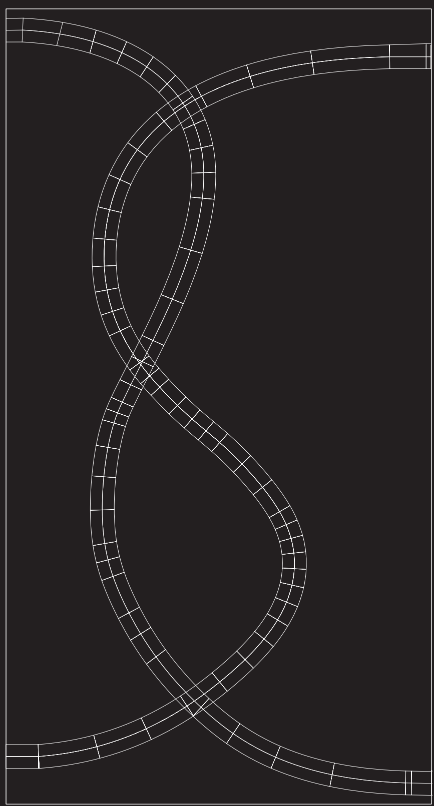
3.FUTURE STEPS

Following a comprehensive and in-depth review, as well as a rigorous SWOT analysis, a wealth of invaluable knowledge has been gained that will not only inform but also shape the future development of the ALGAE FAÇADE system. After a year dedicated to the meticulous study of this pioneering concept, which ingeniously combines the worlds of architecture and material science, it is undeniable that there is a vast landscape of opportunities for further exploration and innovation.

The SWOT analysis serves as an indispensable framework through which we can meticulously identify and scrutinise areas within the system that need improvement. It is not only a tool for highlighting the current weaknesses of the system, but it also has the transformative power to turn these flaws into windows of opportunity. This strategic perspective allows us to address the project's deficiencies in a methodical and efficient way, thereby contributing to its gradual refinement in a more practical and results-oriented manner.

In exploring this complex area, the quest for knowledge and human curiosity will remain the driving force behind our research and development. Therefore, the recommendations and approaches we are considering today are important. However, they will evolve significantly in the coming years. The urgency and significance of the challenge of climate change have given our project added urgency and importance, as a small but powerful contribution to the collective effort to address this immense crisis.

Looking to the future, with the introduction of new technologies, new materials and increased environmental awareness, the impact of these developments will inevitably extend beyond the original scope of the ALGAE FAÇADE system. By remaining versatile and responsive in the face of change, and consistently positioning ourselves as innovators, our primary goal is to significantly increase our contribution to effectively addressing the pressing climate-related issues facing humanity today.



VI

3

RESOURCES

The chapter "Fabrication" explores the practical aspects of the research project, detailing rigorous laboratory tests to validate and refine concepts. It examines parameters, such as algae harvesting techniques and fluid circulation patterns, ensuring seamless integration with the proposed architectural system. The chapter establishes the feasibility and practicality of the proposed solutions through thorough testing and refinement.

1.Biblography

- Lee, J. W., et al. (2021). Biofuel production by microalgae: Challenges, technologies, and opportunities. Bioresource Technology, *337, 125418. doi:10.1016/j.biortech.2021.125418*
- Baier, M. C., et al. (2018). Algae bioreactor design and engineering for biofuel production. Sustainable Energy Technologies and Assessments, *29, 94-104. doi:10.1016/j.seta.2018.09.009*
- Du, Y., et al. (2019). Thermosensitive hydrogels as scaffolds for tissue engineering. Frontiers in Chemistry, *7, 789. doi:10.3389/fchem.2019.0078*9
- Khosravi-Darani, K., et al. (2021). Advances in thermoresponsive hydrogels for drug delivery applications. International Journal of Biological Macromolecules, 1*92, 1254-1273. doi:10.1016/j.ijbiomac.2021.06.169*
- Sarrafzadeh, M. H., et al. (2017). A comprehensive review on photobioreactor design for microalgae and cyanobacteria. Renewable and Sustainable Energy Reviews, 73, *68-79. doi:10.1016/j.rser.2017.01.168*
- González-García, Y., et al. (2020). Strategies to increase the productivity and efficiency of microalgae photobioreactors: An overview. Energies, *13(20), 5324. doi:10.3390/en13205324*
- Chisti, Y. (2007). Biodiesel from microalgae. Biotechnology advances, *25(3), 294-306. doi:10.1016/j.biotechadv.2007.02.001*
- Mata, T. M., Martins, A. A., & Caetano, N. S. (2010). Microalgae for biodiesel production and other applications: A review. Renewable and Sustainable Energy Reviews*, 14(1), 217-232. doi:10.1016/j.rser.2009.07.020*
- Brennan, L., & Owende, P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. Renewable and Sustainable Energy Reviews, *14(2), 557-577. doi:10.1016/j.rser.2009.10.009*
- Safi, C., Ursu, A. V., Laroche, C., & Zebib, B. (2014). Biomass, lipid production and pigments content of a marine microalgae collected from Algerian coastline. International Journal of Agronomy and Plant Production*, 5(13), 1463-1476.*

- Chua, E. T., Zaini, N. M., Das, P., & Chisti, Y. (2011). Recent developments in photobioreactors for large-scale algal cultivation. Journal of Chemical Technology & Biotechnology, *86(6), 761-769. doi:10.1002/jctb.2594*
- Pacheco-Torgal, F., Ivanov, V., & Karakosta, C. (Eds.). (2019). Bioreactors in Building Facades: State-of-the-Art and Emerging Research. Springer.
- Zaini, N. M., Lim, C. J., & Ossen, D. R. (2019). Bioreactor Facade System: A Review of Facade Integration with Biological Elements. Frontiers of Architectural Research, *8(3), 369-382*.
- Liu, Y., Zhang, X., & Yang, Y. (2020). Performance Evaluation of Vertical Greenery Systems as Passive Environmental Control for Buildings. Building and Environment, *168, 106531*.
- Matzarakis, A., & Mayer, H. (1996). Another Kind of Environmental Stress: Thermal Stress. WHO Regional Publications, European Series, *No. 78*.
- Kellert, S. R., Heerwagen, J. H., & Mador, M. L. (Eds.). (2008). Biophilic Design: The Theory, Science and Practice of Bringing Buildings to Life. Wiley.
- Orians, G. H. (1986). An Ecological and Evolutionary Approach to Landscape Aesthetics. In The Perception of Nature: Essays on the Aesthetics of Nature (pp. 107-129). Springer.
- Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., & Georgakis, C. (2011). On the Impact of Urban Climate on the Energy Consumption of Buildings. Solar Energy, *85(7), 1179-1193*.
- Lam, C. K., & Chan, A. P. (2017). Integration of Vertical Greenery Systems (VGS) into Buildings for Urban Sustainability: A Review on Development, Challenges, and Opportunities. Renewable and Sustainable Energy Reviews, *67, 683-695*.
- Sayce, S., & Sundberg, P. (Eds.). (2018). Green Building Handbook: A Companion Guide to Building Products and Their Impact on the Environment. Routledge.
- Eichholtz, P., Kok, N., & Quigley, J. M. (2010). Doing Well by Doing Good? Green Office Buildings. American Economic Review, *100(5), 2492-2509.*

- Journal of Surveying, Construction and Property (JSCP Volume5, Issue 1 2014 ISSN: 1985-752
- Smith & Brown, Healthy Buildings: Integrating Sustainability and Well-being, 2018
- Green et al., Biodiversity Conservation in Sustainable Architecture, 2021
- Picon, A. (2017). Ornament: The Politics of Architecture and Subjectivity.
- Armstrong, R. (2010). Living Architecture: How Synthetic Biology Can Remake Our Cities and Reshape Our Lives. TED Books.
- Van den Heuvel, D., & Jong, A. (Eds.). (2013). IBA Hamburg: Projects + Concepts. Jovis Verlag.
- Picon, A. (2010). Digital Culture in Architecture. Birkhäuser.
- Hensel, M., Menges, A., & Weinstock, M. (2010). Emergent Technologies and Design
- Arons, D. Properties and Applications of Double-Skin Building Facades. Master's Thesis, Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA, USA, 2000. [Google Scholar]
- Bestfacade. WP 5 Report Best Practice Guidelines. Best Practice for Double Skin Facades; Intelligent Energy Europe: Brussels, Belgium, 2007. [Google Scholar]
- Crespo, A.M. History of the Double Skin Façades. n.d. Available online: http://envelopes.cdi.harvard.edu/envelopes/content/resources/PDF/doubleskins.pdf (accessed on 15 February 2019).
- Boake, T.; Harrison, K.; Chatham, A. The Tectonics of the Double Skin: Green Building or Just More Hi-Tech Hi-Jinx? University of Waterloo: Waterloo, ON, Canada, 2001. [Google Scholar]
- Straube, J. A Critical Review of the Use of Double Façades for Office Buildings in Cool Humid Climates. J. Build. Enclos. Des. 2007, 48–53. [Google Scholar]
- Penić, M.; Vatin, N.; Murgul, V. Double skin facades in energy efficient design. In Applied Mechanics and Materials; Trans Tech Publications Ltd.: Zurich, Switzerland, 2014; Volume 680, pp. 534–538. [Google Scholar]
- Lang, W.; Herzog, T. Using Multiple Glass Skins to Clad Buildings. Architectural Record. 2000. Available online: http://archrecord.construction.com/features/green/archives/0007edit-1.asp (accessed on 20 June 2015).

- Uuttu, S. Study of Currnet Structures in Double-skin Facades. Master's Thesis, Department of Civil and Environmental Engineering, Helsinki University of Technology, Helsinki, Finland, 2001. [Google Scholar]
- Saelen, D. Energy Performance Assessments of Single Storey Multiple-Skin Facades. Ph.D. Thesis, Laboratory for Building Physics, Department of Civil Engineering, Catholic University of Leuven, Brussels, Belgium, 2002. [Google Scholar]
- Selkowitz, S. Energy efficiency perspectives: Intelligent networks and the challenge of zero energy buildings. In Proceedings of the Presentation to Connected Urban Development Global Conf., Amsterdam, The Netherlands, 10 April 2008. [Google Scholar]
- Saelens, D.; Roels, S.; Hens, H. Strategies to improve the energy performance of multiple-skin facades. Build. Environ. 2008, 43, 638–650. [Google Scholar] [CrossRef]
- Pollard, B.; Beatty, M. Double skin façades more is less? In Proceedings of the ISES-AP—3rd International Solar Energy Society Conference—Asia Pacific Region, Sydney, Australia, 25–28 November 2008. [Google Scholar]
- Danesh, M.; Escamilla, E.; Pariafsai, F.; Ostadalimakhmalbaf, M. Characteristics of Glazing Layers of Double-Skin Facades and Energy Consumption: A Case Study in Arid Climate of Tehran. In AEI 2019: Integrated Building Solutions—The National Agenda; American Society of Civil Engineers: Reston, VA, USA, 2019; pp. 204–215. [Google Scholar]
- Gratia, E.; De Herde, A. Guidelines for improving natural daytime ventilation in an office building with a double-skin facade. Sol. Energy 2007, 81, 435–448. [Google Scholar] [CrossRef]
- Moon, K.S. Structural Design of Double Skin Facades as Damping Devices for Tall Buildings. In Proceedings of the Twelfth East Asia-Pacific Conference on Structural Engineering and Construction, Hong Kong, China, 26–28 January 2011; pp. 1351–1358. [Google Scholar]
- Siebert, B. Double Skin Facades Made of Glass—Aspects of Structural Design and Static Analysis. In Structures and Archetecture: Concepts, Applications and Challenges; Cruz, P.J.S., Ed.; Taylor & Francis

Group: London, UK, 2013; pp. 289–298. [Google Scholar]
- Vaglio, J.; Patterson, M.; Hooper, S. Emerging Applications and Trends of Double-skin Facades. In Proceedings of the International Conference on Building Envelope Systems and Technologies, ICBEST, Vancouver, BC, Canada, 27–30 June 2010. [Google Scholar]
- New Barbosa, S.; Ip, K. Perspectives of double skin façades for naturally ventilated buildings: A review. Renew. Sustain. Energy Rev. 2014, 40, 1019–1029. [Google Scholar] [CrossRef]
- New Kalyanova, O. Double-Skin Facade: Modelling and Experimental Investigations of Thermal Performance; Department of Civil Engineering, Aalborg University: Aalborg, Denmark, 2008. [Google Scholar]
- New Høseggen, R.; Wachenfeldt, B.; Hanssen, S. Building simulation as an assisting tool in decision making: Case study: With or without a double-skin façade? Energy Build. 2008, 40, 821–827. [Google Scholar] [CrossRef]
- New Ghaffarianhoseini, A.; Ghaffarianhoseini, A.; Berardi, U.; Tookey, J.; Li, D.H.W.; Kariminia, S. Exploring the advantages and challenges of double-skin façades (DSFs). Renew. Sustain. Energy Rev. 2016, 60, 1052–1065. [Google Scholar] [CrossRef]
- Diprose, P.R.; Robertson, G. Towards A Fourth Skin? Sustainability and Double-Envelope Buildings; Department of Architecture, University of Auchland: Auckland, New Zealand, 1996. [Google Scholar]
- DOE. Buildings Energy Data Book. Energy Efficiency and Renewable Energy Dept. 2011. Available online: http://buildingsdatabook.eren.doe.gov/docs/DataBooks/2010_BEDB.pdf (accessed on 27 December 2016).
- Crawley, D.B.; Hand, J.W.; Kummert, M.; Griffith, B.T. Contrasting the capabilities of building energy performance simulation programs. Build. Environ. 2008, 43, 661–673. [Google Scholar] [CrossRef]
- Berardi, U. A cross-country comparison of the building energy consumptions and their trends. Resour. Conserv. Recycl. 2017, 123, 230–241. [Google Scholar] [CrossRef]
- Charalambides, J.; Wright, J. Effect of early solar energy gain according to building size, building

openings, aspect ratio, solar azimuth, and latitude. J. Archit. Eng. 2013, 19, 209–216. [Google Scholar] [CrossRef]

- Oesterle, E.; Oesterle, R.-D.; Lutz, L.M.; Heusler, W. Double Skin Facades—Integrated Planning; Prestel Verlag: Munich, Germany, 2001. [Google Scholar]
- Silvestre, J.D.; de Brito, J.; Pinheiro, M.D. Building's external walls in life-cycle assessment (LCA) research studies. In Proceedings of the of SB 10–Sustainable Building Affordable to All; iiSBE–Portugal: Vilamoura, Portugal, 2010; pp. 629–638. [Google Scholar]
- Saleem, M.; Chhipi-Shrestha, G.; Túlio Barbosa Andrade, M.; Dyck, R.; Ruparathna, R.; Hewage, K.; Sadiq, R. Life cycle thinking–based selection of building facades. J. Archit. Eng. 2018, 24, 4018029. [Google Scholar] [CrossRef]
- Incropera, F.P. Introduction to Heat Transfer; John Wiley and Sons: New York, NY, USA, 2011. [Google Scholar]
- Ihm, P.; Krarti, M.; Nemri, A. Estimation of lighting energy savings from daylighting. Build. Environ. 2009, 44, 509–514. [Google Scholar] [CrossRef]
- Shehabi, A.; DeForest, N.; McNeil, A.; Masanet, E.; Greenblatt, J.; Lee, E.S.; Masson, G.; Helms, B.A.; Milliron, D.J. U.S. energy savings potential from dynamic daylighting control glazings. Environ. Energy Build. 2013, 66, 415–423. [Google Scholar] [CrossRef]
- Johnson, R.; Selkowitz, S.; Sullivan, R. How Fenestration Can Significantly Affect Energy Use in Commercial Buildings. In Proceedings of the 11th Energy Technology Conference, Washington, DC, USA, 19–21 March 1984. [Google Scholar]
- Jafari, A.; Valentin, V. An Investment Allocation Approach for Building Energy Retrofits; ConstructionResearch Congress (CRC): San Juan, Puerto Rico, 2016; p. 107. [Google Scholar] [CrossRef]
- Aksamija, A.; Peters, T. Heat transfer in facade systems and energy use: Comparative study of different exterior wall types. J. Archit. Eng. 2017, 23, C5016002. [Google Scholar] [CrossRef]

- Fuliotto, R.; Cambuli, F.; Mandas, N.; Bacchin, N.; Manara, G.; Chen, Q. Experimental and numerical analysis of heat transfer and airflow on an interactive building facade. Energy Build. 2010, 42, 23–28. [Google Scholar] [CrossRef]
- Taborianski, V.M.; Prado, R.T. Methodology of CO2 emission evaluation in the life cycle of office building façades. Environ. Impact Assess. Rev. 2012, 33, 41–47. [Google Scholar] [CrossRef]
- Moghtadernejad, S.; Mirza, M.S.; Chouinard, L.E. Facade design stages: Issues and considerations. J. Archit. Eng. 2019, 25, 4018033. [Google Scholar] [CrossRef]
- Pickering, C.; Byrne, J. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. High. Educ. Res. Dev. 2014, 33, 534–548. [Google Scholar] [CrossRef]
- Boell, S.; Cezec-Kecmanovic, D. Are systematic reviews better, less biased and of higher quality? In Proceedings of the ECIS 2011 Proceedings, Helsinki, Finland, 9–11 June 2011; p. 223. [Google Scholar]
- Gelesz, A.; Reith, A. Classification and re-evaluation of double-skin facades. Int. Rev. Appl. Sci. Eng. 2011, 2, 129–136. [Google Scholar] [CrossRef]
- Doebber, I.; McClintock, M. Analysis process for designing double skin facades and associated case study. In Proceedings of the Second National IBPSA-USA Conference, San Francisco, CA, USA, 2–4 August 2006; pp. 160–167. [Google Scholar]
- Knaack, U.; Klein, T.; Bilow, M.; Auer, T. Façades: Principles of Construction; Birkhäuser: Boston, MA, USA, 2014. [Google Scholar]
- Compagno, A. Intelligent Glass Facades; Birkhauser: Boston, MA, USA, 1999. [Google Scholar]
- Loncour, X.; Deneyer, A.; Blasco, M.; Flamant, G.; Wouters, P. Ventilated Double Facade: Classification and Illustration of Facade Concepts; Belgian Building Research Institute: Saint-Gilles, Belgium, 2004. [Google Scholar]
- Patterson, M.; Matusova, J. High-performance facades. Insight 2013, 3, 134–149. [Google Scholar]

- Boake, T.M.; Harrison, K.; Collins, D.; Balbaa, T.; Chatham, A.; Lee, R.; Bohren, A. The Tectonics of the Double Skin: Green Building or Just More Hi-Tech Hi-Jink?—What Are Double Skin Façades and How Do They Work? University of Waterloo: Waterloo, ON, Canada, 2008; Available online: http://www.architecture.uwaterloo.ca/faculty_projects/terri/ds/tectonic.pdf (accessed on 4 July 2013).
- Kallioniemi, J. Joint and Fastenings in Steel-Glass Facades. Master's Thesis, Department of Civil and Environmental Engineering, Helsinki University of Technology, Helsinki, Finland, 1999. [Google Scholar]
- Ariosto, T.; Memari, A.M.; Solnosky, R. A Comparative Energy Efficiency Study Of Different Glazing Systems In Residential And Commercial Building Applications. Int. J. Archit. Eng. Constr. 2019, 8, 1–18. [Google Scholar] [CrossRef]
- Schittich, C. Glass Construction Manual; Birkhauser Architecture: Boston, MA, USA, 2007. [Google Scholar]
- Oldfield, P.; Trabucco, D.; Wood, A. Five Generations of Tall Buildings: An Historical Analysis of Energy Consumption in High Rise Buildings. J. Archit. 2009, 14, 591–613. [Google Scholar] [CrossRef]
- Minor, J.E. Focus on Glass. APT Bull. J. Preserv. Technol. 2001, 32, 47–50. [Google Scholar] [CrossRef]
- Goupil, J.; Kestner, D.M.; Lorenz, E. Sustainability Guidelines for the Structural Engineer; ASCE Press: Reston, VA, USA, 2010. [Google Scholar]
- Jayasinghe, C. Embodied energy of alternative building materials and their impact on life cycle cost parameters. ICSECM 2011, 201, 1–20. [Google Scholar]
- Haynes, R. Embodied Energy Calculations within Life Cycle Analysis of Residential Buildings. 2010. Available online: http://etool.net.au/wp-content/uploads/2012/10/Embodied-Energy-Paper-Richard-Haynes.pdf (accessed on 25 July 2018).
- Ghoshal, S.; Neogi, S. Advance Glazing System—Energy Efficiency Approach for Buildings a Review. Energy Procedia 2014, 54, 352–358. [Google Scholar] [CrossRef]

- Ariosto, T.; Memari, A.; Solnosky, R. A comparative thermal properties evaluation for residential window retrofit solutions for U.S. markets. Adv. Build. Energy Res. 2018, 15, 87–116. [Google Scholar] [CrossRef]
- Binions, R.; Ridley, I.; Warwick, M.E.A. The effect of transition gradient in thermochromic glazing systems. Energy Build. 2014, 77, 80–90. [Google Scholar]
- Issa, R.R.A.; Olbina, S.; Raheem, A.A. Environmental Performance and Economic Analysis of Different Glazing–Sunshade Systems Using Simulation Tools. J. Comput. Civ. Eng. 2016, 30, C5016001. [Google Scholar] [CrossRef]
- Hernández, J.A.; Sierra, P. Solar heat gain coefficient of water flow glazings. Energy Build. 2017, 139, 133–145. [Google Scholar]
- IEA (International Energy Agency). Technology Roadmap Energy Efficient Building Envelopes. 2013. Available online: http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyEfficientBuildingEnvelopes.pdf (accessed on 25 December 2013).
- Papaefthimiou, S. Chromogenic technologies: Towards the realization of smart electrochromic glazing for energy-saving applications in buildings. Adv. Build. Energy Res. 2010, 4, 77–126. [Google Scholar] [CrossRef]
- Piccolo, A.; Marino, C.; Nucara, C.; Pietrafesa, M. Energy performance of an electrochromic switchable glazing: Experimental and computational assessments. Energy Build. 2018, 165, 390–398. [Google Scholar] [CrossRef]
- Granqvist, C.G. Electrochromic tungsten oxide films: Review of progress 1993–1998. Sol. Energy Mater. Sol. Cells 2000, 60, 201–262. [Google Scholar] [CrossRef]
- Lee, E.S.; Gehbauer, C.; Coffey, B.E.; McNeil, A.; Stadler, M.; Marnay, C. Integrated control of dynamic facades and distributed energy resources for energy cost minimization in commercial buildings. Sol. Energy 2015, 122, 1384–1397. [Google Scholar] [CrossRef]
- Pierucci, A.; Cannavale, A.; Martellotta, F.; Fiorito, F. Smart windows for carbon neutral buildings: A life

cycle approach. Energy Build. 2018, 165, 160–171. [Google Scholar] [CrossRef]

- Zhang, W.; Lu, L.; Peng, J.; Song, A. Comparison of the overall energy performance of semi-transparent photovoltaic windows and common energy-efficient windows in Hong Kong. Energy Build. 2016, 128, 511–518. [Google Scholar] [CrossRef]
- Cuce, E.; Cuce, P.M.; Wood, C.J.; Riffat, S.B. Toward aerogel based thermal superinsulation in buildings: A comprehensive review. Renew. Sustain. Energy Rev. 2014, 34, 273–299. [Google Scholar] [CrossRef]
- Berardi, U. The development of a monolithic aerogel glazed window for an energy retrofitting project. Appl. Energy 2015, 154, 603–615. [Google Scholar] [CrossRef]
- Martinez, R.G.; Goiti, E.; Reichenauer, G.; Zhao, S.; Koebel, M.; Barrio, A. Thermal assessment of ambient pressure dried silica aerogel composite boards at laboratory and field scale. Energy Build. 2016, 128, 111–118. [Google Scholar] [CrossRef]
- Blanc, S.L.; Hakkarainen, P.; Lee, E.S.; Levi, M.S.; McClintock, M.; McConahey, E.; Myser, M.P.; Sbar, N.L.; Selkowitz, S.E. Active load management with advanced window wall systems: Research and industry perspectives. In ACEEE 2002 Summer Study on Energy Efficiency in Buildings: Teaming for Efficiency; American Council for an Energy-Efficient Economy: Washington, DC, USA, 2002. [Google Scholar]
- Weggel, D.C.; Zapata, B.J. Laminated glass curtain walls and laminated glass lites subjected to low-level blast loading. J. Struct. Eng. 2008, 134, 466–477. [Google Scholar] [CrossRef]
- Tenhunen, O.; Lintula, K.; Lehtinen, T.; Lehtovaara, J.; Viljanen, M.; Kesti, J.; Mäkeläinen, P. Double Skin Facades-Structures and Building Physics. In Proceedings of the 9th Nordic Steel Construction Conference, Helsinki, Finland, 18–20 June 2001; pp. 141–148. [Google Scholar]
- Shirazi, A. Development of a Seismic Vulnerability Evaluation Procedure for Architectural Glass Curtain Walls; The Pennsylvania State University: University Park, PA, USA, 2005. [Google Scholar]
- Memari, A.M.; Hartman, K.H.; Kremer, P.A. Racking Test Evaluation of EN-WALL 7250 Unitized Curtain

- Curtain Wall System with 3M™ VHB™ Structural Glazing Tape; Report Submitted to 3M Industrial Adhesives & Tapes Division; Penn State University: St. Paul, MN, USA, 2011; p. 72. [Google Scholar]
- Memari, A.M. (Ed.) Curtain Wall Systems—A Primer, Consisting of 12 Chapters; American Society of Civil Engineers (ASCE): Reston, VA, USA, 2013. [Google Scholar]
- Dow Corning. Silicone Structural Glazing Manual; Form Number 62-0979H-01; Dow Corning Europe: Brussels, Belgium, 2011. [Google Scholar]
- Jain, A. Hurricane Wind-Generated Debris Impact Damage to the Glazing of a High-Rise Building. In Proceedings of the Seventh Congress on Forensic Engineering, Miami, FL, USA, 15–18 November 2015; pp. 361–370. [Google Scholar]
- Adhikary, S.D. Review of Glazing and Glazing Systems under Blast Loading. Pract. Period. Struct. Des. Constr. 2015, 21, 4015009. [Google Scholar] [CrossRef]
- Fu, T.S.; Zhang, R. Integrating double-skin façades and mass dampers for structural safety and energy efficiency. J. Archit. Eng. 2016, 22, 4016014. [Google Scholar] [CrossRef]
- Githerlet, S.; Gay, J.B.; Guglielmo, F. Window and advanced glazing systems life cycle assessment. Energy Build. 2000, 32, 225–234. [Google Scholar] [CrossRef]
- Wiener, M. Unitized Double Skin Façade Assemblies: Achieving the Needs of Future Envelope Systems through Construction and Performance Advances; University of Southern California: Los Angeles, CA, USA, 2012. [Google Scholar]
- Eli, U.S.C.; Center, E.B.; Square, F.; Center, S.J. Double-Skin Facades in the United States. Available online: https://enclos.com/wp-content/uploads/2020/08/Insight01-Chapter03-Emerging_Applications_and_Trends_of_Double-Skin_Facades.pdf (accessed on 8 September 2019).
- Schmid, F.; Cseh, X.; Rohrer, E.; Teich, M. Double-Skin Façades: Boundary Conditions, Challenging Examples and Developments. CE/Papers 2018, 2, 103–112. [Google Scholar] [CrossRef]
- Brown, B. An Introduction to the Design and Application of Double Skin Facades in North American High-Rise Architecture. Ph.D. Thesis, Institute of Technology, Cork Irland, Ireland, 2016. [Google

Scholar]
- Eslamirad, N.S.; Sanei, A. Double Skin Facades in Use, a Study of Configuration and Performance of Double Skin Façade, Case Studies Some Office Buildings. In Proceedings of the 2nd International Conference on Research in Science and Technology, Istanbul, Turkey, 14 March 2016. [Google Scholar]
- Poirazis, H. Double Skin Façades for Office Buildings–Literature Review; Report EDB-R—04/3; Department of Construction and Architecture, Lund University of Technology: Lund, Sweden, 2004. [Google Scholar]
- Gratia, E.; De Herde, A. The most efficient position of shading devices in a double-skin facade. Energy Build. 2007, 39, 364–373. [Google Scholar] [CrossRef]
- Stec, W.; Van Paassen, A.; Maziarz, A. Modelling the double skin façade with plants. Energy Build. 2005, 37, 419–427. [Google Scholar] [CrossRef]
- Chan, Y.C.; Protzman, B.; Tzempelikos, A. Solar optical properties of roller shades: Modeling approaches, measured results and impact on energy use and visual comfort. In Proceedings of the 3rd International High Performance Buildings Conference, West Lafayette, IN, USA, 14–17 July 2014; Purdue University: West Lafayette, IN, USA, 2014. [Google Scholar]
- Choi, W.; Joe, J.; Kwak, Y.; Huh, J.O. Operation and control strategies for multi-storey double skin facades during the heating season. Energy Build. 2012, 49, 454–465. [Google Scholar] [CrossRef]
- Manz, H.; Frank, T. Thermal simulation of buildings with double-skin façades. Energy Build. 2005, 37, 1114–1121. [Google Scholar] [CrossRef]
- Ding, W.; Hasemi, Y.L.; Yamada, T. Natural ventilation performance of a double-skin façade with a solar chimney. Energy Build. 2005, 37, 411–418. [Google Scholar] [CrossRef]
- Moghtadernejad, S.; Chouinard, L.E.; Mirza, M.S. Design strategies using multi-criteria decision-making tools to enhance the performance of building façades. J. Build. Eng. 2020, 30, 101274. [Google Scholar] [CrossRef]

- Guardo, A.; Coussirat, M.; Valero, C.; Egusquiza, E.; Alavedra, P. CFD assessment of the performance of lateral ventilation in Double Glazed Façades in Mediterranean climates. Energy Build. 2011, 43, 2359–2547. [Google Scholar] [CrossRef]
- Yellamraju, V. Evaluation and Design of Double-Skin Façades for Office Buildings in Hot Climates. Master's Thesis, College of Architecture, Texas A&M University, College Station, TX, USA, 2004. [Google Scholar]
- Silva, F.M.; Gomes, M.G. Gap inner pressures in multi-storey double skin facades. Energy Build. 2008, 40, 1553–1559. [Google Scholar] [CrossRef]
- Ock, J.; Issa, R.R.A.; Olbina, S. Climate Responsive Automatic Operation Strategies for Double Skin Façade (DSF) System of High-Rise Buildings. In Computing in Civil and Building Engineering; ASCE: Reston, VA, USA, 2014; pp. 917–924. Available online: https://itc.scix.net/pdfs/w78-2014-paper-114.pdf (accessed on 7 August 2022).
- Cole, R.J.; Kernan, P.C. Life-cycle energy use in office buildings. Build. Environ. 1996, 31, 307–317. [Google Scholar] [CrossRef]
- Lee, E.; Selkowitz, S.; Bazjanac, V.; Inkarojrit, V.; Kohler, C. High-Performance Commercial Building Façades; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2002. [Google Scholar]
- Barkkume, A. Innovative Building Skins: Double Glass Wall Ventilated Façade; New Jersey School of Architecture: Newark, NJ, USA, 2007. [Google Scholar]
- Mohotti, D.; Lunmantara, R.; Ngo, T.; Mendis, P. Improving the safety of buildings through an innovative sustainable façade system. In Proceedings of the International Conference on Sustainable Built Environment (ICSBE), Kandy, Sri Lanka, 13–14 December 2010; University of Moratuwa: Kandy, Sri Lanka, 2010. [Google Scholar]
- Hens, H.; Saelens, D.; Meulenaer, V.D.; Elsen, P. Multiple-skin facades: High tech blessing or not? In Proceedings of the 8th Symposium on Building Physics in the Nordic Countries, Copenhagen, Denmark, 16–18 June 2008; pp. 1–8. [Google Scholar]

- Colantonio, A.; Quirouette, R. Verification of dynamic buffer zone (DBZ) wall assembly performance using infrared thermography. In Thermosense XXIV; International Society for Optics and Photonics: San Diego, CA, USA, 2002; Volume 4710, pp. 288–298. [Google Scholar]
- Chow, W.; Hung, W.; Gao, Y.; Zou, G.; Dong, H. Experimental study on smoke movement leading to glass damages in double-skinned façade. Constr. Build. Mater. 2007, 21, 556–566. [Google Scholar] [CrossRef]
- Moghtadernejad, S.; Mirza, S. Service life safety and reliability of building facades. In Vulnerability, Uncertainty, and Risk: Quantification, Mitigation, and Management; ASCE: Reston, VA, USA, 2014; pp. 116–124. [Google Scholar]
- Popovic, P.L.; Arnold, R.C. Preventing failures of precast concrete facade panels and their connections. In Proceedings of the 2nd Forensic Engineering Congress, San Juan, Puerto Rico, 21–23 May 2000; ASCE: Reston, VA, USA, 2000; pp. 532–539. [Google Scholar]
- Hay, R.; Ostertag, C.P. Innovative Double Skin Façade (DSF) with High Performance Green Hybrid Fiber-Reinforced Concrete (HP-G-HyFRC) for Resilient and Sustainable Buildings. In Proceedings of the AEI 2015, Milwaukee, WI, USA, 24–27 March 2015; pp. 120–133. [Google Scholar]
- Ding, C.; Ngo, T.; Mendis, P.; Lumantarna, R.; Zobec, M. Dynamic response of double skin façades under blast loads. Eng. Struct. 2016, 123, 155–165. [Google Scholar] [CrossRef]
- Kim, D.; Park, C. Difficulties and limitations in performance simulation of a double skin façade with EnergyPlus. Energy Build. 2011, 43, 3635–3645. [Google Scholar] [CrossRef]
- Hensen, J.; Bartak, M.; Drkal, F. Modelin and simulation of a double skin facade system. ASHRAE Trans. 2002, 108, 1251–1259. [Google Scholar]
- Pasut, W.; De Carli, M. Evaluation of various CFD modelling strategies in predicting airflow and temperature in a naturally ventilated double skin façade. Appl. Therm. Eng. 2012, 37, 267–274. [Google Scholar] [CrossRef]
- Safer, N.; Woloszyn, M.; Roux, J.J. Three-dimensional simulation with a CFD tool of the airflow

- Equa Simulation AB. User Manual, IDA Indoor Climate and Energy, Version 4.5. 2014. Available online: http://www.equaonline.com/iceuser/pdf/ICE45eng.pdf (accessed on 20 August 2021).
- TRNSYS User Manual; Version 16; University of Wisconsin: Madison, WI, USA, 2004.
- El-Sadi, H.; Haghighat, F.; Fallahi, A. CFD analysis of turbulent natural ventilation in double-skin façade: Thermal mass and energy efficiency. J. Energy Eng. 2010, 136, 68–75. [Google Scholar] [CrossRef]
- Walton, G.N.; Dols, W.S. CONTAM User Guide and Program Documentation; US Department of Commerce, Technology Administration, National Institute of Standards and Technology: Gaithersburg, MD, USA, 2013. [Google Scholar]
- Weber, A.; Koschenz, M.; Holst, S.; Hiller, M.; Welfonder, T. TRNFLOW: Integration of COMIS into TRNSYS TYPE 56; University of Wisconsin Madison: Madison, WI, USA, 2002. [Google Scholar]
- Pipitone, G.; Barone, G.; Palmeri, A. Optimal design of double-skin façades as vibration absorbers. Struct. Control. Health Monit. 2018, 25, e2086. [Google Scholar] [CrossRef][Green Version]
- Fu, T.S. Double skin façades as mass dampers. In Proceedings of the 2013 American Control Conference, Washington, DC, USA, 17–19 June 2013; IEEE: Washington, DC, USA, 2013; pp. 4742–4746. [Google Scholar]
- Azad, A.; Ngo, T.; Samali, B. Control of wind-induced motion of tall buildings using smart façade systems. Electron. J. Struct. Eng. 2015, 14, 33–40. [Google Scholar] [CrossRef]
- Samali, B.; Attard, M.M.; Song, C. (Eds.) From Materials to Structures: Advancement through Innovation; CRC Press: Boca Raton, FL, USA, 2013; pp. 431–435. [Google Scholar]
- Carpenter, L.D. Influences on structural engineering. Struct. Des. Tall Spec. Build. 2005, 14, 419–425. [Google Scholar] [CrossRef]
- Solnosky, R.L. Analytical, Communication, and Information Technology Directions in the Structural Industry. Pract. Period. Struct. Des. Constr. 2016, 21, 4015002. [Google Scholar] [CrossRef]
- Solnosky, R.L. Integrated structural processes on innovative multidisciplinary projects supported by building information modeling. J. Archit. Eng. 2017, 23, 5016004. [Google Scholar] [CrossRef]

- Ding, C.; Ngo, T.; Ghazlan, A.; Lumantarna, R.; Mendis, P. Numerical simulation of structural responses to a far-field explosion. Aust. J. Struct. Eng. 2015, 16, 226–236. [Google Scholar] [CrossRef]
- Ngo, T.; Ding, C.; Lumantarna, R.; Ghazlan, A.; Zobec, M. Structural performance of double-skin façade systems subjected to blast pressures. J. Struct. Eng. 2015, 141, 4015064. [Google Scholar] [CrossRef]
- Hu, G.; Hassanli, S.; Kwok, K.C.; Tse, K.T. Wind-induced responses of a tall building with a double-skin façade system. J. Wind. Eng. Ind. Aerodyn. 2017, 168, 91–100. [Google Scholar] [CrossRef]
- Finnveden, G.; Hauschild, M.Z.; Ekvall, T.; Guinée, J.; Heijungs, R.; Hellweg, S.; Koehler, A.; Pennington, D.S. Suh Recent developments in life cycle assessment. J. Environ. Manag. 2009, 91, 1–21. [Google Scholar] [CrossRef] [PubMed]
- Pomponi, F.; D'Amico, B.; Moncaster, A.M. A method to facilitate uncertainty analysis in LCAs of buildings. Energies 2017, 10, 524. [Google Scholar] [CrossRef]
- Ortiz, O.; Castells, F.; Sonnemann, G. Sustainability in the construction industry: A review of recent developments based on LCA. Constr. Build. Mater. 2009, 23, 28–39. [Google Scholar] [CrossRef]
- Jones, C.; Hammond, G. Inventory of Carbon & Energy (ICE) Version 2.0. In Sustainable Energy Research Team (SERT); SERT, Ed.; University of Bath: Bath, UK, 2011. [Google Scholar]
- SimaPro. SimaPro Database Manual Methods Library. Available online: https://simapro.com/wp-content/uploads/2022/07/DatabaseManualMethods.pdf (accessed on 12 September 2022).
- GreenConcrete LCA. GreenConcrete LCA Web Tool. Available online: http://greenconcrete.berkeley.edu (accessed on 1 September 2022).
- Sphera. GaBi Sphera US LCI Database. Available online: https://gabi.sphera.com/america/databases/us-lci-database/ (accessed on 4 September 2022).
- In Proceedings of the Ninth International PLEA Conference, Seville, Spain, 24–27 September 1991; pp. 257–262. [Google Scholar]

- A.E. Fennera, C.J. Kiberta, J.W. ooa, S. Morquea, M. Razkenaria, H. Hakima, X. Lub, The carbon footprint of buildings: a review of methodologies and applications, Renew. Sustain. Energy Rev. 94 (2018) 1142–1152, https://doi. org/10.1016/j.rser.2018.07.012.
- A. Martínez-Rocamora, J. Solís-Guzm an, M. Marrero, Toward the Ecological Footprint of the use and maintenance phase of buildings: utility consumption and cleaning tasks, Ecol. Indicat. 69 (2016) 66–77, https://doi.org/10.1016/j. ecolind.2016.04.007.
- M. Ho€ok, € X. Tang, Depletion of fossil fuels and anthropogenic climate change—a review, Energy Policy 52 (2013) 797–809, https://doi.org/10.1016/j. enpol.2012.10.046.
- J. Pruvost, B.L. Gouic, J. Legrand, Symbiotic integration of photobioreactors in a factory building façade for mutual benefit between Buildings and Microalgae Needs, 21st International Congress of Chemical and Process Engineering CHISA 2014 Prague 17th Conference on Process Integration, Modelling and Optimisation for Energy Saving and Pollution Reduction PRES 2014, (Praha, Czech Republik).
- G.M. Elrayies, Microalgae: prospects for greener future buildings, Renew. Sustain. Energy Rev. 81 (2018) 1175–1191, https://doi.org/10.1016/j.rser.2017.08.032.
- R.E. Lee, Phycology, first ed., Cambridge University Press, New York, 1980.
- M.R. Edwards, Green Algae Strategy: End Oil Imports and Engineer Sustainable Food and Fuel, Create Space, Tempe, Arizona, 2008.
- R.B. Draaisma, M.J. Barbosa, P.M. Slegers, L.B. Brentner, A. Roy, R.H. Wijffels, Food commodities from microalgae, Curr. Opin. Biotechnol. 24 (2013) 169–177, https://doi.org/10.1016/j. copbio.2012.09.012. [9] M.R. Brown, S.W. Jeffrey, J.K. Volkman, G.A. Dunstan, Nutritional properties of microalgae for mariculture, Aquaculture 151 (2013) 315–331, https://doi.org/ 10.1016/S0044-8486(96)01501-3.
- A.R. Rao, C. Dayananda, R. Sarada, T.R. Shamala, G.A. Ravishankar, Effect of salinity on growth of green alga Botryococcus braunii and its constituents, Bioresour Technol 2007 98 (2007) 560–564,

https://doi.org/10.1016/j. biortech.2006.02.007.

- F. Bumbak, S. Cook, V. Zachleder, S. Hauser, K. Kovar, Best practices in heterotrophic high-cell-density microalgal processes: achievements, potential and possible limitations, Appl. Microbiol. Biotechnol. 91 (2011) 31–46, https://doi. org/10.1007/s00253-011-3311-6. [12] M.A. Borowitzka, Limit to growth, in: Y.S. Wong, N.F.Y. Tam (Eds.), Wastewater Treatment with an Algae, Springer., Berlin, 1998, pp. 203–218.
- S.S¸ . Oncel, € A. Kose, € D.S¸ . Oncel, € Façade integrated photobioreactors for building energy efficiency, in: F. Pacheco-Torgal, E.S. Rasmussen, C.G. Granqvist, V. Ivanov, H.A. Kaklauskas (Eds.), Start-Up Creation. The Smart Eco-Efficient Built Environment, Woodhead Publishing Inc., Amsterdam, 2016, pp. 237–299.
- A. Richmond, Principles for attaining maximal microalgal productivity in photobioreactors: an overview, Hydrobiologia 512 (1-3) (2004) 33–37.
- J. Pruvost, B. Le Gouic, O. Lepine, J. Legrand, F. Le Borgne, Microalgae culture in building-integrated photobioreactors: biomass production modeling and energetic analysis, Chem. Eng. J. 284 (2016) 850–861, https://doi.org/10.1016/ j.cej.2015.08.118.
- S. Hindersin, M. Leupold, M. Kerner, D. Hanelt, Irradiance optimization of outdoor microalgal cultures using solar tracked photobioreactors, Bioproc. Biosyst. Eng. 36 (2013) 345–355, https://doi. org/10.1007/s00449-012-0790-5.
- J.U. Grobbelaar, Factors governing algal growth in photobioreactors: the "open" versus "closed" debate, J. Appl. Phycol. 21 (2008) 489–492, https://doi.org/ 10.1007/s10811-008-9365-x.
- S. Hindersin, M. Leupold, M. Kerner, D. Hanelt, Key parameters for outdoor biomass production of Scenedesmus obliquus in solar tracked photobioreactors, J. Appl. Phycol. 26 (2014) 2315–2325. [19] S. Hindersin, in: U. Hamburg (Ed.), Photosynthetic Efficiency of Microalgae and Optimization of Biomass Production in Photobioreactors, 2013.
- V. Goetz, F. Le Borgne, J. Pruvost, G. Plantard, J. Legrand, A generic temperature model for solar

photobioreactors, Chem. Eng. J. 175 (2011) 443–449, https://doi. org/10.1016/j.cej.2011.09.052.

- A.M. Kunjapur, R.B. Eldigre, Photobioreactor design for commercial biofuel production from microalgae, Ind. Eng. Chem. Res. 49 (2010) 3516–3526, https:// doi.org/10.1021/ie901459u.
- I.S. Suh, C.G. Lee, Photobioreactor engineering: design and performance, Biotechnol. Bioproc. Eng. 8 (2003) 313–321, https://doi.org/10.1007/ BF02949274. A. Burns, Photobioreactore Design for Improved Energy Efficiency of Microalgae Production, Master Thesis, California Polytechnic State University, San Luis Obispo, 2014
- H.C.P. Matthijs, H. Balke, U.M. VanHes, B.M.A. Kroon, L.R. Mur, R.A. Binot, Application of light-emitting diodes in bioreactors: flashing light effects and energy economy in algal culture (Chlorella pyrenoidosa), Biotechnol. Bioeng. 50 (1996), https://doi.org/10.1002/(SICI)1097-0290(19960405)50:13.0.CO;2-3, 98–10.
- M. Janssen, J.R. Tramper, L.H. Mur, R. Wijffels, Enclosed outdoor photobioreactors: light regime, Photosynthetic efficiency, Scale-Up, and future prospects, Biotechnol. Bioeng. 81 (2003) 193–210, https://doi.org/10.1002/ bit.10468.
- Y. Chisti, Biodiesel from microalgae, Biotechnol. Adv. 25 (2007) 294–306, https://doi.org/10.1016/j.biotechadv.2007.02.001.
- J. Wurm, Photobioreactors on facades for energy generation, alternative technologies in the building envelope, in: Int. Rosenheim Window and Facade Conference, 2013, pp. 83–87.
- J. Masojidek, M. Sergejevova, K. Rottnerova, V. Jirka, J. Kore cko, J. Kopecky, I. Za tkovaG, TorzilloD. Stys, A two-stage solar photobioreactor for cultivation of microalgae based on solar concentrators, J. Appl. Phycol. 21 (2009) 55–63, https://doi.org/10.1007/s10811-008-9324-6.
- M. Marani, This algae facade curtain naturally filters polluted air. https://arch paper.com/2018/12/this-algae-facade-curtain-naturally-filters-pollutedair/#gallery-0-slide-0, 2018 accessed 25 December 2018.
- A.G. Jacquin, S. Brul e-Josso, M.L. Cornish, A.T. Critchley, P. Gardet, Selected comments on the role

of algae in sustainability, Adv. Bot. Res. 71 (2014) 1–30, https://doi.org/10.1016/B978-0-12-408062-1.00001-9.

- S. Phipps, Slime render. Construction Research and Innovation, 12-13, https:// doi.org/10.1080/20450249.2013.11873879, 2013, 4.
- N.S. Genin, J.S. Aitchison, D.G. Allen, Photobioreactor-based energy sources, in: F. Pacheco-Torgal, C. Buratti, S. Kalaiselvam, C.G. Granqvist, V. Ivanov (Eds.), Nano and Biotech-Based Materials for Energy Building Efficiency, Springer, Switzerland, 2016, pp. 429–456.
- H. Wolkers, M. Barbosa, D.M. Kleinegris, R. Bosma, R.H. Wijffels (Eds.), Microalgae: the Green Gold of the Future, Large-Scale Sustainable Cultivation of Microalgae for the Production of Bulk Commodities, The Ministry of Economic Affairs AaI, Netherlands, 2011.
- E.S. Umdu, I. Kahraman, N. Yildirim, L. Bilir, Optimization of microalgae panel bioreactor thermal transmission property for building facade applications, Energy. Build. 175 (2018) 113–120, https://doi.org/10.1016/j. enbuild.2018.07.027.
- J. Chen, J. Li, W. Dong, X. Zhang, R.D. Tyagi, P. Drogui, R.Y. Surampallic, The potential of microalgae in biodiesel production, Renew. Sustain. Energy Rev. 90 (2018) 336–346, https://doi.org/10.1016/j.rser.2018.03.073.
- W. Klinthong, Y.-H. Yang, C.-H. Huang, C.-S. Tan, A review: microalgae and their applications in CO2 capture and renewable energy, Aerosol Air Qual Res 15 (2015) 712–742.
- K.-H. Kim, A feasibility study of an algae façade system, in: Proceedings of International Conference on Sustainable Building Asia (SB13), July 2013, pp. 8–10. Seoul, South Korea.
- BuildUp, The BIQ House: first algae-powered building in the world. http://www. buildup.eu/en/practices/cases/biq-house-first-algaepowered-building-world, 2015 accessed 15 November 2018.
- H. Lakenbrink, Smart Mater. House. BQI., in: International Building Exhibition, 2013, p. 1e22. Hamburg, https://www.iba-hamburg.de/fileadmin/Mediath ek/Whitepaper/130716_White_Paper_BIQ_en.pdf.

- J.K. Pittman, A.P. Dean, O. Osundeko, The potential of sustainable algal biofuel production using waste water resources, Bioresour. Technol. 102 (2011) 17–25, https://doi.org/10.1016/j.biortech.2010.06.035. M. Talaei et al. Journal of Building Engineering 28 (2020) 101011 13
- Y. Wang, S.H. Ho, C.L. Cheng, W.Q. Guo, J.S. Chang, Perspectives on the feasibility of using microalgae for industrial wastewater treatment, Bioresour. Technol. 222 (2016) 485–497, https://doi.org/10.1016/j.biortech.2016.09.106.
- A.F. Clarens, E.P. Resurreccion, M.A. White, L.M. Colosi, Environmental life cycle comparison of algae to other bioenergy feedstocks, Environ. Sci. Technol. 44 (2010) 1813–1819, https://doi.org/10.1021/es902838n.
- L. Reijnders, Lipid-based liquid biofuels from autotrophic microalgae: energetic and environmental performance, WIREs. Energy Environ. 2 (2012) 73–85, https://doi.org/10.1002/9781118957844.ch3.
- L. Zhu, Z. Li, E. Hiltunen, Theoretical assessment of biomethane production from algal residues after biodiesel production, WIREs. Energy Environ. 7 (2018) e273, https://doi.org/10.1002/wene.273.
- R.C. Sard a, C.A. Vicente, Case studies on the architectural integration of photobioreactors in building Façades, in: P.F. Torgal, C. Buratti, S. Kalaiselvam, C.G. Granqvist, V. Ivanov (Eds.), Nano and Biotech Based Materials for Energy Building Efficiency, Springer, Switzerland, 2016, pp. 457–484.
- G.C. Dismukes, D. Carrieri, N. Bennette, G.M. Ananyev, M.C. Posewitz, Aquatic phototrophs: efficient alternatives to land-based crops for biofuels, Curr. Opin. Biotechnol. 19 (2008) 235–240, https://doi.org/10.1016/j.copbio.2008.05.007.
- L.E.K. Advanced, Biofuels Study: Strategic Directions for Australia. Appendix, vol.2011, 2011. [48] S. Naik, V.V. Goud, P.K. Rout, A.K. Dalai, Production of first and second generation biofuels: a comprehensive review, Renew. Sustain. Energy Rev. 14 (2010) 578–597, https://doi.org/10.1016/j.rser.2009.10.003.
- N. Buzalo, P. Ermachenko, A. Bulgakov, N. Zakharchenko, Mathematical modeling of energy balance

in the photobiological treatment plants, Procedia Eng 123 (2015) 117–124, https://doi.org/10.1016/j.proeng.2015.10.067.

- A. Elnokaly, I. Keeling, An empirical study investigating the impact of microalgal technologies and their application within intelligent building fabrics, Procedia Soc Behav Sci 216 (2016) 712–723, https://doi.org/10.1016/j. sbspro.2015.12.067.
- M. Casini, Energy-generating glazing, in: Smart Buildings, Advanced Materials and Nanotechnology to Improve Energy-Efficiency and Environmental Performance, first ed., Woodhead Publishing, 2016, pp. 327–353.
- J. Al Dakheel, K.T. Aoul, Building applications, opportunities and challenges of active shading systems: a state-of-the-art review, Energies 10 (2017), e1672, https://doi.org/10.3390/en10101672.
- A.M. Posthuma, Microalgae Biofuel Production, Master's Thesis, Utrecht University, The Netherlands, 2009.
- ANSI/ASHRAE Standard 55-2013, Thermal Environmental Conditions for Human Occupancy.
- J.R. Howell, R.O. Buckius, Fundamentals of Engineering Thermodynamics, McGraw-Hill, New York, 1987.
- J.T. Kim, M.S. Todorovic, Tuning control of buildings glazing's transmittance dependence on the solar radiation wavelength to optimize daylighting and building's energy efficiency, Energy Build. 63 (2013) 108–118, https://doi.org/ 10.1016/j.enbuild.2013.03.036.
- M. Decker, G. Hahn, L.M. Harris, Bio-enabled façade systems-managing complexity of life through emergent technologies, in: Proceedings of the 34th eCAADe Conference on Complexity & Simplicity, Oulu, Finland: University of Oulu, 2016.
- E. Flynn, Experimenting with living architecture: a practice perspective, Architect. Res. Q 20 (2016) 20–28, https://doi.org/10.1017/ S1359135516000166.
- F. Dutt, S. Jige Quana, E. Woodworth, D. Castro-Lacouture, B.J. Stuart, P.P. J. Yanga, Modeling algae powered neighborhood through GIS and BIM integration, Energy Procedia 105 (2017) 3830–3836,

https://doi.org/10.1016/j. egypro.2017.03.896.

- L. Xu, P.J. Weathers, X.R. Xiong, C.Z. Liu, Microalgal bioreactors: challenges and opportunities, Eng. Life Sci. 9 (2009) 178–189, https://doi.org/10.1002/ elsc.200800111.
- J.C.M. Pires, M.C.M. Alvim-Ferraz, F.G. Martins, Photobioreactor design for microalgae production through computational fluid dynamics: a review, Renew. Sustain. Energy Rev. 79 (2017) 248–254, https://doi.org/10.1016/j. rser.2017.05.064.
- J. Wolf, E. Stephens, S. Steinbusch, J. Yarnold, I.L. Ross, C. Steinweg, C. Steinweg, A. Doebbe, C. Krolovitsch, S. Müller, G. Jakob, O. Kruse, C. Posten, B. Hankamer, Multifactorial comparison of photobioreactor geometries in parallel microalgae cultivations, Algal Res 15 (2016) 187–201, https://doi.org/10.1016/j. algal.2016.02.018.
- P.M. Slegers, R.H. Wijffels, G. van Straten, A.J.B. van Boxte, Design scenarios for flat panel photobioreactors, Appl En 88 (2011) 3342–3353, https://doi.org/ 10.1016/j.apenergy.2010.12.037.
- N.O. Santos, S.M. Oliveira, L.C. Alves, M.C. Cammarota, Methane production from marine microalgae Isochrysis galbana, Bioresour. Technol. 157 (2014) 60–67, https://doi.org/10.1016/j. biortech.2014.01.091.
- M. Solana, C.S. Rizza, A. Bertucco, Exploiting microalgae as a source of essential fatty acids by supercritical fluid extraction of lipids: comparison between Scenedesmus obliquus, Chlorella protothecoides and Nannochloropsis salina, J. Supercrit. Fluids 92 (2014) 311–318, https://doi.org/10.1016/j. supflu.2014.06.013.
- F. Saladini, N. Patrizi, F.M. Pulselli, N. Marchettini, S. Bastianoni, Guidelines for emergy evaluation of first, second and third generation biofuels, Renew. Sustain. Energy Rev. 66 (2016) 221–227, https://doi.org/10.1016/j.rser.2016.07.073.
- L. Brennan, P. Owende, Biofuels from microalgae—a review of technologies for production, processing, and extractions of biofuels and co-products, Renew. Sustain. Energy Rev. 14 (2010) 557–577, https://doi.org/10.1016/j. rser.2009.10.009.

- V.G. Dovì, F. Friedler, D. Huisingh, J. Klemes, Cleaner energy for sustainable future, J. Clean. Prod. 17 (2009) 889–895, https://doi.org/10.1016/j. jclepro.2009.02.001.
- K.K. Sharma, H. Schuhmann, P.M. Schenk, High lipid induction in microalgae for biodiesel production, Energies 5 (2012) 1532–1553, https://doi.org/10.3390/ en5051532.
- H.G. Wang, F.S. Li, E.X. Zu, S. Dai, D. Chen, X.H. Zhang, W. Du, Experimental study on the quantitative relationship between oxidation stability and composition of biodiesel, J. Biobased Mater. Bioenergy 1 (2017) 216–222, https://doi.org/10.1166/jbmb.2017.1656
- X. Li, D. He, S. Lu, F. Shu, A new mixture topological index a in the related research of biomass blended fuels, J. Biobased Mater. Bioenergy 11 (2017) 230–235, https://doi.org/10.1166/jbmb.2017.1658. [72] Y. Ren, A. Harvey, R. Zakaria, Biorefining based on biodiesel production: chemical and physical characterisation of reactively extracted rapeseed, J. Biobased Mater. Bioenergy 4 (2010) 79–86, https://doi.org/10.1166/ jbmb.2010.1069.
- R.L. Coppo, J.L. Pereira, H.C. Da Silva, K.G. Angilelli, P.R.P. Rodrigues, D. Galvan, D. Borsato, Effect of natural antioxidants on oxidative stability of biodiesel from soybean oil. Applying simplex-centroid design, J. Biobased Mater. Bioenergy 8 (2014) 545–551, https://doi.org/10.1166/jbmb.2014.1468.
- G. Kim, G. Mujtaba, K. Lee, Effects of nitrogen sources on cell growth and biochemical composition of marine chlorophyte Tetraselmis sp. for lipid production, ALGAE 31 (2016) 257–266, https://doi.org/10.4490/ algae.2016.31.8.18.
- T.M. Mata, A.A. Martins, N.S. Caetano, Microalgae for biodiesel production and other applications: a review, Renew. Sustain. Energy Rev. 14 (2010) 217–232, https://doi.org/10.1016/j.rser.2009.07.020.
- I. Rawat, R. Ranjith Kumar, T. Mutanda, F. Bux, Biodiesel from microalgae: a critical evaluation from laboratory to large scale production, Appl. Energy 103 (2013) 444–467, https://doi.org/10.1016/j.apenergy.2012.10.004.
- A.L. Ahmad, N.H.M. Yasin, C.J.C. Derek, J.K. Lim, Microalgae as a sustainable energy source for biodiesel production: a review, Renew. Sustain. Energy Rev. 15 (2011) 584–593, https://doi.

org/10.1016/j.rser.2010.09.018.

- J.W. Moody, C.M. McGinty, J.C. Quinn, Global evaluation of biofuel potential from microalgae, Proc. Natl. Acad. Sci. 111 (2014) 8691–8696, https://doi.org/ 10.1073/pnas.1321652111.
- G. Sibi, V. Shetty, K. Mokashi, Enhanced lipid productivity approaches in microalgae as an alternate for fossil fuels – a review, J. Energy Inst. 89 (2016) 330–334, https://doi.org/10.1016/j.joei.2015.03.008.
- S. Venkata Mohan, M.V. Rohit, P. Chiranjeevi, R. Chandra, B. Navaneeth, Heterotrophic microalgae cultivation to synergize biodiesel production with waste remediation: progress and perspectives, Bioresour. Technol. 184 (2015) 169–178, https://doi.org/10.1016/j.biortech.2014.10.056.
- M.K. Lam, K.T. Lee, Microalgae biofuels: a critical review of issues, problems and the way forward, Biotechnol. Adv. 30 (2012) 673–690, https://doi.org/10.1016/ j.biotechadv.2011.11.008.
- N. Rashid, M.S. Ur Rehman, M. Sadiq, T. Mahmood, J-I Han, Current status, issues and developments in microalgae derived biodiesel production, Renew. Sustain. Energy Rev. 40 (2014) 760–778, https://doi.org/10.1016/j.rser.2014.07.104
- M. Talaei, M. Mahdavinejad, Probable cause of damage to the panel of microalgae bioreactor building façade: hypothetical evaluation, Eng. Fail. Anal. 101 (2019) 9–21.
- A. Richmond, Biological principles for mass cultivation, in: A. Richmond (Ed.), Microalgae Culture, Black well science Ltd., Oxford, 2004, 177-25.
- T.M. Araji, I. Shah, Symbiosis optimization of building envelopes and micro-algae photobioreactors, J. Build Eng. 18 (2018) 58–65, https://doi.org/10.1016/j. jobe.2018.02.008.
- K. Skjånes, U. Andersen, T. Heidorn, S.A. Borgvang, Design and construction of a photobioreactor for hydrogen production, including status in the field, J. Appl. Phycol. 28 (2016) 2205–2223, https://doi.org/10.1007/s10811-016-0789-4.
- M. Marsullo, A. Mian, A.V. Ensinas, G. Manente, A. Lazzaretto, F. Marechal, Dynamic modeling of the microalgae cultivation phase for energy production in open raceway ponds and flat panel

photobioreactors, Front Energy Res 3 (2015) 18, https://doi.org/10.3389/fenrg.2015.00041.

- R. Singh, S. Sharma, Development of suitable photobioreactor for algae production– a review, Renew. Sustain. Energy Rev. 16 (2012) 2347–2353, https://doi.org/10.1016/j.rser.2012.01.026.
- S.L. Pagliolico, V.R.L. Verso, F. Bosco, C. Mollea, C. La Forgia, A novel photobioreactor application for microalgae production as a shading system in buildings, Energy Procedia 111 (2017) 151–160, https://doi.org/10.1016/j. rser.2015.07.090.
- J. Wurm, Algae-powered architecture, INGENIA 64 (2015) 31–32. [91] J. Wurm, Developing bio-responsive façades: BIQ house — the first pilot project, Arup J (2013) 90–95.
- Y. Jia, G. Alva, G. Fan, Development and applications of photovoltaic–thermal systems: a review, Renew. Sustain. Energy Rev. 102 (2019) 249–265.
- P. Spolaore, C. Joannis-Cassan, E. Duran, A. Isambert, Commercial applications of microalgae, J. Biosci. Bioeng. 101 (2006) 87–96, https://doi.org/10.1263/ jbb.101.87.
- G. Vox, I. Blanco, E. Schettini, Green façades to control wall surface temperature in buildings, Build. Environ. 129 (2018) 154–166, https://doi.org/10.1016/j. buildenv.2017.12.002. M. Talaei et al. Journal of Building Engineering 28 (2020) 101011 14
- G. P erez, J. Coma, I. Martorell, L.F. Cabeza, Vertical Greenery Systems (VGS) for energy saving in buildings: a review, Renew. Sustain. Energy Rev. 39 (2014) 139–165, https://doi.org/10.1016/j. rser.2014.07.055.
- G. P erez, L. Rincon, A. Vila, J.M. Gonz alez, L.F. Cabeza, Green vertical systems for buildings as passive systems for energy savings, Appl. Energy 88 (2011) 4854–4859, https://doi.org/10.1016/j. apenergy.2011.06.032.
- A.M. Hunter, N.S.G. Williams, J.P. Rayner, L. Aye, D. Hes, S.J. Livesley, Quantifying the thermal performance of green facades: a critical review, Ecol. Eng. 63 (2014) 102–113, https://doi. org/10.1016/j.ecoleng.2013.12.021.
- B. Raji, M.J. Tenpierik, A. van den Dobbelsteen, The impact of greening systems on building energy

performance: a literature review, Renew. Sustain. Energy Rev. 45 (2015) 610–623, https://doi.org/10.1016/j.rser.2015.02.011.

- M. Ottel e, K. Perini, A.L.A. Fraaij, E.M. Haas, R. Raiteri, Comparative life cycle analysis for green façades and living wall systems, Energy Build. 43 (2001) 3419–3429, https://doi.org/10.1016/j.enbuild.2011.09.010.
- F. Yang, F. Yuan, F. Qian, Z. Zhuang, J. Yao, Summertime thermal and energy performance of a double-skin green facade: a case study in Shanghai, Sustain Cities Soc 39 (2018) 43–51, https://doi.org/10.1016/j.scs.2018.01.049.
- M.M. Davis, S. Hirmer, The potential for vertical gardens as evaporative coolers: an adaptation of the 'Penman Monteith Equation', Build. Environ. 92 (2015) 135–141, https://doi.org/10.1016/j.buildenv.2015.03.033.
- D. Tilley, J. Price, S. Matt, B. Marrow, Vegetated Walls: Thermal and Growth Properties of Structured Green Facades. Final Report to Green Roofs for Healthy Cities-Green Walls Group, 2012.
- S. Barbosa, K. Ip, Perspectives of double skin façades for naturally ventilated buildings: a review, Renew. Sustain. Energy Rev. 40 (2014) 1019–1029, https:// doi.org/10.1016/j.rser.2014.07.192.
- T.E. Jiru, Y.-X. Tao, F. Haghighat, Air flow and heat transfer in double skin façades, Energy Build. 43 (2011) 2760–2766, https://doi.org/10.1016/j. enbuild.2011.06.038.
- A.L.S. Chan, T.T. Chow, K.F. Fong, Z. Lin, Investigation on energy performance of double skin façade in Hong Kong, Energy Build. 41 (2009) 1135–1142, https:// doi.org/10.1016/j.enbuild.2009.05.012.
- S. Wilkinson, P. Stoller, P. Ralph, B. Hamdorf, Feasibility of Algae Building Technology in Sydney, Technical report, University of Tehnology Sydney, 2016.
- B. Rahmani, M.Z. Kandar, P. Rahmani, How double skin Façade's air-gap sizes effect on lowering solar heat gain in tropical climate? World Appl. Sci. J. 18 (2012) 774–778, https://doi.org/10.5829/idosi.wasj.2012.18.06.3184.
- M. Torres, P. Alavedra, A. Guzm an, E. Cuerva, C. Planas, R. Clemente, V. Escalona, Double skin

facades—cavity and exterior openings dimensions for saving energy on Mediterranean climate, Proc. Build. Simul. (2007) 198–205.

- H. Radhi, S. Sharples, F. Fikiry, Will multi-façade systems reduce cooling energy in fully glazed buildings? A scoping study of UAE buildings, Energy Build. 56 (2013) 179–188, https://doi.org/10.1016/j.enbuild.2012.08.030.
- M. Haase, F. Marques da Silva, A. Amato, Simulation of ventilated facades in hot and humid climates, Energy Build. 41 (2009) 361–373, https://doi.org/10.1016/ j.enbuild.2008.11.008.
- N. Hamza, Double versus single skin facades in hot arid areas, Energy Build. 40 (2008) 240–248, https://doi.org/10.1016/j.enbuild.2007.02.025.
- E. Gratia, A. De Herde, Greenhouse effect in double-skin façade, Energy Build. 39 (2007) 199–211, https://doi.org/10.1016/j.enbuild.2006.06.004.
- W. Lou, M. Huang, M. Zhang, N. Lin, Experimental and zonal modeling for wind pressures on double-skin facades of a tall building, Energy Build. 54 (2012) 179–191, https://doi.org/10.1016/j.enbuild.2012.06.025.
- P.J. Schnurr, D.G. Allen, Factors affecting algae biofilm growth and lipid production: a review, Renew. Sustain. Energy Rev. 52 (2015) 418–429, https:// doi.org/10.1016/j.rser.2015.07.090.
- R.C. Sarda, J.G. Pioz, Architectural bio-photo reactors: harvesting microalgae on the surface of architecture, in: F. Pacheco-Torgal, J. Labrincha, M. Diamanti, C. P. Yu, H.K. Lee (Eds.), Biotechnologies and Biomimetics for Civil Engineering, Springer INc., London, 2014, pp. 163–180. [116] M. Tampier, A. Alabi, E. Bilbeau, Current Technology, Suitability and Barriers to Implementation, The Britisch Columbia Innovation Council, 2009.
- W. Stec, A. Van Paassen, A. Maziarz, Modelling the double skin façade with plants, Energy Build. 37 (2005) 419–427, https://doi.org/10.1016/j. enbuild.2004.08.008.
- W. Fanga, Z. Xiaosong, T. Junjie, L. Xiuwei, The thermal performance of double skin facade with Tillandsia usneoides plant curtain, Energy Build. 43 (2011) 2127–2133, https://doi.org/10.1016/j.

enbuild.2011.04.021. [119] J. Peng, L. Lu, H. Yang, An experimental study of the thermal performance of a novel photovoltaic double-skin façade in Hong Kong, Sol. Energy 97 (2013) 293–304, https://doi.org/10.1016/j.solener.2013.08.031.

- Y. Li, J. Darkwa, G. Kokogiannakis, Heat transfer analysis of an integrated double skin façade and phase change material blind system, Build. Environ. 125 (2017) 111–121, https://doi.org/10.1016/j.buildenv.2017.08.034.
- A. Ghaffarianhoseini, A. Ghaffarianhoseini, U. Berardi, J. Tookey, D.H. Wa Li, S. Kariminia, Exploring the advantages and challenges of double-skin façades (DSFs), Renew. Sustain. Energy Rev. 60 (2016) 1052–1065, https://doi.org/ 10.1016/j.rser.2016.01.130.
- S. Saadon, L. Gaillard, st E. Giroux-Julien, C. Menezo, Simulation study of a naturally-ventilated building integrated photovoltaic/thermal (BIPV/T) envelope, Renew. Energy 87 (2016) 517–531, https://doi.org/10.1016/j. renene.2015.10.016.
- H. Elarga, F. Goia, A. Zarrella, A. Dal Monte, E. Benini, Thermal and electrical performance of an integrated PV-PCM system in double skin façades: a numerical study, Sol. Energy 136 (2016) 112–124, https://doi.org/10.1016/j. solener.2016.06.074.
- C.Y. Cheng, K.K.S. Cheung, L.M. Chu, Thermal performance of a vegetated cladding system on facade walls, Build. Environ. 45 (2010) 1779–1787, https:// doi.org/10.1016/j.buildenv.2010.02.005.
- J. Coma, G. P erez, A. Gracia, S. Bur es, M. Urrestarazu, L.F. Cabeza, Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green facades, Build. Environ. 111 (2017) 228–237, https://doi. org/10.1016/j.buildenv.2016.11.014.
- N.R. Moheimani, The Culture of Coccolithophorid Algae for Carbon Dioxide Bioremediation, Ph.D. thesis, Murdoch University, 2005.
- G. Koktürk, € A. Ünal, A. Tokuç, A new approach for a control system of an innovative building-integrated photobioreactor author links open overlay panel, in: I. Dincer, C.O. Colpan, O. Kizilkan (Eds.), Exergetic, Energetic and Environmental Dimensions, Academic Press, 2018, pp. 71–85. [128]

O. Pulz, Photobioreactors: production systems for phototrophic microorganisms, Appl. Microbiol. Biotechnol. 57 (2001) 287–293, https://doi.org/10.1007/ s002530100702.

- C. Posten, Design principles of photo-bioreactors for cultivation of microalgae, Eng. Life Sci. 9 (2009) 165–177, https://doi.org/10.1002/elsc.200900003.
- K.K. Vasumathi, M. Premalatha, P. Subramanian, Parameters influencing the design of photobioreactor for the growth of microalgae, Renew. Sustain. Energy Rev. 16 (2012) 5443–5450, https://doi.org/10.1016/j.rser.2012.06.013.
- E. Sierra, F. Aci en, J. Fernandez, J. García, C. Gonzalez, E. Molina, Characterization of a flat plate photobioreactor for the production of microalgae, Chem. Eng. J. 138 (2008) 136–147, https://doi.org/10.1016/j.cej.2007.06.004.
- P.M. Slegers, Scenario Studies for Algae Production, Ph.D. thesis, Wageningen University, Wageningen, 2014.
- F. Qiu, Algae Architecture, Master Thesis, Delft University of Technology, Delft, 2014.
- A.P. Carvalho, L.A. Meireles, F.X. Malcata, Microalgal reactors: a review of enclosed system designs and performances, Biotechnol. Prog. 22 (2006) 1490–1506, https://doi.org/10.1021/bp060065r.
- S. Elliot, Cohousing in the Flower City: a Carbon Capture Design, Rochester Institute of Technology, Golisano Institute for Sustainability, New York, 2016.
- A. Chemodanov, A. Robin, A. Golberg, Design of marine macroalgae photobioreactor integrated into building to support seagriculture for biorefinery and bioeconomy, Bioresour. Technol. 241 (2017) 1084–1093, https://doi.org/ 10.1016/j.biortech.2017.06.061.
- J. Pruvost, J.F. Cornet, Knowledge models for engineering and optimization of photobioreactors, in: C. Posten, C. Walter (Eds.), Microalgal Biotechnology, Potential and Production, Walter de Gruyter Gmbh., Boston, 2012, pp. 181–220.
- M. Koller, A. Salerno, P. Tuffner, M. Koinigg, H. Bochzelt, € S. Schober, S. Pieber, H. Schnitzer, M. Mittelbach, G. Braunegg, Characteristics and potential of microalgal cultivation strategies: a review,

J. Clean. Prod. 37 (2013) 377–388, https://doi.org/10.1016/j.jclepro.2012.07.044.

- M. Zollmann, H. Traugott, A. Chemodanov, A. Liberzon, A. Golberg, Exergy efficiency of solar energy conversion to biomass of green macroalgae Ulva (Chlorophyta) in the photobioreactor, Energy Convers. Manag. 167 (2018) 125–133, https://doi.org/10.1016/j.enconman.2018.04.090.
- W. Martokusumo, M.D. Koerniawan, H.W. Poerbo, N.A. Ardiani, S.H. Krisanti, Algae and building façade revisited. a study of façade system for infill design, J. Archit. Urbanism 41 (2017) 296–304, https://doi.org/10.3846/ 20297955.2017.1411847.
- S. Chang, D. Castro-Lacouturea, F. Dutt, P.P.J. Yang, Framework for evaluating and optimizing algae façades using closed-loop simulation analysis integrated with BIM, Energy Procedia 143 (2017) 237–244, https://doi.org/10.1016/j. egypro.2017.12.677.

2.SITOGRAPHY

- https://www.enviroscreen.org.uk/what-is-solar-shading/
- https://en.wikiarquitectura.com/building/media-tic/
- https://www.ecologicstudio.com/projects/biobolla
- https://www.ecologicstudio.com/projects/airbubble-playground-and-exhibition
- https://www.ecologicstudio.com/projects/bi-o-serie
- https://www.internationale-bauausstellung-hamburg.de
- https://www.ecologicstudio.com/projects/expo-milano-2015-urban-algae-folly
- https://www.frontiere.polimi.it/a-modular-kit-for-growing-microalgae-at-home-and-improving-the-environment/?lang=en
- https://www.fosterandpartners.com/projects/media-tic/
- https://www.dezeen.com/2021/09/27/algae-filled-airbubble-ecologicstudio-purifies-air-design-architecture/
- https://www.archdaily.com/339451/worlds-first-algae-bioreactor-facade-nears-completion?ad_source=search&ad_medium=projects_tab&ad_source=search&ad_medium=search_result_all
- https://www.archdaily.com/801558/99-percent-invisible-discusses-how-algae-biotechnology-can-affect-the-urban-environment?ad_source=search&ad_medium=projects_tab&ad_source=search&ad_medium=search_result_all
- https://www.dezeen.com/2019/07/04/hyunseok-an-algae-the-coral-micro-farm/
- https://www.dezeen.com/2012/08/04/dezeen-archive-algae/
- https://www.dezeen.com/2009/08/18/flower-street-bioreactor-by-emergent/
- https://iopscience.iop.org/article/10.1088/1755-1315/397/1/012007/pdf
- https://www.designboom.com/architecture/algae-building-material-eco-village-concept-china-10-02-2020/
- https://carloratti.com/project/algaetecture/

- https://pubmed.ncbi.nlm.nih.gov/17814034/
- https://ancecomo.it/download/408/atti-del-seminario/13638/slides-sicurezza-antincendio-negli-interventi-di-riqualificazione-energetica-claudio-giacalone-seconda-parte.pdf
- https://www.falpsrl.it/facciate-a-doppia-pelle-come-cambia-linvolucro-temporaneo/
- https://www.architetturaecosostenibile.it/argomenti/tag/alghe
- https://www.italiandesigninstitute.com/larchitettura-vernacolare-in-danimarca/
- https://www.green.it/struttura-produzione-alghe-ikea/
- https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118493441.ch14
- https://onlinelibrary.wiley.com/doi/pdf/10.1002/9781118493441.ch14
- https://news.cornell.edu/stories/2017/09/bioreactors-chip-renew-promises-algal-biofuels
- https://pubmed.ncbi.nlm.nih.gov/22028591/
- https://www.globalccsinstitute.com/archive/hub/publications/155688/biofuels-policies-standards-technologies.pdf
- https://biotechnologyforbiofuels.biomedcentral.com/articles/10.1186/s13068-021-01977-z
- https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8583215/
- https://cordis.europa.eu/project/id/308518/reporting
- https://peer.asee.org/bioreactor-design-automation-and-optimization-a-multidisciplinary-approach.pdf
- https://www.frontiersin.org/articles/10.3389/fbioe.2021.694484/full
- https://onlinelibrary.wiley.com/doi/pdf/10.1002/elsc.200900003
- https://onlinelibrary.wiley.com/doi/pdf/10.1002/elsc.200800111
- https://www.tatup.de/index.php/tatup/article/view/718/1303
- https://scholarsjournal.net/index.php/ijier/article/view/2840
- https://academic.oup.com/ijlct/article/13/2/122/4883371

- https://www.biofueljournal.com/
- https://www.icheme.org/media/9263/xxii-paper-49.pdf
- https://smbb.mx/congresos%20smbb/acapulco09/TRABAJOS/magistrales/WAYNE_CURTIS.pdf
- https://microbiologynote.com/bioreactor/
- https://www.globalccsinstitute.com/archive/hub/publications/155688/biofuels-policies-standards-technologies.pdf
- https://dergipark.org.tr/tr/download/article-file/747526
- https://hagamosmeiosis.wordpress.com/2013/09/24/advantages-and-disadvantages-of-bioreactors/
- http://biotechisfuture.weebly.com/uploads/1/4/1/6/14160671/bioreactor_design.pdf
- https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3755438/
- https://pubmed.ncbi.nlm.nih.gov/23494432/
- https://lms.su.edu.pk/download?filename=1588526676-introduction-to-factors-affecting-bioreactor-design-38.docx&lesson=6441
- https://www.biotecharticles.com/Biotech-Research-Article/Design-and-Operational-Key-Factors-of-Bioreactor-1558.html
- https://pharsol.com/de/wissenszentrum/blog/bioreactor-parameters