POLITECNICO
DI TORINO

Ph.D. Program in Management,
Production and Design (XXXIII Cycle)

Design and microalgae

A self-produced system to grow Spirulina for food use

Doctoral Dissertation by
Maurizio Vrenna

Politecnico di Torino, 17 March 2021

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Maurizio Vrenna

Supervisor
Prof. Pier Paolo Peruccio, Politecnico di Torino, Italy

Co-Supervisor
Prof. Liu Xin, Tsinghua University, China

Doctoral Examination Committee
Prof. Silvia Barbero, Politecnico di Torino, Italy
Dr. Beatriz Castelar, Università degli Studi di Torino, Italy
Prof. Elena Comino, Politecnico di Torino, Italy
Prof. Lorenzo Imbesi, Università degli Studi di Roma 'La Sapienza', Italy
Dr. David Kusuma, World Design Organization, Canada

Politecnico di Torino, 17 March 2021

Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Maurizio Vrenna

Turin, 17 March 2021

Abstract

The global population is exponentially growing, and it is estimated that more people will be living in metropolitan areas in the next decades. Considering the finiteness of agricultural lands, finding alternative sustainable ways to produce food is imperative. Microalgae have many properties – including the capacity of fixing carbon dioxide – and some particular strains like *Spirulina* are gaining in popularity as a superfood mainly due to their high amount of protein, and high consumer acceptance. This design research studies the integration of microalgal production in urban contexts. The work is an innovative attempt to utilize microalgae as a driving force to foster environmental sustainability and economic profitability. The most recent design and architectural projects that have entailed the use of microalgae are analyzed, and their limits and possibilities are traced. Afterward, two innovative products and the related service-systems are presented. The practice-based work outlines the transversal role of design and emphasizes multidisciplinary approaches from the fields of biology, economics, and sociology. Finally, new potential open-source design applications and guidelines are defined to be used as a basis for future research and projects.

Keywords: Microalgae; Future Superfoods; Product-Service System Design; Sustainability; Urban Contexts.

Contribution to knowledge

Design culture and practice are undergoing radical transformations. Designers are embracing more inclusive and multidisciplinary approaches to respond to binding needs urgently. For instance, new conventions linked to biological sciences are emerging in the world of design and architecture. In recent years various pioneering projects have involved the use of living organisms and biomaterials, including microalgae. The media interest in these projects is high. Although publications about microalgae are numerous and continuously growing in number in many scientific disciplines, studies in the field of design are still quite limited, and the approaches to these projects are highly diverse and uneven. The contributions to the knowledge offered by this doctoral dissertation revolve around the topics of Design for Sustainability, Product-Service System Design, Systemic Design, and Biodesign, by answering two research questions: '*How can design researchers contribute to microalgal studies?*' and '*How to design products, services, and systems involving microalgae that are beneficial and sustainable for the society?*' The questions have been answered through theoretical abstraction and practical work: in-depth multidisciplinary literature review, case study analysis, surveys and workshops, and demonstrative products and services. This study is a relevant academic product useful for designers who want to experiment with microalgae, but not limited. It paves the way for further technical and humanistic researches and raises interest in a new branch of study.

Publications arising from the Ph.D.

Vrenna, M.; Peruccio P. P.; Liu, X.; Zhong, F.; Sun, Y. (forthcoming). Microalgae as future superfoods: Fostering adoption through practice-based design research. *Sustainability*, *13*(8).

Peruccio, P. P., Menzardi, P., Savina, A., & Vrenna, M. (Eds.) (forthcoming). *Design Studies: Talks*. Rome, Italy: Quodlibet.

Peruccio, P. P., & Vrenna, M. (forthcoming). Circular economy in rural areas. In L. Topliceanu (Ed.), *Circular economy in rural areas comparative study among participant countries (comparative study among regions from Italy, Spain, Greece and Romania)*. Bacau, Romania: University of Bacau.

Vrenna, M. (forthcoming). Systemic design. In X. Liu (Ed.), *Sustainable design*. Beijing, China: Beijing University Press.

Peruccio, P. P., Menzardi, P., & Vrenna, M. (2020). Designing for territorial revitalization. A diffused art exhibition to foster northwest Italian inner areas. In J. Sánchez Merina (Ed.), *Eurau Alicante. Retroactive research in architecture* (pp. 190–197). Alicante, Spain: Universidad de Alicante.

Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019

Peruccio, P. P., Menzardi, P., & Vrenna, M. (2019). Transdisciplinary knowledge: A systemic approach to design education. In N. A. G. Z. Börekçi, D. Ö. Koçyıldırım, F. Korkut, & D. Jones (Eds.), *Proceedings of DRS Learn X Design 2019: Insider Knowledge* (pp. 17–23). Ankara, Turkey: METU Department of Industrial Design. doi:10.21606/learnxdesign.2019.13064

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Savina, A., Peruccio, P. P., Vrenna, M., & Menzardi, P. (2018). The impact of food production on public health: Systemic strategies for a diffused and transversal prevention plan. In S. Barbero (Ed.), *Proceedings of Relating Systems Thinking and Design (RSD7) 2018 Symposium* (pp. 315–330). Turin, Italy: Systemic Design Association.

Menzardi, P., Peruccio, P. P., & Vrenna, M. (2018). Design strategies for enhancing territorial legacy. The case study of a diffused art exhibition to revitalize specific territories in Piedmont region - Italy. In J. Sánchez Merina (Ed.), *EURAU18 Alicante: Retroactive Research: Congress Proceedings* (pp. 446–451). Alicante, Spain: Universidad de Alicante. Escuela Politécnica Superior. doi:10.14198/EURAU18alicante

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List of abbreviations

BPV Biophotovoltaic

FCM Food Contact Material

Ga Giga-annum (10^9 years)

HAPS Hybrid Algae Production Systems

IBA International Building Exhibition

IMTA Integrated Multi-Trophic Aquaculture

MVP Minimum Viable Product

PBR Photobioreactor

PoliTo Politecnico di Torino

PSSD Product-Service System Design

PSSDS Product-Service System Design for Sustainability

SD Systemic Design

SDGs Sustainable Development Goals

SDO Sustainability Design-Orienting

THU Tsinghua University

UAF Urban Algae Folly

WUR Wageningen University & Research

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Acknowledgements

I wish to express deep gratitude to Prof. Pier Paolo Peruccio and Prof. Liu Xin, who expertly guided me through these years of discovery. I also thank my colleagues Paola Menzardi, Alessandra Savina, and Massimiliano Viglioglia with whom I shared ideas and worked on many interesting projects. My appreciation also extends to the many academics, professionals, and collaborators who provided constructive suggestions, among them Fabrizio Alessio, Venanzio Arquilla, Albert Attila, Silvia Barbero, Niccolò Bassi, Luigi Bistagnino, Alberto Bologna, Marco Bozzola, Maurizio Capra, Elena Carmagnani, Beatriz Castelar, Salvatore Cava, Yi-Heng Cheng, Thomas Chung, Mevce Çıracı, Elena Comino, Federico Curiél, Elsa Dagný Ásgeirsdóttir, Stefania De Santis, Fábio Duarte, Vincenzo Fogliano, Fabrizio Galliano, Gao Ge, Nuccio Garoscio, Vincenzo Gerbi, Claudio Germak, Roberto Giordano, Federico Giuliato, Nicolò Gnecchi, Roberta Gorra, Cesare Griffa, Gianluca Grigatti, Ehsanul Karim, David Kusuma, Paul Kusuma, Luca Langellotti, Lee Yi-Wen, Li Tian, Liang Ji, Ian Charles Lister, Joris Lipsch, Marta Mancini, Valentina Marino, Paolo Mastropaolo, Giuliano Movio, Gunnar Mühlstädt, Roberto Pagani, Margaret Pate, Vincenzo Andrea Riggio, Michela Rota, Andrea Schubert, Enrique Manuel Serventi, Song Jia-Jia, Sun Yu-Chi, Marco Toscano, Patrizia Vrenna, Wang Bosen, Zhong Fang, Liao Zhuo-Ying. Their contributions are sincerely appreciated. Finally, I wish to acknowledge the support and love of my family – my parents Flavia Bruno and Antonio Vrenna, my wife Mao Yu and her parents Ma Yan-Ling and Mao Fu-Sheng.

Preface

I clearly remember the first design courses in 2009, when I started a Bachelor's Degree in Industrial Design at Politecnico di Torino, Italy. I was fascinated by the possibility of shaping my ideas, inspired by the great designers who made history. At that time, I was mainly interested in learning hard skills like representation techniques, industrial production processes, and the properties of materials to realize the most different kinds of products. 'Methodology' and 'research' were difficult concepts to understand, and I thought that design was a much less structured discipline closer to art than science. I was lucky enough to put the acquired knowledge into practice by working at private design firms in Italy and China. I was one of the youngest in these companies, and I used to ask many questions to senior colleagues: they taught me a lot. I also realized that the world of industry is frenetic, and the pace is accelerated. Decisions have to be made quickly, respecting deadlines, budgets, and meeting customer requests – even the strangest ones. There was no time to stop and reflect.

Parallel to these work experiences, I concluded an M.Sc. in Ecodesign at Politecnico di Torino, and an M.A. in Design Innovation at Tongji University, China. The Professors I met in those years have become a reference, and they taught me to have a different view of the world. These multidisciplinary approaches to design have been fundamental for this research and will be presented later. I understood that to complete meaningful design projects, it is necessary to adopt radical methodologies and out-of-the-box strategies: not only for designing products but also services. Living in Shanghai, one of the world's biggest cities and economies, I experienced firsthand the effects of environmental degradation, including air, water, and food pollution. This has raised my awareness of the urgent importance of sustainable development, which cannot be realized without a profound change in the current patterns, concrete actions, and targeted projects. This is not only in the interest of present societies but also of future generations. For these reasons, I decided to start a Ph.D.

After more than ten years of design study and practice, I have concluded an important chapter in my professional and academic career, and I am proud to have reached this point. The last few years have been decisive for my life development: I am also aware that this milestone is only the starting point for new, exciting, and harder challenges. The work in this doctoral thesis is the result of a research conducted from September 2017 to October 2020, mainly at Politecnico di Torino, and during a semester of mobility abroad at Tsinghua University in Beijing, China. The research project has been approved by the Ph.D. supervisor Prof. Pier Paolo Peruccio, who helped me formulate the research questions and provided constant support. Since the first research proposal, the topic has undergone substantial evolutions over the months. In a second moment, and after being updated on the preliminary results, Prof. Liu Xin (刘新) gave his availability to be a co-supervisor, providing a valuable contribution, particularly in the design phase.

The basis of this doctoral thesis lies in the interest in sustainability and design, particularly the multiple disciplinary intersections with biology, chemistry, and food. The themes of sustainable design and biodesign are extraordinarily topical nowadays and have seen a massive diffusion in the last years. This doctoral dissertation is an original work and not a collection of papers. I have revised and expanded most of the conference proceedings, journal articles, and book chapters that I have authored in these years. Furthermore, the reflections I made are the result of dialogues and interviews with professional experts from the most varied fields, to whom I have requested guidance and who have provided critical pieces of advice. This work is mainly addressed to researchers and professionals in the field of design, as well as scientists working with microalgae who wish to adopt a broader systemic approach in their projects. Concluding the thesis has been a difficult job, but the best thing about this Ph.D. was meeting brilliant minds from all over the world, who are working on similar subjects. I hope you will enjoy your reading.

CHAPTER 1

Introduction

The intent of this thesis is to contribute to food production issues by providing innovative and healthy solutions, with evident positive impacts on local communities. The aim is advancing knowledge in the field of sustainable design and investigating the intersection of multiple disciplines that are design, ecology, chemistry, economics, and food science touching on current topical issues. Confidently this thesis will arouse the interest of multiple researchers and practitioners, and it can find applications in the real world. The work addresses – directly and indirectly – several interconnected topics (Fig. 1.1).

The global population is exponentially growing, and it is estimated that by 2050 the Earth will be inhabited by 2.4 billion people more (United Nations, 2015). Urban conglomerates need to adopt innovative strategies to make cities more resilient. Primary responsibilities are to find sustainable ways to ensure clean air, fair jobs, and food security, while especially facing a food demand increase of more than 50% (Alexandratos & Bruinsma, 2012). Considering the unprecedented urban sprawl, with 68% of the global citizens that will be living in metropolitan areas (United Nations, 2018), and the finiteness of agricultural lands, novel solutions are taking place in cities worldwide. Successful attempts have been made to produce vegetables in vertical systems, community gardens, and rooftop farms with the direct involvement of citizens and with positive effects on the liveability of these areas. Scientists, researchers, and entrepreneurs are also exploring novel fields in food production and food design. Superfoods are gaining momentum as well: they are mostly plant-based foods that are thought to be nutritionally dense and thus good for health. The definition of the term 'superfood' is ambiguous, let alone the unique criteria for classification. For this reason, it is mostly a marketing tool with no roots in academic research. Nevertheless, the market for these products is snowballing.[1]

Among fungi, insects, and yeasts, microalgae – that are considered to be superfoods – are quite popular mainly due to their high amount of protein, flexible metabolism, and limited water and land needed for the production. An extensive literature demonstrates that microalgae can be used for a great variety of applications. These include the production for human food, cattle feed, and nutraceuticals, to capture CO_2, for biofertilizers and biofuels, among many other uses. Research on this area is already surging and will increase in the next decades. At the same time, design culture and practice have undergone radical transformations as well. Nowadays, design is embracing more inclusive and multidisciplinary approaches to respond to binding needs urgently. This means designing not only products but also implementing services and systems. Limited design experimentations mainly from practitioners have been recently conducted to embed algae and microalgae in the fields of product, interior, landscape design, and novel bioproducts. Architects, artists, and exhibit designers have been realizing buildings, installations, and pavilions to showcase and promote the underused potential of these microscopic organisms. Nevertheless, few of these projects specifically focus on urban contexts and effectively contribute to the transformation to a sustainable society. A bibliography in design connected to this topic is minimal too.

Therefore, guidelines that designers can follow for projects of this type are needed. These have to be supported by scientific evidence. At the same time, this field of research needs to be further explored in the discipline of design, in order to align – at least in part – with the numerous studies conducted in other fields. Purely technical studies are essential but often lose an overall view. A systemic but also humanistic and qualitative scientific approach, typical of design, could contribute considerably to the advancement of multidisciplinary research.

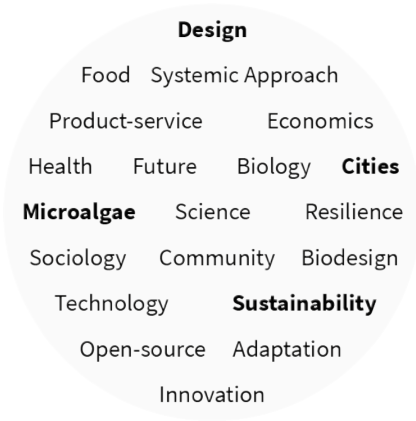

Figure 1.1. The main topics addressed by this research.

1.1 Objectives and structure of the study

The main objective of this study is to advance research in the field of design but not limited, understanding how nature-based solutions, particularly the production of microalgae for food use, could favor the transition toward environmental, social, and economic sustainability. The specific objectives are:

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1 The theme of novel superfoods is analyzed in detail in chapter 3 – Feeding the world.

- Gain relevant knowledge in the field of phycology, to apply it in sustainable design research;
- Improve critical skills in practice-based design research;
- Map and categorize relevant projects worldwide involving the use of microalgae;
- Understanding the limits and possibilities of the case studies;
- Identify new fields of sustainable action;
- Leverage fresh and innovative design possibilities for food production and CO_2 mitigation;
- Experiment with the design of new technical solutions;
- Test and assess the identified solutions;
- Extrapolate, from the practice, the necessary elements to define the guidelines for designers who want to embed microalgae in their projects;
- Pave the way for further research aimed at raising public interest and awareness on the topic;
- Outline the transversal role of design in this study;
- Contribute to the publication of relevant papers in international design journals and conferences.
- Aspire at concrete real-world applications in support of citizens and disadvantaged communities, and improve the resiliency of territories;
- Facilitate the replicability/improvability of the research through scientific dissemination and by embedding open-source principles in the project.

Researching such specific areas of study requires an understanding of phycology and design. The preliminary research question to which this doctoral research answer is: '*How can design researchers contribute to microalgal studies?*'. An extensive desk literature review was conducted by scrutinizing publications from multiple databases to answer this question. The results have shown that, to date, an increasing number of designers are interested in this topic, but methodological approaches – as well as scientific publications – are still lacking. Some case studies were then defined and categorized. This analysis was preparatory to the definition of the second and main research question, which is: '*How to design products, services, and systems involving microalgae that are beneficial and sustainable for the society?*' To answer this question, the limits and possibilities of the case studies were traced, highlighting likely areas of action. It was subsequently chosen to focus on the topic of microalgal production for food use, with the design of two products (a home device and a public-use device), to be joined in an urban network. Practice-based research has allowed gaining new knowledge, demonstrating through artifacts the validity of the proposed theoretical framework, and defining useful design guidelines.

This thesis is based on the framework in Fig. 1.2. It consists of a brief introduction that declares the structure of the dissertation, the research questions, the timeline of the studies, and the methodological approach. These steps are

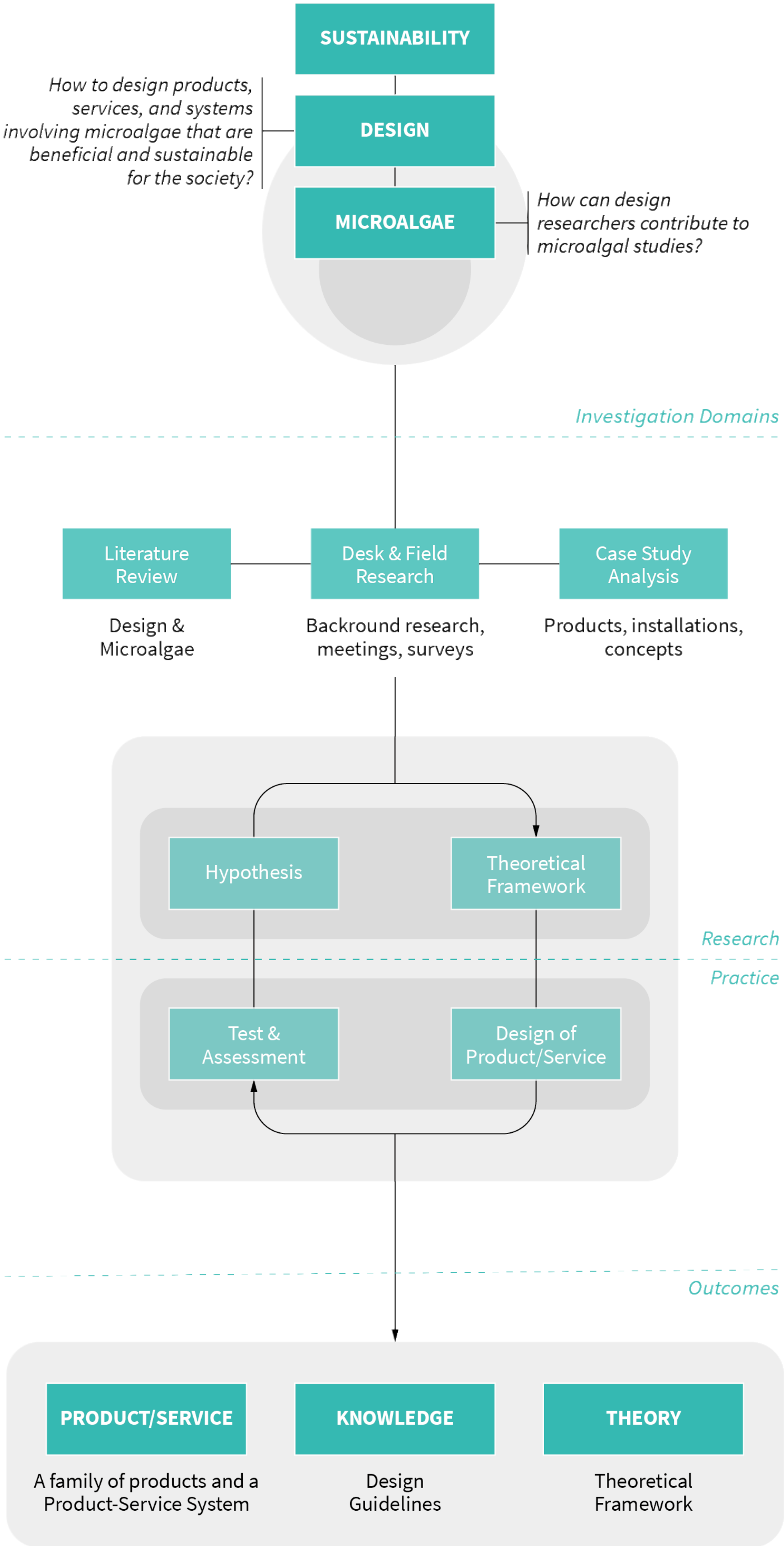


Figure 1.2. Research framework of the thesis.

explicit for guaranteeing a high level of scientific objectivity and the replicability of the study, which is, in all respects, an innovative design experimentation. The main body of the paper is made up of three parts. The first part is devoted to the literature review. Here, the research domains are clarified: the main approaches to sustainability and sustainable design are described, the urban context is analyzed as a place of action that requires targeted actions, and the main characteristics of microalgae are illustrated. In this part, it is also better explained why it was chosen to focus on microalgae, compared to other possible nature-based solutions.

The second part analyzes the state of the art in the fields of design. A total of 53 case studies were considered, divided into three categories: design experimentations (20), innovative small-scale solutions, mainly products; Microalgae in urban contexts (18), city-scale architectural installations showcasing the properties of microalgae, but also social design projects; Concepts for future cities (15), futuristic concepts that outline future design directions and trends. The case studies were classified by type, place, and period. Their pros and cons manifested the gaps in the practice. The projects carried out in urban contexts have been analyzed thoroughly, identifying the contribution of each project to six different challenges. These data were displayed on a composite radar chart. The results of this analysis were published in 2019 on Agathón, an international journal of architecture, art, and design – see: Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019.

The third part concerns the project development. The project was a fundamental part of the research because it overcame the previously identified practical gaps and confirmed some design guidelines and the theoretical framework. The project, apart from some final tests, was conducted at Tsinghua University in Beijing, China. This part of the thesis describes the methodologies adopted and the different phases of the project: an experiment of cultivation of microalgae in a domestic environment, an online survey and a workshop for the collection of quantitative and qualitative data, the product development phase, the definition of possible Product Service-Systems, the assessment tests.

Finally, the research outcomes are described, including new design guidelines for the design of integrated adaptive products, services, and systems. These are useful for the implementation of projects which involve the use of microalgae as driving forces for fostering economic profitability, environmental sustainability, and social inclusion primarily in urban areas, but also everywhere. In this part, the potential direct and indirect repercussions of the project were drawn, together with limits and future research steps. Part of the project was made available online as open-source to allow designers and makers from all over the world to replicate it, and decentralize microalgae

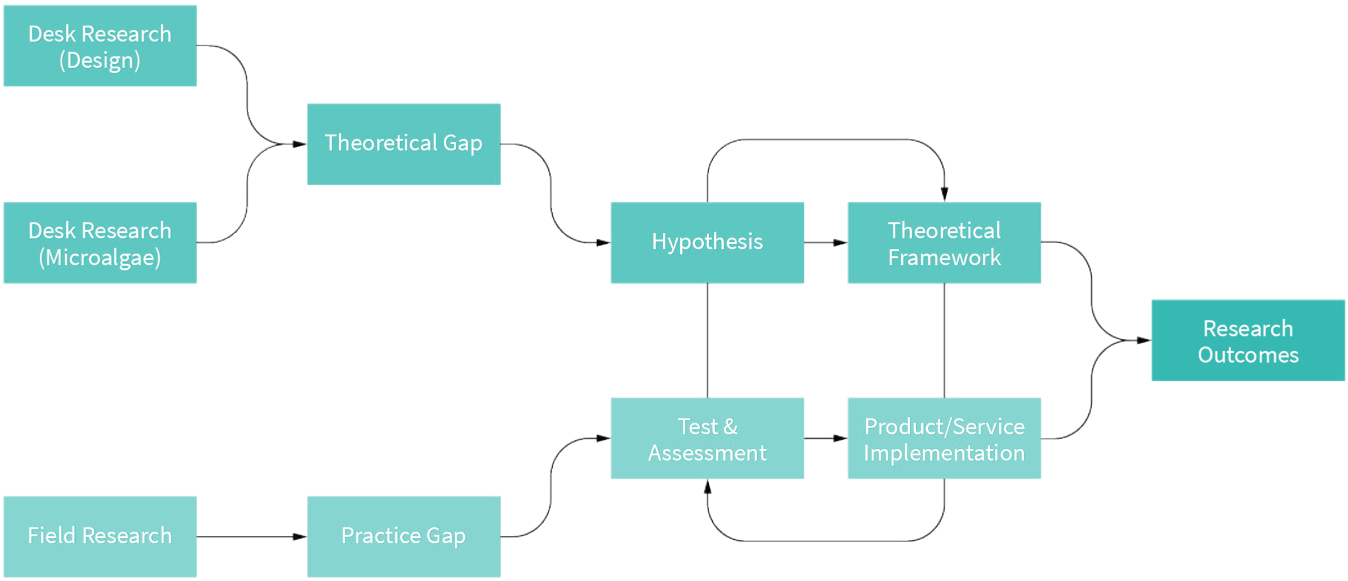


Figure 1.3. Research methodology.

production. Some of them already started to work on it. Media interest has been very high too. Interviews, surveys, presentations, the material used during the workshops, as well as technical product drawings and detailed images of the models, are included in a rich appendix at the end of the thesis.

1.2 Research approach, methodology, and timeline

Adopting one or more methodologies is important in design research, particularly in a doctoral thesis, because the methodology describes the broad philosophical grounding to the research methods that are going to be used. There are several ways of approaching a research problem. In this thesis, a quantitative, qualitative, systemic, and applied research approach is adopted. *"There is always a benefit in using multiple sources of evidence when conducting research. This process of cross-referencing your research is called 'triangulation'. This way of working can help you establish credible, valid, and reliable research practice"* (Muratovski, 2016, p. 39). The qualitative approach allows gaining an in-depth, critical understanding of the topic. The quantitative approach measures, through questionnaires, surveys, or statistical data, specific attributes, and characteristics, in support of a particular theory (Creswell, 2003). Applied research is, in this case, practice-based, because the design of one or more products becomes the basic research to extrapolate general and practical guidelines. The Department of Architecture and Design at Politecnico di Torino is well-known for Systemic Design studies. This thesis adopts a Systemic Design approach, but does not include a traditional Systemic Design project (input-output analysis), focusing mainly on product development and service creation.

The research methodology adopted is described above (Fig. 1.3). The first step was to conduct desk research mainly in the fields of design and phycology. The analysis involved the literature review related to research methodologies and sustainable design in its broader meaning (Systemic Design, Product-Service System Design, Redirective Design, Transition Design, Design for Sustainability, Biodesign, Biophilic Design), but also including readings related to ecology, economics, politics, and sociology. Numerous papers and books on algae and microalgae have also been revised. The papers are quite assorted and include scientific, technical, economic, historical, food, culinary, and descriptive notions. In parallel with the desk research, field research was conducted, with missions to multiple countries, participation in conferences, targeted interviews with experts, and case study analysis. The desk research served to identify the theoretical gap; field research has made it possible to recognize the practice gap. This step of the study was significant because it placed the research in a domain that is still mostly unexplored, straddling design, environmental sustainability, and biology. Subsequently, some hypotheses were assumed in an attempt to answer the research questions. A hypothetical, theoretical framework was defined, which was improved and subsequently confirmed through the realization of two products and the conceptualization of multiple services. The products have been tested and validated. The production of the products is not the final term of the research, but only one of the results. The other research outcomes are a set of design guidelines and the confirmation of a theoretical framework that informs on the implications of microalgae-based design projects and can be used as a reference for the development of other similar projects in the future. The steps of the methodology just described are following a rather linear and straightforward logic. Nevertheless, the actual research path was much more complex and iterative and required several critical corrections and revisions.

As for the timeline (Fig. 1.4), the research took place over a period of three years. The first year was exploratory and educational because it has been possible to read about miscellaneous topics (desk research and literature review). Reading has expanded general and specific knowledge in some fields of study. The first year of the Ph.D. included the participation in the Club of Rome Summer Academy[2] – a program that offered in-depth, cutting-edge insights into the problems of our economic system – and the attendance of several third-level multidisciplinary courses offered by the Graduate School of Politecnico di Torino (ScuDo). Propaedeutical classes were chosen, including courses like ‘Design studies’, ‘Firms, markets and institutions’, ‘Innovation and urban governance’, ‘Systemic innovation design’, ‘Responsible research

2 The Club of Rome is an organization of scientists, economists, entrepreneurs, and high civil servants with the aim of promoting the systemic understanding of global challenges and proposing solutions through scientific research. It was founded in 1968. See: https://www.clubofrome.org

and innovation, the impact on social challenges', as well as 'Writing scientific papers in English'. Among these courses, 'Innovation for change' is noteworthy. It is a learning program jointly developed by Politecnico di Torino, Collège des Ingénieurs Italia, and CERN IdeaSquare that aims to promote the creation of startups able to identify innovative solutions to the problems of contemporary society.[3] It was also possible to personally meet Gunter Pauli and Federico Curiél, an internationally renowned economist and an established architect in Shenzhen who have already been using microalgae in their projects.

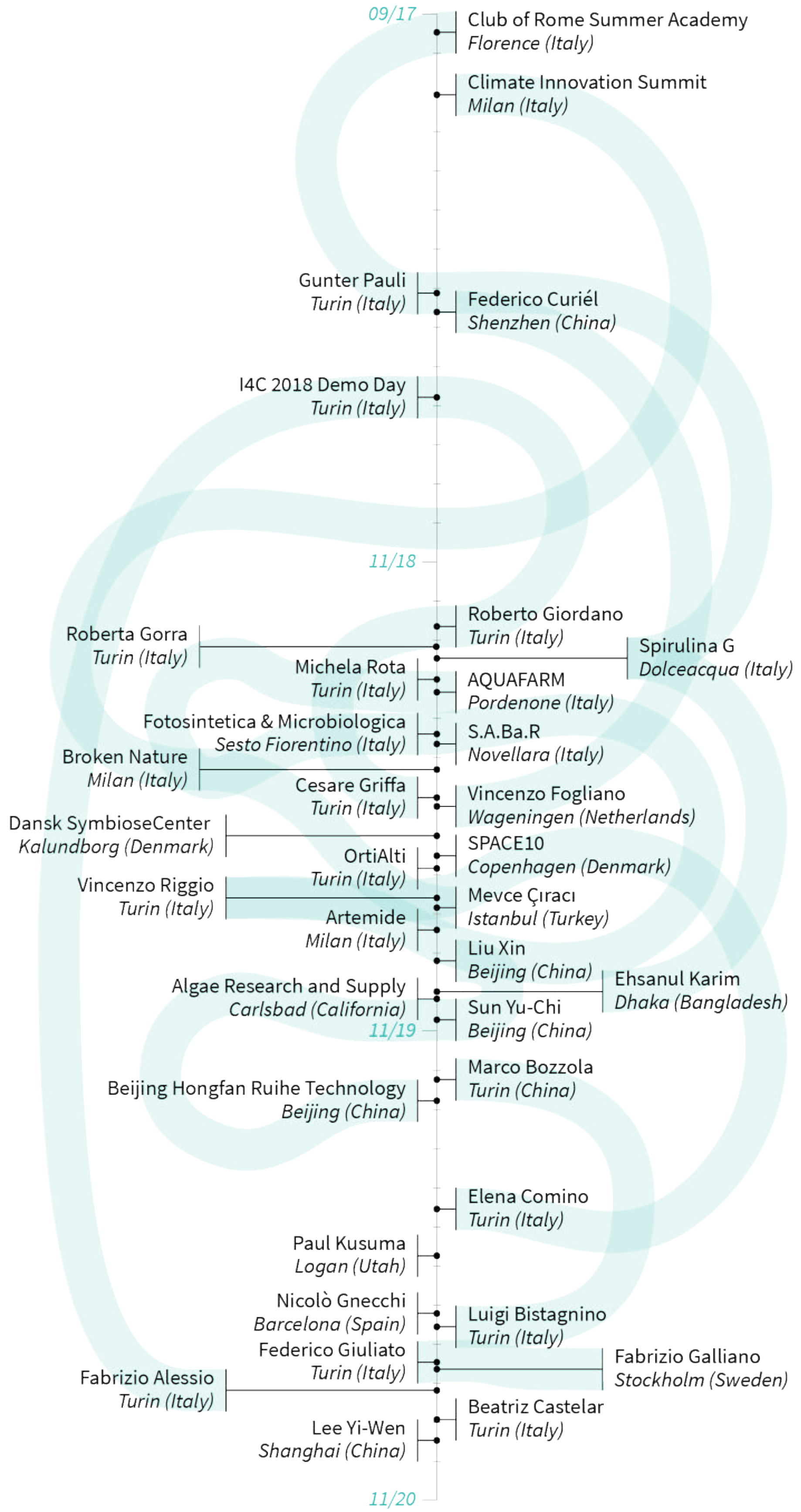
The second year, starting from December 2018, was characterized by extensive field research. Face-to-face and online meetings were organized with different experts in multiple sectors. Among these Prof. Roberto Giordano, Arch. Cesare Griffa and Dr. Valentina Marino, from Politecnico di Torino, who designed and patented innovative microalgae-based green walls; Dr. Michela Rota, engaged in the development of a small-scale microalgae production plant in an abandoned area of Turin; Nuccio Garoscio, a self-taught *Spirulina* producer from Dolceacqua in the Liguria region and the company S.A.Ba.R of Novellara, in the Emilia Romagna region, Italy; Prof. Vincenzo Andrea Riggio from Politecnico di Torino, Prof. Vincenzo Gerbi and Dr. Roberta Gorra from University of Turin, the laboratory Fotosintetica & Microbiologica in Tuscany and Prof. Vincenzo Fogliano from Wageningen University & Research in the Netherlands, international microbiology and phycology experts; the Dansk SymbioseCenter and SPACE10 in Denmark; Mevce Çıracı, design practitioner and researcher in Istanbul, Turkey; Arch. Elena Carmagnani of OrtiAlti in Turin and Arch. Carlotta De Bevilacqua, Artemide's CEO, who showed a particular interest in microalgae-based solutions for urban garden projects. During 2019, the 3rd edition of AQUAFARM was also organized in Pordenone, Italy, an international conference and trade show on aquaculture and algaculture with researchers and professional operators mainly from Europe. The international exhibition Broken Nature: Design Takes on Human Survival at the XXII Triennale di Milano[4] was also organized by Paola Antonelli from MoMA, which celebrates the ability of design to face main global challenges, with nature-inspired solutions of artists and designers from all over the world. All these meetings were necessary to have a 360-degree vision on the theme of biology applied to design.

From September 2019, with the beginning of the third year of research, the design phase started, which was conducted mainly at Tsinghua University, Academy of Arts and Design, in Beijing. Prof. Liu Xin (刘新) provided support in the different phases, together with Dr. Zhong Fang (钟芳). Part of the project

3 More information about the program at http://dottorato.polito.it/it/innovation_for_change

4 More information at http://www.brokennature.org

Figure 1.4. Timeline and main meetings/ events occurred in the field research.



was developed with the help of Sun Yu-Chi (孙宇驰), a brilliant recent graduate in Mechanical Engineering at Beijing Information Science & Technology University (BISTU). The design and prototyping phase lasted for around four months. More than five hundred people from all over the world were involved in an online survey and around thirty in a thematic workshop organized to collect quantitative and qualitative data to support the project. Marco Bozzola, a product design expert and Associate Professor at the Department of Architecture and Design of Politecnico di Torino, was consulted to receive additional feedback on the design of the two devices. Later, a local factory in Beijing – Beijing Hongfan Ruihe Technology – was involved in the realization of the final models, a high-fidelity prototype, and a scale model. Unfortunately, this activity took longer than expected due to the COVID-19 outbreak in January 2020. The tests of the products were conducted remotely only in June 2020, and some of them had to be canceled.

Parallelly, from February to May 2020, Prof. Elena Comino and Dr. Paul Kusuma were contacted. They provided valuable suggestions concerning chemical-biological aspects and the optimization of lighting systems. Prof. Luigi Bistagnino, founder of the research group on Systemic Design and coordinator of the Industrial Design School at Politecnico di Torino (1996-2015), gave great recommendations particularly for the final part of this thesis and the connections with systemic design. Fabrizio Galliano and Federico Giuliato, finance analyst experts, helped with the economic assessment of part of the service-systems proposed. In July 2020, I also had the chance to get in touch with Nicolò Gnecchi, who demonstrated deep interest in the project – specifically in one of the prototypes – and decided to feature it on from Wikifactory, an online platform for collaborative open design. Some articles have been published on international design blogs, creating media feedback. I was therefore contacted by Beatriz Castelar, Brazilian oceanographer and botanist researcher at the University of Turin, who is currenlty replicating and improving some aspects of the project. Besides, in September 2020, I had the opportunity to interview the visionary chef educator Lee Yi-Wen, a noted member of 'The Chef's Manifesto' initiative by the Sustainable Development Goal 2 (Zero Hunger) Advocacy Hub, who appreciated and confirmed the quality of the product of this research (see Appendix: A chat with Lee Yi-Wen).

The last months were used to conclude the thesis work and layout of the final essay. During the Ph.D., research progress has been periodically published in conferences and scientific design journals. The first contributions were overall generic, while the lasts were more specific. Additional publications are forthcoming.

PART I

Investigation domains

CHAPTER 2

Sustainability and design

This chapter describes in a concise but as exhaustive way the meaning of sustainability and how important it is today, through a critical and historical reading of contributions from different fields.[1] The relationship with the design discipline and its evolution over time are also analyzed. The chapter is a necessary introduction to the research because it lays the foundations for understanding the general approach adopted and the peculiar design choices.

Contemporary global societies are facing unprecedented climatic, social, and economic changes that will affect future generations. Addressing these challenges is no easy task, especially if a reductionist vision is used with the

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1 Part of the work described in this chapter was also previously published in: Peruccio, P. P., Menzardi, P., & Vrenna, M. (2020). Designing for territorial revitalization. A diffused art exhibition to foster northwest Italian inner areas. In J. Sánchez Merina (Ed.), *Eurau Alicante. Retroactive research in architecture* (pp. 190–197). Alicante, Spain: Universidad de Alicante.; Peruccio, P. P., Menzardi, P., & Vrenna, M. (2019). Transdisciplinary knowledge: A systemic approach to design education. In N. A. G. Z. Börekçi, D. Ö. Koçyıldırım, F. Korkut, & D. Jones (Eds.), *Proceedings of DRS Learn X Design 2019: Insider Knowledge* (pp. 17–23). Ankara: METU Department of Industrial Design. doi:10.21606/learnxdesign.2019.13064; Peruccio, P. P., Vrenna, M., Menzardi, P., & Savina, A. (2018). From 'The limits to growth' to systemic design: Envisioning a sustainable future. In Z. Linghao, L. Yanyan, X. Dongjuan, M. Gong, & S. Di (Eds.), *Cumulus Conference Proceedings Wuxi 2018 - Diffused Transition and Design Opportunities* (pp. 751–759). Wuxi: Huguang Elegant Print Co.

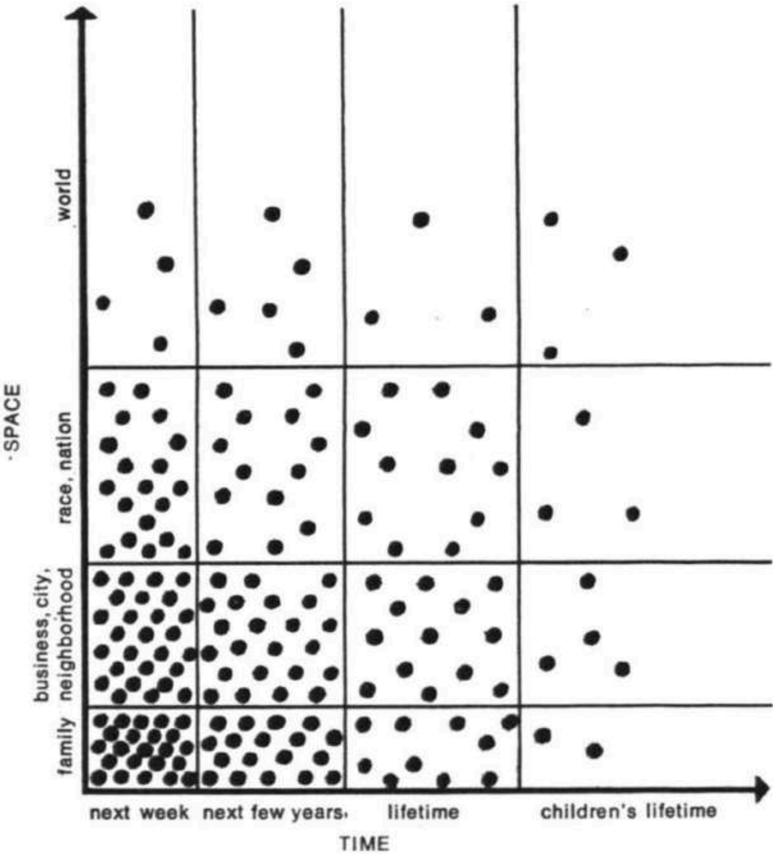

Figure 2.1. Human perspectives: every human concern falls somewhere on the space-time graph. Reprinted from The limits to growth (p. 19), by D. H. Meadows, D. L. Meadows, J. Randers, & W. W. Behrens III, 1972, New York, NY: Universe Books. Copyright 1972 by Universe Books.

conceitedness of solving problems with the same kind of thinking they were created. Unfortunately, only a small fraction of the world's population can understand the repercussions of their actions over time and space. The graph in Fig. 2.1 describes the different levels of human concern. *"Every human concern can be located at some point on the graph, depending on how much geographical space it includes and how far it extends in time. Most people's worries are concentrated in the lower left-hand corner of the graph. [...]. Other people think about and act on problems farther out on the space or time axes"* (Meadows, Meadows, Randers, & Behrens III, 1972, p. 18). It is fundamental to see well beyond the personal 'comfort zone', with a forward-looking and future-oriented gaze to understand sustainability – and make the right decisions. Experts from all over the world, but also ordinary citizens, are called to action: addressing sustainability problems is imperative, and a contribution is needed immediately.

If sustainability is, therefore, a hot topic, design has also become a game-changer in our lives. *"In the English language the noun design means 'project'; it comes from the Latin pro-iacere (to throw something forward) and implies an activity that embodies the concept of moving forward, of the future. Instead the etymology of the term design (from the Latin designare, a derivation of signum 'sign') refers to the concept of 'meaning': using a sign to distinguish between things, in other words to give things meaning. Design means a project for the future but also an activity that gives things meaning"* (Bistagnino & Peruccio, 2014, p.

1582). Design discipline is questioning about its identity and competencies. The center of the discussion is on how design can carry out its original purposes according to the changes of time, societies, and mentalities. Undoubtedly, design cannot remain a restricted discipline, but it assumes an increasingly important role also for sustainability-related problems. At the same time, ecologically-literate designers must be aware of their leading role toward a positive transition for society and endangered natural ecosystems. "*This demands high social and moral responsibility from the designer*" (Papanek, 1973, p. 14), that has to be adequately educated, and that should make himself fully conscious of the implications of his choices.

This chapter includes an excursus about the definition of sustainability, the rise of environmental movements and the international debate, the present status, and agenda for the future, with strategies to mitigate climate change and resource depletion. The connections between design and sustainability, the changing role of present-day designers, and the different approaches to design for sustainability are further explored (Green Design, Ecodesign, Biophilic Design, Cradle to Cradle Design, Biomimicry, Biodesign, Transition Design, Systemic). Design, Product-Service System Design for Sustainability). As for Systemic Design (SD) and Product-Service System Design for Sustainability (PSSDS), these two approaches will be analyzed more deeply, as in this research, their thinking, methodologies, and tools will be more widely adopted. In conclusion, the chapter deals with the relevance of nature-based solutions in design practice, with particular references to the use of algae and microalgae.

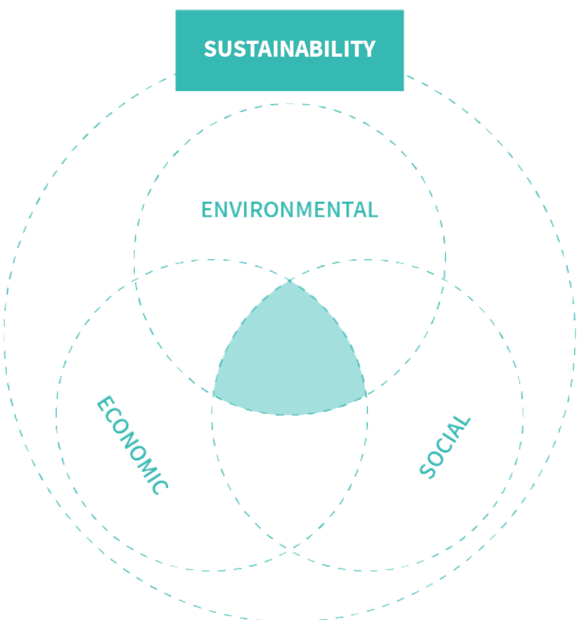

Figure 2.2. Sustainability framework involving the conventional interactions between environmental, social and economic factors. Adapted from *Green economics: An introduction to theory, policy and practice* (p. 37), by M. Scott Cato, 2009, London, United Kingdom: Earthscan. Copyright 2009 by Molly Scott Cato.

2.1 What is sustainability?

The term 'sustainability' is adopted by the experts and by a broader public, but it is often misused. According to the Oxford Dictionary of English, sustainability is *"the ability to be maintained at a certain rate or level"* and the *"avoidance of the depletion of natural resources in order to maintain an ecological balance"* (Oxford Dictionary of English, 2017). The definitions of sustainability are, indeed, manifold and somewhat different for each discipline and context. The most accepted definition of sustainability – or rather of 'sustainable development' – is the one described in Our Common Future, also known as the Bruntland Report, a work published in 1987 by the United Nations.[2] Sustainable development is the *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development, 1987, p. 27). This definition, despite its wide diffusion and acceptance, has been partly contested because of the paradox of being able to achieve economic growth reconciled with environmental sustainability, with business-as-usual solutions (Sachs, 2015).

The domains of sustainability are, therefore, various. In 2005, at the 'United Nations World Summit on Social Development' meeting in New York, attended by around 200 leaders of the member states, the main domains of sustainability were identified. These are economic development, social development, and environmental protection (United Nations, 2005). These domains are not separate from each other, but strongly interconnected. The Venn diagram (Fig. 2.2) shows the relationships between the three main domains: all these factors must be taken into consideration to achieve sustainability. To these dimensions, we can add some more: there has been growing interest among scholars to consider also culture (Soini & Birkeland, 2014), and human (Goodland, 2002) as fundamental pillars for sustainability. Reaching sustainability should not be considered as a final goal, but just a starting point: the value of natural capital, social capital, and human capital are equally important to the economic capital, or even more.

Acting sustainably is imperative today. The 20th century was an astonishing moment in the history of humanity, dominated by a series of events that heralded significant metamorphoses in our cultures, societies, and economies. These radical transitions, glorified within a globalizing and capitalist pattern, have been both beneficial and disrupting for many. Nevertheless, in the name of myopic progress and of the insane pursuit of economic returns, the implications of our past and current actions on natural and artificial environments

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2 The World Commission on Environment and Development (WCED) was set up as an independent body by the United Nations. The report had a significant media impact and – for the first time – the concept of sustainable development was introduced. The report is also known as the 'Brundtland Report' in recognition of former Norwegian Prime Minister Gro Harlem Brundtland, who was leading WCED at that time.

have not been appropriately taken into account. Business as usual, inefficient production processes and consumerism are leading to the damage of natural resources at an exponentially fast pace. Climate destabilization, air and water pollution, limited resources, and food production are hence just a few of the main challenges that present and future societies have to face. We have long since entered a new geological era, in which understanding the impact of our development on the global environment is a complicated task. This epoch is called Anthropocene, a time in which humankind is responsible for the alteration of the Earth system (Crutzen & Stoermer, 2000, p. 17; Steffen, Crutzen, & McNeill, 2007).[3] *"The second half of the twentieth century is unique in the entire history of human existence on Earth. Many human activities reached take-off points sometime in the twentieth century and have accelerated sharply towards the end of the century. The last 50 years have without doubt seen the most rapid transformation of the human relationship with the natural world in the history of humankind"* (Steffen et al., 2004, p. 131). Experts defined this period as the 'Great Acceleration'.

The graphs in Fig. 2.3 show the global exponential growth trends in the last 250 years of values such as carbon dioxide, surface temperature, ocean acidification, marine fish capture, shrimp aquaculture, tropical forest loss, and domesticated land, among others, caused by anthropogenic activities. The term Anthropocene outlines the fact that humans live by abusing natural resources. The disaster we are witnessing and contributing to, however, cannot be attributed to the whole humanity because many people have not taken part in this change, and are only suffering the consequences – for instance, the poorest countries in the world. Therefore this geological era could be defined, perhaps more correctly, 'Capitalocene' (Moore, 2016). A paradigm shift is indispensable for rebalancing natural systems that have so far proved to be remarkably resilient, but which will soon collapse. Sustainability is essential to guarantee a decent future for our children.

2.1.1 Rise of environmental movements

In recent years, attention to environmental issues revived in public opinion, thanks also to the continuous media pressure from activists all over the world. In particular, Greta Thunberg, a young Swedish girl who has gained international recognition for criticizing the failure of world leaders in taking sufficient actions to address climate change. At just 17 years old, Greta Thunberg was mentioned as '2019 Time Person of the Year' (Alter, Haynes, & Worland,

3 Scholars are debating on the start date of the Anthropocene. Some dated it to when humankind began modifying stones to make spikes for spears, others instead date it back to World War II, with the explosion of the world's first nuclear bomb explosion on 16 July 1945 (Zalasiewicz et al., 2015).

2019), was included in the Forbes list[4] of The World's 100 Most Powerful Women, and received two nominations for the Nobel Peace Prize in 2019 and 2020. Thunberg has started a global movement of young people concerned for their future, who engaged in periodical pacific protests in their communities called 'Fridays for Future'.

Environmental movements, however, are not just an invention of the last decade. After World War II, nuclear testing by the American government continued for several years, from 1946 to 1958, at Bikini Atoll and in the Nevada Desert. The tests included explosions on the sea, the reef, underwater, and in the air, aimed at investigating the effects of explosions and radiation on animals and the surrounding natural and artificial ecosystem. The first test at Bikini Atoll took place on July 1, 1946 – the so-called 'Able Day' – and had irradiation consequences that were massively underestimated (Weisgall, 1994). These experiments sparked public outrage in the United States and rallied numerous protests. In 1962 Rachel Carson, scientist, biologist, and American ecologist, published the book 'Silent spring', which was soon considered as a

4 The full list is available on Forbes website: https://www.forbes.com/power-women/list/#tab:overall

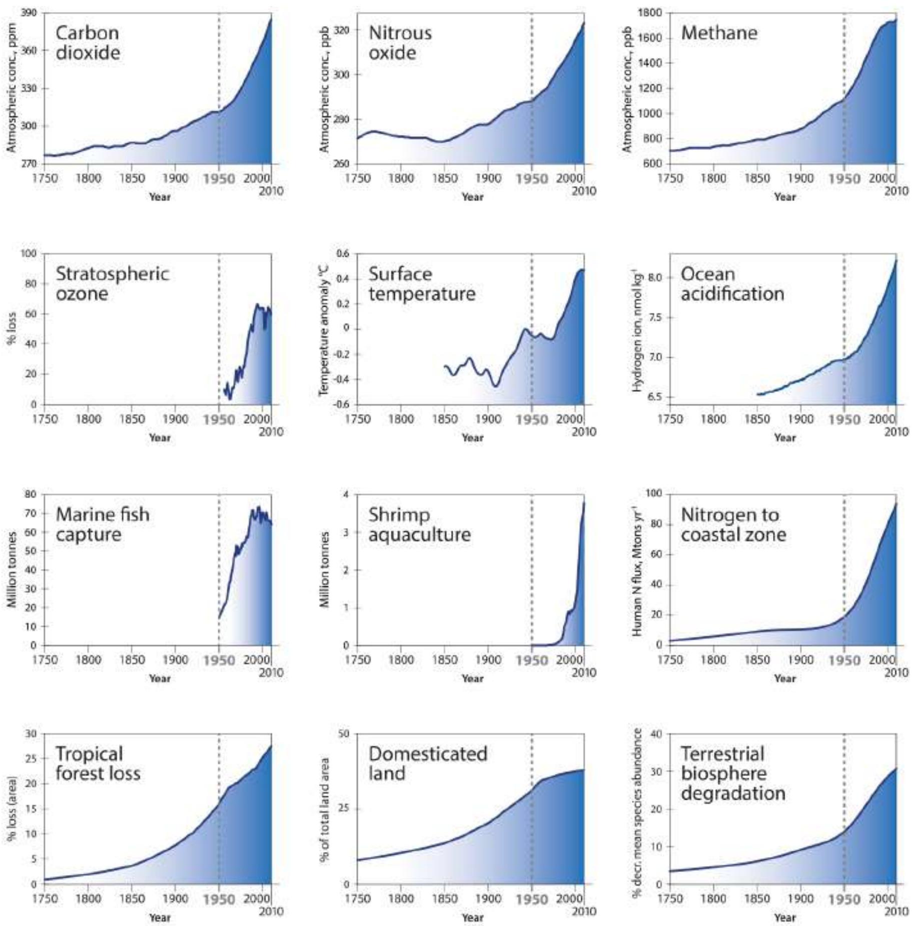

Figure 2.3. The great acceleration: Earth system trends. Reprinted from "The trajectory of the anthropocene: The great acceleration", by Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C., 2015, *Anthropocene Review*, *2*(1), p. 87. Copyright 2015 by Will Steffen, Wendy Broadgate, Lisa Deutsch, Owen Gaffney, and Cornelia Ludwig.

manifesto of the American environmental movement. The title derives from the observation of birds, which no longer chirped as much as in the past because the massive amount of pesticides used in agriculture caused their death. Carson explains, using detailed scientific research and analysis, the irreversible effects on ecosystems of pesticides, herbicides, and other commonly-used plant protection products, including DDT[5] (Carson, 1962). Carson, therefore, suggested the use of other natural substances to replace synthetic pesticides that were abused. The chemical industry severely attacked the activist's work, which was, however, endorsed by President John F. Kennedy in his speech after winning the Democratic nomination for president. In 1968 biologist Steward Brand – one of the most influential thinkers of our time – persuaded NASA to release the first picture of Earth seen from space entitled 'The Blue Marble'. The image has entered history because it showed the fragility and finiteness of our world and is representative of an era. The picture was published on the cover of the first issue of the 'Whole Earth catalog', a periodic issue that included scientific, cybernetics, communication, media, and system dynamics articles, and book reviews. The magazine also became a catalog of products for sale. Other fathers of the environmental movement are the biologist Barry Commoner, author of 'The closing circle', which designates the primary laws of ecology (Commoner, 1971) and the German economic thinker and statesman Ernst Friedrich Schumacher, author of 'Small is beautiful', a book that denounces the depletion of resources made by capitalism (Schumacher, 1973).

The reading and understanding of the past are the basics of the actions that are perpetrated in the present. "*Between 1964 and 1972 the groundwork was laid for a debate on design based on ecological criteria which considered the environment as umwelt (literally the world around us) - not just the natural environment, but also a socio-cultural environment strongly influenced by the contribution of systemic philosophy*" (Peruccio, 2014, p. 207). The environmental movements of those years are not so different from those of now, characterized by the same ardor, fervor, and enthusiasm. Unfortunately, the demands of the protesters have not been heeded by governments. For the sake of short-termism, political and economic interests were given priority, rather than safeguarding the health of citizens and the environment.

2.1.2 The limits to growth

The birth of environmental movements certainly lays the foundations for thinking about the future. The fundamental question was: '*Where are we, and where will we go?*' Such an elaborate question for societies, governments,

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5 DDT (Dichlorodiphenyltrichloroethane) was initially developed as an insecticide by Swiss chemist P. H. Müller in 1939 and was also used during World War II to control malaria among troops and civilians. It became infamous for its acute toxicity on the human body and natural ecosystems. Since 2001, its use is banned worldwide.

communities, and individuals deserved careful analysis and comprehensive response. It could not have been decoded with a simplistic and static investigation. An attempt was made in 1972 when a group of researchers from MIT published a report entitled 'The limits to growth' (Fig. 2.4). The report was commissioned by the Club of Rome, an organization of individual scientists, economists and high-level civil servants with the mission to promote understanding of the global challenges facing humanity – the so-called 'world problematique' – and to propose solutions through scientific research.[6] The intention was to examine the predicament of mankind through computer simulations of exponential economic and population growth with a finite supply of resources. The MIT research group managed to gain insights into the limits of the world system and identify the dominant elements and their mutually influential long-term interactions. The system dynamics model that was generated was based on five variables: population, food per capita, resources, industrial outputs, and environmental pollution. The final remarks were unexpected and not encouraging. If the current growth trends continued unchanged, planetary limits would be reached within the next one hundred years, with a sudden decline in population and industrial capacity. A state of equilibrium could be achieved by altering the trends and striving for equal opportunities in the interest of the global community (Meadows et al., 1972).

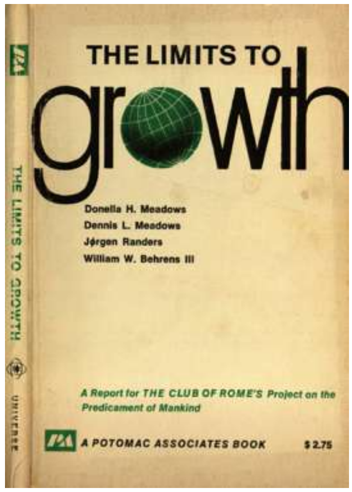

Figure 2.4. The cover of the first edition of the book: Meadows, D. H., Meadows, D. L., Randers, J., & Behrens III, W. W. (1972). *The limits to growth*. New York, NY: Universe Books.

The publication was not only a warning about the negative repercussions of our business as usual but was intended as a call to action on the necessity of radically changing our ingrained production and consumption models. Decidedly, The limits to growth had a broad mediatic resonance. Criticism from academics and business was immediate, mainly condemning the methodology, the conclusions, and the rhetoric behind the research. Nevertheless, it broadened the debate on environmental issues, boosting the awareness of the necessity of acting with a higher sensitivity to ecology. Several reviews of the book have been published, confirming the deleterious trends that emerged in the first work and proposing predictions of what may happen in the next forty years (Meadows, Meadows, & Randers, 1992; Meadows, Randers, & Meadows, 2004; Bardi, 2011a; Randers, 2012).

After decades of discussions, a sustainable vision has not yet been embraced. Uncurbed individualism, the yearning of possession and consumer-

6 Since 1970 the cyberneticist Hasan Özbekhan, co-founder and first director in 1968 of The Club of Rome together with Aurelio Peccei, an Italian entrepreneur and philanthropist, and Alexander King, applied system theory to global issues, inspiring scientists, planners, and academics to join the Club. Although his proposal was neglected, it defined global issues as an interconnected system of 49 continuous, critical problems, today recognized as persistent and increasingly arduous challenges. It is suggested to read: Özbekhan, H. (1969). *The predicament of mankind: A quest for structured responses to growing world-wide complexities and uncertainties*. New York, NY: Club of Rome.

ism, are leading to the destruction of ecosystems, through overexploitation of natural resources, actually reflecting a severe lack of qualitative, long-lasting relations among people, nature and societies. According to the philosopher and writer Ulrich Beck, today we are living in a risk society in which the production of goods and services aimed at increasing welfare became directly proportional to the generation of environmental and societal risks. The introduction of polluting and toxic substances into the soil, air, water, and food, have even been legitimated by some maximum acceptable limits, which are dangerous strategies that will lead to irreversible consequences (Beck, 2012). The reasons for these unsustainable behaviors have to be found within the complexity of the world ecosystem, the natural environment, and societies. System theories may provide insightful models to understand and discuss complex issues and systemic problems.

2.1.3 The international debate

The ecological movements that began in the 1960s and the sustainability-related scientific publications arouse international public opinion. Socio-economic and political models were disrupted, and an increasing number of aware citizens began to claim their rights. The positions of industries, political parties, and even the Church were conflicting. 'The limits to growth' was severely condemned by the industrialists' lobby, who recognized the purpose of the report, but who rejected the methodology employed. The industrialists were aware of the repercussions that such a new movement could have had on their business as usual. The report also suggested the effectiveness of birth control methods to limit exponential population growth, contain pollution levels and ensure sufficient per capita food to avoid – or at least postpone – collapse. This position was condemned by the Catholic Church, hostile to any limitation of economic and demographic growth.

The debate on sustainability issues has gone on for years – or rather for decades – without ever reaching universally accepted conclusions. However, significant progress has been made, especially in the world of research, which is currently seeing concrete results. Nevertheless, there is still room for improvement. Several politicians have also embraced a 'green' philosophy, making it the workhorse of their parties. Exemplary are the green parties in Europe and the work of Albert Gore, an American politician and environmentalist who was the 45th vice president of the United States from 1993 to 2001. Gore is the protagonist of a 2006 documentary film on global warming, based on a live Keynote presentation. The film, entitled 'An inconvenient truth', was highly appreciated and won the 2007 Oscar for best documentary.[7] Anders Wijkman,

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7 Guggenheim, P. D. (Director). (2006). *An inconvenient truth* [Motion picture]. United States: Paramount Classics.

a Swedish politician and former member of the European parliament, is also very active at the moment. Member of the Club of Rome, he is an opinion maker, consultant of public and private bodies and co-author of numerous publications, including 'Bankruptcy nature: Denying our planetary boundaries'.[8] Many economists have also theorized new social, financial, and alternative business models to continue to thrive in the future.[9] Now, although the time to discuss is limited (if not over), the debate is open and requires the contribution of the United Nations, single countries, politicians, economists, famous show-business people and actors, but also ordinary citizens. Today, the situation has changed compared to a few decades ago. The great acceleration has seen exponential growth in pollution, the loss of biodiversity, and the degradation of natural ecosystems, which will never return to the previous state. Radical stances are needed no longer to prevent, but to mitigate the problems we have created in the last centuries.

2.2 Present status and agenda for the future

Present generations are probably facing the most significant environmental and societal challenges our species has ever seen. Much of the trends that had been predicted turned out to be plausible (Randers, 2012). The words of Dr. Dennis Meadows' speech on the occasion of the 40th anniversary celebration of The limits to growth held in Washington DC on March 1, 2012, are quoted: *"Forty years ago I stood up and presented a question:' How can global society organize itself to provide a just, peaceful, equitable, decent living for the people? Now, after forty years, finally, the question is starting to be considered seriously. But I'm apprehensive. I have to say that although the question is still important, the answer is different than it was forty years ago. Forty years ago, it was still theoretically possible to slow things down and come to an equilibrium. Now, that's no longer possible"* (Cerasuolo, 2013, 08:47). Almost another ten years have passed since this speech, and we have just entered a new decade that will be crucial. The next few paragraphs describe the current limits of our ecosystems and the planetary boundaries, which, according to scientists, have already been partially overcome. The strategies that are being adopted to ensure sustainable development are also described, with particular reference to the possible solutions for feeding the planet. 2030 and 2050 mark significant dates in modern history, and achieving the set goals will require a collective effort.

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8 Wijkman, A., & Rockström, J. (2013). *Bankrupting nature: Denying our planetary boundaries*. Abingdon, United Kingdom: Routledge.

9 It is suggested to read: Jackson, T. (2011). *Prosperity without growth: Economics for a finite planet*. London, United Kingdom: Earthscan; Maxton, G., & Randers, J. (2016). *Reinventing prosperity*. Vancouver, Canada: Greystone Books; Nair, C. (2011). *Consumptionomics: Asia's role in reshaping capitalism and saving the planet*. New York, NY: Wiley; Pauli, G. (2017). *The third dimension*. Easthampton, MA: JJK Books.

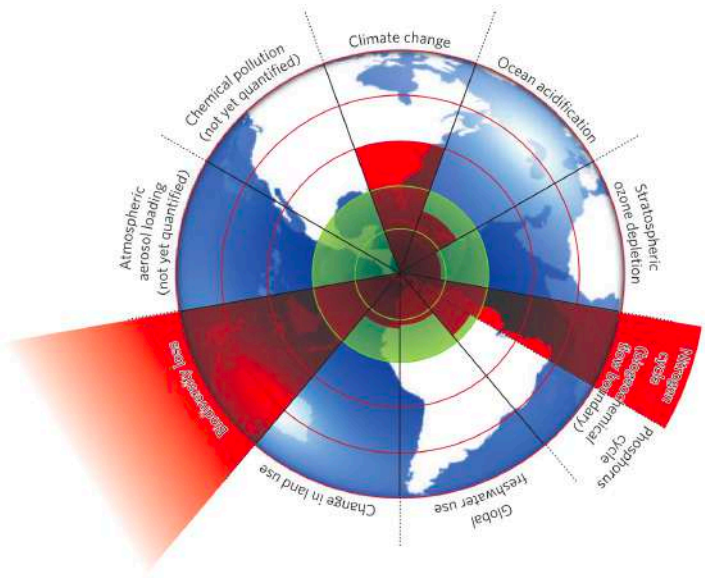

Figure 2.5. Beyond the boundary. The inner green shading represents the proposed safe operating space for nine planetary systems. The red wedges represent an estimate of the current position for each variable. The boundaries in three systems (rate of biodiversity loss, climate change and human interference with the nitrogen cycle), have already been exceeded. Reprinted from "A safe operating space for humanity", by Rockström et al., 2009, *Nature*, *461*, p. 472. Copyright 2009 by Macmillan Publishers Limited.

2.2.1 Planerary boundaries and resource depletion

The study by the research group of the Stockholm Resilience Center, led by the internationally-recognized Prof. Johan Rockström, is particularly popular. In the Anthropocene, to meet the challenge of maintaining the Holocene state, scientists proposed a framework based on 'planetary boundaries' to define the limits of the safe operating space for humanity (Fig. 2.5). The quantification of certain biophysical thresholds (climate change, ocean acidification, stratospheric ozone depletion, nitrogen and phosphorus cycle, global freshwater use, change in land use, biodiversity loss, atmospheric aerosol loading, and chemical pollution) showed that three out of nine boundaries have already been overreached, with potential and unpredictable disastrous consequences for humanity. The evidence also suggested that if all human activities operated within limits, long-term social and economic development could be pursued (Rockström et al., 2009). Economist Kate Raworth is working in this direction and theorized the 'Doughnut economics', based on this study. The Doughnut economics is a new and radical approach to modern economic models, which takes into account basic human needs, including water, food, health, housing, energy, education, work, gender, and social equity and the environmental threshold that must not be overcome. Raworth describes the Doughnut as a compass to guide humanity in this century (Raworth, 2018).[10]

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10 Kate Raworth is a British economist, member of the Club of Rome, Visiting Research Associate at the University of Oxford – Environmental Change Institute, and Senior Associate at the Cambridge Institute for Sustainability Leadership. She wrote the book Raworth, K. (2018). *Doughnut economics: Seven ways to think like a 21st century economist*. White River Junction, VT: Chelsea Green Publishing. Her theories inspired many students, politics, and business people.

If some of the planetary boundaries have already been reached, resources are also starting to run low. Resources refer to natural materials that are used (or are usable) by humans. Water, air and food are resources, as well as coal, iron, oil, natural gas, phosphorus, and other minerals. Resource depletion studies are manifold. The economy of global societies is directly dependent on minerals and metals but, while metals are recyclable, mineral deposits are instead non-renewable over human timescales, and peak minerals is approaching (Prior, Giurco, Mudd, Mason, & Behrisch, 2012). Studies have also shown that phosphorus, commonly used as fertilizer for plants and crops, is undergoing a rapid depletion and about 40 to 60% of the current resource base would be extracted by 2100 (van Vuuren, Bouwman, & Beusen, 2010). These studies suggest the urgent need to find innovative economic, technical, and behavioral solutions to limit the use of resources, produce enough food in an alternative way, and also limit CO_2 emissions. If we continue to follow this trend, "*what we leave to our descendants is a different planet, an emptied Earth that has climatic and environmental characteristics that are no longer what they once were. [...] We cannot exclude that the climatic effect of CO_2 does not transport the entire planet to a state that could resemble what the climate was a few tens of millions of years ago*" (Bardi, 2011b, pp. 289-290).

2.2.2 Toward 2050

2050 marks an important date in this century. In order to cope with the problems humanity will face, it is necessary to prevent – where and if still possible – and mitigate damages. Future generations will face a different world, with new environmental, social, economic, and geopolitical equilibria. Unfortunately, most people, businesses, and governments have a short-term vision. In his book '2052: A global forecast for the next forty years', Jorgen Randers traces pretty well what may be the fate of different geographic macro areas and also suggests a series of guidelines to be followed in order not to get unprepared. The author also questions the ability of democratic political systems to face the significant challenges of the present and future (Randers, 2012).

Although it is not possible to have a clear prediction of what will happen, research, investments, and plans for a better future are manifold. Banks, companies, and governments are adopting long-term plans, as well as the United Nations, which are looking ahead to challenges and opportunities on a global scale. The Sustainable Development Goals (SDGs) (Fig. 2.6), set in 2015 by the United Nations General Assembly, are 17 broad and interconnected goals, addressed to the whole world, and communicated in a way that is easy to understand.Each goal has a list of targets and indicators to verify its success, which is intended to be achieved by the year 2030 (United Nations, 2015). To fully meet the goals, targeted interventions, and multidisciplinary projects with top-down and bottom-up approaches are required. Most likely, some coun-

Figure 2.6. The 17 Sustainable Development Goals by the United Nations. This research focuses on goals no. 2, 3, 8, 11, and 12.

tries will not be able to achieve these goals until 2050. The contribution of this thesis aims at satisfying, at least in some parts, the goals no. 2 (Zero hunger), 3 (Good health and well-being), 8 (Decent growth and economic growth), 9 (Sustainable cities and communities), and 12 (Responsible consumption and production).[11] The research is, therefore, not only relevant today but hopefully useful for the years to come.

As will be discussed further on, design plays a fundamental role in the transition and achievement of the Sustainable Development Goals: in recent years, as a matter of fact, the discipline of design has become even more inclusive and attentive to environmental issues.

2.3 Design for sustainability

Design for sustainability is an approach that considers the broader domains of sustainability, which are economic development, social development, and environmental protection in particular. The well-being of people and the care of ecosystems are a priority, but being less harmful does not mean being completely sustainable. To design sustainably is complex: it requires a high degree of qualification and cannot only be reduced to the use of natural, recycled, or

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11 The full description of the SDGs and sub-goals is available in the report: United Nations. (2015). *Transforming our world: The 2030 agenda for sustainable development* (Report No. A/RES/70/1). Retrieved from https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E

recyclable materials for the production of objects, as it was happening until a few years ago. Furthermore, sustainability must not be considered as an end-point but as a process.

Design for sustainability is consistent with one of the most recent and complete definitions of Industrial Design, which was once closely connected to industrial production. The World Design Organization suggests that *"Industrial Design is a strategic problem-solving process that drives innovation, builds business success, and leads to a better quality of life through innovative products, systems, services, and experiences. Industrial Design bridges the gap between what is and what's possible. It is a trans-disciplinary profession that harnesses creativity to resolve problems and co-create solutions with the intent of making a product, system, service, experience or a business, better. At its heart, Industrial Design provides a more optimistic way of looking at the future by reframing problems as opportunities. It links innovation, technology, research, business, and customers to provide new value and competitive advantage across economic, social, and environmental spheres"* (World Design Organization, 2015).[12]

According to this recent definition and on the points on which sustainability is based, a complete rethinking of the context, theory, and practice of design is needed for a sustainable change. Nowadays, designers must realize that redirection in design theory activities is imperative, and specific design practices should be recoded from scratch. *"Certainly, redirective practice does imply the acquisition of some new knowledge [...]. Sustain-ability clearly demands new understanding and values as well as new professional and political alignments to neutralize the defuturing content of what one already knows and does"* (Fry, 2009, p. 55). Although this is not always possible in the modern design industry – where designers' activities are mainly oriented toward the design of economically profitable products and communications according to the logic of capitalism – design must be understood as a broader practice that can address eco-social problems (Boehnert, 2018).

There are many approaches to sustainable design, and they have been influenced by modern history, environmental movements, new technologies, and social behaviors. Studies on design for sustainability have been, are, and will be extremely topical, albeit with limitations. Design for sustainability is at the core of this thesis, and its principles were followed throughout this study. The following paragraphs discuss the changing role of present-day designers and the different methodological approaches to sustainability. Product-Service System Design for Sustainability and Systemic Design are also analyzed

12 The World Design Organization (WDO) is a non-governmental organization that promotes the profession of industrial design. It has over 170 member and partner organizations coming from 40 nations. Members include private companies, designer associations, universities, and public bodies. The full definition of industrial design can be found on the World Design Organization website: wdo.org/about/definition/

Figure 2.7. The hand of Le Corbusier over the scale model of Plan Voisin, Paris, 1925. Reprinted from *Fondation Le Corbusier* website, 2020, retrieved from http://www.fondationlecorbusier.fr/ Copyright 1925 by Le Corbusier.

deeper, because are the approaches mainly adopted in the design phase of this thesis.

2.3.1 The changing role of present-day designers

Experts have been discussing the role, functions, and dynamics of design since its origins. Design, born and spread as industrial design and strictly related to the creation of mass-produced objects in the last century, has lived – and it is currently going through – significant cultural and formal changes. The rising of complexity as a decisive component of the world's phenomena, pushed design discipline gradually away from the modalities and the scopes of its earliest stages. In this way, design became something that may even seem very distant – and sometimes hardly ascribable – to its original area of expertise. The industrial attitude partly dissolved except, for example, for influential market segments like furniture, automotive, and textile, where it still holds a leading role. As Victor Papanek suggested, designers' work requires continuous analysis and conformity to its principles, together with a higher degree of responsibility (Papanek, 1973). Due to the somewhat reductionist origins, design discipline was probably mainly characterized by a short-sighted and incomplete vision. Today instead – and more than ever – the focus is pointed to the effectiveness of a responsible design that can lead to more significant benefits, and primarily driven by the urgency of responding to binding needs. Ecologically literate design is one of the means to respond to environmental problems and has to become a pedagogic priority in design education. Designing in such a responsible way is the only option to confront environmental

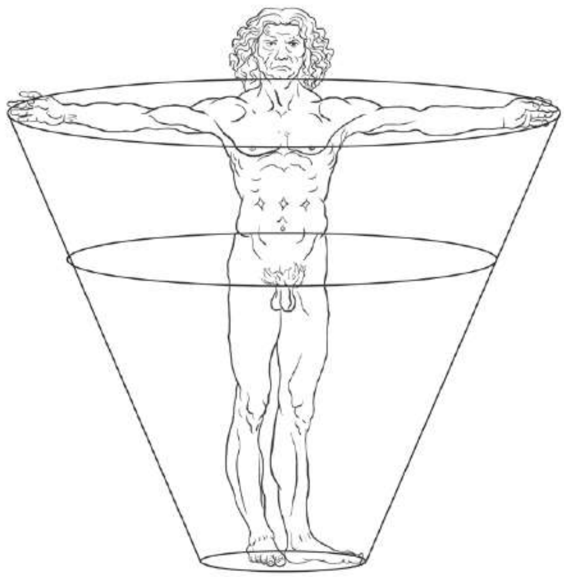


Figure 2.8. Prometheus dance. The upper part of the body traces a large volume that symbolizes the mediation between the disciplines. The lower part represents the scientific grounding. Designers work with humility in this system. Adapted from *Non industrial design. Contributi al discorso progettuale* (p. 101), by F. Celaschi, 2016, Bologna, Italy: Luca Sossella Edizioni. Copyright 2016 by Flaviano Celaschi.

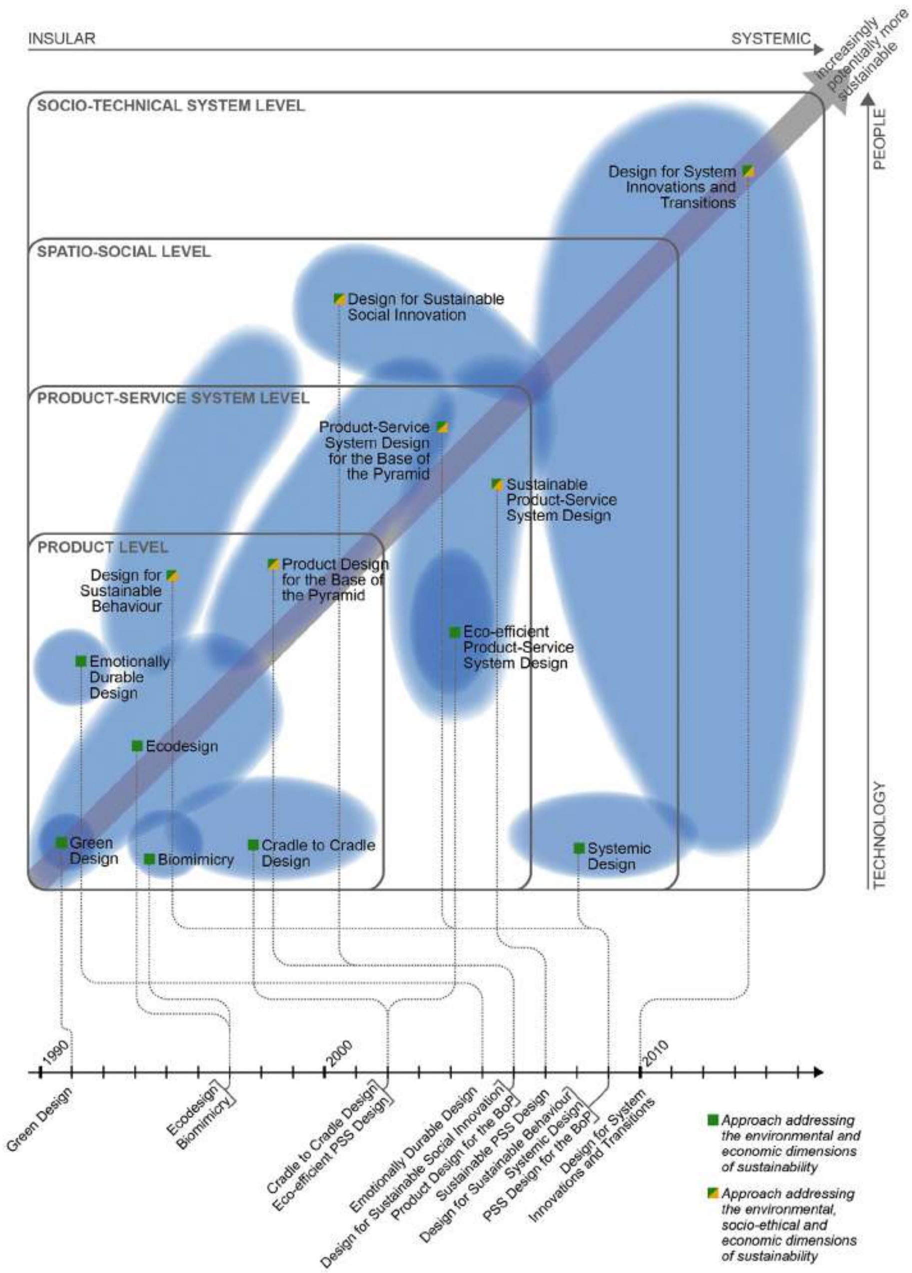
issues, transitioning from the Anthropocene toward the Ecocene[13] (Boehnert, 2018).

A dematerialization of doing design but also a conceptual opening and a growth of the subject is happening. Assuming a guiding position in the global scenario is an increasing responsibility of designers, who have to work together with other professionals. The design community has to become aware that it has come the time to relate more with other disciplines, broadening the gaze to complexity as a world-shaping force and trying to help explain it as such (Fry, 2009). The evolutionary phase that has invested design recently – as well as the framework in which all the sciences act – demands upgraded models. The way of carrying out these moves is a change at the methodological-operational level. The designer, born as a sole and independent author, has gradually abandoned his despotic and absolute aura[14] to assume the identity of someone who proceeds and looks for collaborations, as an interacting part

13 The concept of 'Ecocene' was coined in 2015 by Rachel Armstrong, design theorist and Professor of Experimental Architecture at Newcastle University. She opposed the excess of Anthropocene and Capitalocene to new ways of conceiving and managing design, architecture, and social and ecological relations, suggesting Ecocene as a curative catalyst for the cultural change needed for human survival.

14 The term 'Starchitect' is a portmanteau word used to describe famous architects or designers, who are at the center of public opinion for their projects or for their private lives. In the face of a few starchitects, there are many anonymous architects and designers who work in multidisciplinary teams. A famous photo represents the hierarchical and somewhat superior role that architects assumed, especially in the past. The photo pictures Le Corbusier's hand above the scale model of Plan Voisin, a visionary and disruptive planned redevelopment of the city center of Paris (1925). A single designer is able to shape the lives of millions of citizens (Fig. 2.7).

Figure 2.9. Design for sustainability evolutionary framework and action levels. Reprinted from “Evolution of design for sustainability: From product design to design for system innovations and transitions”, by Ceschin, F. & Gaziulusoy, I., 2016, *Design Studies*, *47*, p. 144. Copyright 2016 by Fabrizio Ceschin and Idil Gaziulusoy.



with other figures (Celaschi, 2016). The interplay is not only an internal necessity but a peremptory condition of its current being and the responsibilities of the design discipline. Design becomes an intermediary among disciplines for which new modalities of dialogue and common continuous knowledge turn out to be essential to deal with the complex challenges of today and tomorrow. Design is also profoundly based on scientific disciplines (Fig. 2.8). Design is shifting from being an elitarian practice to a universal tool that everyone can use to modify, improve, forecast, and create within a living world. Acting in design thus implies conceiving it as capable of systematizing worlds and strategies, considering the relations that influence and determine aspects, phenomena, and mechanisms. The transitions that are affecting the design world are the full expression of global dynamics. Signals of fluidifying processes among disciplinary boundaries are recognizable along with increasing multidisciplinarity and interdisciplinarity, indicators of a developing trend placed on a transversal, and permanent contamination among the branches of knowledge. Unfortunately, there is still a great conflict between the principles of design education and practices in the industry. *"The new generation of designers, trained in design research early in their careers, will eventually start to introduce changes to the profession [...]. This process is unlikely to happen overnight and the changes within the design education will need to be gradually introduced, but an evolution in the design profession through design education is inevitable"* (Muratovski, 2010, p. 385).

2.3.2 Design approaches and methodologies

There are multiple approaches and methodologies to Design for Sustainability. All these approaches tend to a common goal, with linkages, overlaps, and complementarities, but in some cases substantial differences. Over the decades, there has been a progressive transition toward the adoption of sustainable practices, and industrial designers had to reinvent their profession, albeit in part. The words of Victor Margolin – who was a great design theorist and Prof. Emeritus of Design History at the University of Illinois, Chicago – follow: *"The primary question for the design professions thus becomes not what new products to make, but how to reinvent design culture so that worthwhile projects are more clearly identified and likely to be realized. Just as other professionals are finding ways to earn their living in the culture of sustainability, so will designers have to do the same in order to create new forms of practice"* (Margolin, 1998, p. 86). Design practice and theory have advanced in parallel, however *"it was not before the 2000's that one could observe a significant effort in the development of concepts, models, tools and methods aiming at supporting industries and design professionals to include sustainability concerns in the product, service and (or) business development"* (Sousa Rocha, Antunes, & Partidário, 2019, p. 1429).

This section reviews the main approaches to Design for Sustainability, taking as reference the most recent studies conducted by Ceschin and Gaziulusoy (2016; 2020). The two researchers mapped the evolution of Design for Sustainability, taking into account four different innovation levels: Product, Product-Service System, Spatio-Social, and Socio-Technical System innovation level (Fig. 2.9). Within the product innovation level – an approach that is mainly limited to the development of new objects or the improvement of existing ones – there are Green Design, Ecodesign, Emotionally Durable Design, Design for Sustainable Behavior, Cradle-to-cradle Design, Biomimicry Design, and Design for the Base of the Pyramid. At another level and with a broader impact, Product-Service System Design for Sustainability, Systemic

Design, Design for Sustainable Social Innovation, and Transition Design. Below is a brief description of these approaches:

- **Green Design:** It is the earliest and preliminary form of Design for Sustainability. The main expedients consisted in reducing the environmental impact through the partial redesign of some components of the products, by adopting the reduce-reuse-recycle rule. The first examples date back to the '90s (Burall, 1991; Mackenzie, 1997).
- **Ecodesign:** Compared to Green Design, Ecodesign has a more structured approach. Its final goal is to minimize the use of natural resources (and the environmental impact), while maximizing the benefits for the customers. Guidelines and tools for Ecodesign were developed and consolidated between the years 2000 and 2010 (Bistagnino, 2008b; Tischner & Charter, 2001; Vezzoli & Manzini, 2008). Although Ecodesign is an interesting design approach, it has many shortcomings and a limited attention to human-related and social aspects.
- **Emotionally Durable Design:** In the attempt to extend the life of objects and the time of use by users, researchers have begun to study the relationships between humans and objects. Norman's studies (2004) are among the most significant about emotional design. The presence of emotions and personal sensations with the object and a high degree of customization allows reducing the semantic obsolescence of the product. However, manufacturers could be against such solutions as they could lead to a reduction in sales in the medium-long term (Mugge, Schoormans, & Schifferstein, 2005).
- **Design for Sustainable Behavior:** Researchers recognized that even if the product is designed respecting the strictest environmental sustainability criteria, the use by users plays a key role in the actual impact of the product (e.g., energy consumption, water, number of uses). In a recent study, the processes for applying behavioral economics and psychology to practical problems of product design are analyzed (Wendel, 2014). The topic of Design for Sustainable Behavior was further explored by Lockton (2013) in his doctoral thesis, in which the author proposes a toolkit for social and environmental behavior change.
- **Cradle-to-cradle Design:** It is an approach to design firstly theorized by McDonough and Braungart (2002) and based on the concept of eco-effectiveness, that mimics the regenerative cycle of nature and suggests that the industry must protect the nature's biological metabolism. In Cradle-to-cradle Design, products are conceived not only to be efficient, but essentially waste-free, because their parts are fully recyclable.
- **Biomimicry Design:** It is also known as Biomimetics and Bio-inspired design. Like Cradle-to-cradle Design, Biomimicry imitates nature's processes and materials, using nature as a model and mentor (Benyus, 1997).

Mimicks are various: forms, processes, and ecosystems can be inspiring for the design of products, buildings, and systems. However, mimicking or copying natural practices does not necessarily lead to sustainability and can be reductive, especially when inspiration is drawn only from forms and processes (Reap, Baumeister, & Bras, 2005). Biophilic Design, an extension of biophilia, is somewhat similar to Biomimicry and is a concept used in architecture to connect building occupants directly – or indirectly – with nature (Kellert & Calabrese, 2015).

- **Design for the Base of the Pyramid:** The poorest part of the global population is also the most vulnerable. Social issues are topics that deserve to be addressed by the design community of researchers and practitioners. Design for the Base of the Pyramid aims at finding frugal solutions to fulfill the basic needs of the people, such as education, public health, and access to food. Several contributions are coming from developing countries, as well as from developed ones (Kandachar & Halme, 2008; Karnani, 2011).
- **Product-Service System Design for Sustainability:** It is an innovative design approach for innovation, not only at the product level. LeNS (Learning Network on Sustainability) defined an eco-efficient product-service system as: *"an offer model providing an integrated mix of products and services that are together able to fulfil a particular customer demand (to deliver a 'unit of satisfaction') based on innovative interactions between the stakeholders of the value production system (satisfaction system), where the economic and competitive interest of the providers continuously seeks environmentally beneficial new solutions"* (Vezzoli, Kohtala, & Srinivasan, 2014, p. 31). Product-Service System Design for Sustainability is a well-established approach with a set of tools and methodologies adopted by researchers and practitioners worldwide.
- **Systemic Design:** It implies a reformulation of current socio-economic systems. A systemic design approach not only creates industrial products, but implements complex industrial productive systems with the aim of reaching zero emissions. This can be achieved through the redesign of energy and material flows, so that waste from one activity becomes input for another (Bistagnino, 2016). In recent years, numerous design projects have adopted a systemic approach. These focused on diverse topics including – but not limited to – food networks (Ceppa, 2010), industrial processes and water purification (Toso & Re, 2014; Toso, 2017), revitalization of internal areas through art and tourism (Degli Emili & Saracino, 2018; Menzardi, Peruccio, & Vrenna, 2018), exhibition and fairs (Bistagnino, 2009; Fassio, 2017), social inclusion and marginalization (Campagnaro, D'Urzo, & Pezzi, 2017).
- **Design for Sustainable Social Innovation:** It is a quite recent approach included in the broader topic of Design for Social Innovation, which is

	Product	Service	System	Behavior/ Education	Technology
Green design	+				
Ecodesign	+	+			+
Emotionally Durable Design	+			+	
Design for Sustainable Behavior	+			+	
Cradle-to-cradle Design	+				+
Biomimicry Design	+				+
Design for the Base of the Pyramid	+	+		+	
PSSD for Sustainability	+	+	+		
Systemic Design		+	+	+	+
Design for Sustainable Social Innovation		+	+	+	
Transition Design			+	+	

Table 2.1. The main action domains of each approach to Design for Sustainability. The ones adopted in this research are marked with a colored background.

defined as the creative recombination of existing assets, avoiding a sole techno-centric framing (Manzini, 2014; 2015). Social innovations are often emerging with a bottom-up approach from the communities. When it comes to design, the focus is usually on activities, experiences, events, services, and systems.

- **Transition Design:** In a world that is rapidly changing and in which desirable propositions for the future are necessary, Transition Design embodies the principles of Product-Service System Design and Design for Social Innovation to come up with disruptive solutions. Transition Design is a recent proposal of a new area of practice, study, and research, based upon long-term visions and challenging existing cultural, societal, and environmental paradigms (Irwin, 2015). This approach covers a vast area of action. Nevertheless, it is still more theoretical than practical.

These approaches to Design for Sustainability are unique and adopt distinct methods and methodologies. Table 2.1 concisely summarizes the main action domains for each design approach. Five domains have been determined: product, service, system (following the logic 'tangible-intangible' projects), as well as the behavioral/educational value of the project, and the technological component. Apart from Systemic Design, Design for Sustainable Social Innovation, and Transition Design, most of the approaches are linked – more or less directly – to physical objects' design. Different approaches operate within the service and spatio-social levels, such as PSSD for Sustainability, Systemic Design, and Design for the Base of the Pyramid, as well-argued by Ceschin and Gaziulusoy (2016; 2020).

Table 2.1 also displays the approaches used during this research, highlighting them with a colored background. For example, in the project development phase (see Chapter 8 – Project), recyclable materials were used under Cradle-to-cradle criteria, as well as design research tools typical of PSSD and Systemic Design. The behavioral/educational component of the project is essential. As will be seen later in the thesis, the project will use some typical Design for Sustainable Behavior expedients to guide users towards conscious and sustainable choices. Finally, the approaches of Design for the Base of the Pyramid and Design for Sustainable Social Innovation have been useful for creating integrated systems with a broader spectrum and for the benefit of local communities. In this regard, the developed project is based on replicability and openness to benefit as many people as possible.

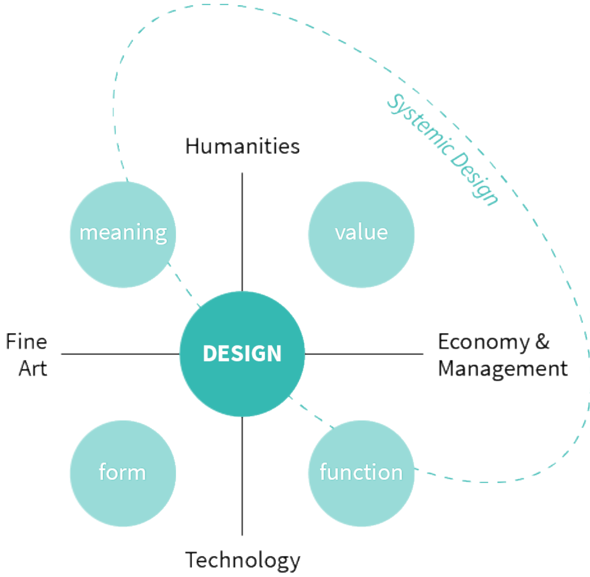
2.3.3 Product-Service System Design for Sustainability

Given the clear limitations of traditional product design to address broader sustainability issues, in recent years, more researchers have started to see Product-Service System (PSS) innovation as a promising approach. PSS is a way of combining products and services to fulfill the needs of the final customers or users (Tukker & Tischner, 2006). In a PSS project, the focus shifts from the sale of an object to its rental, with particular attention on the overall user experience. For example, a car is not considered as a status symbol, but just as a tool to offer efficient mobility to end-users. PSSs are complementary to solid business models and are increasingly popular in the sharing economy era. There is no doubt that this approach is valid for solving complex problems that have to deal with environmental sustainability.

Tischner, Ryan, and Vezzoli (2009, pp. 95-96) defined a sustainable PSS as: "*a system of products and services (and related infrastructure) which are jointly capable of fulfilling client needs or demands more efficiently and with higher value for both companies and customers than purely product based solutions [...] Appropriate system of products and services [...] could be commercially viable in the current or future market place and deliver more value to companies and customers (economic dimension). Decouple the creation of value from consumption of materials and energy and thus significantly reduce the life-cycle environmental load of current product systems leading to factor 4 to factor 10 improvements in eco-efficiency (environmental dimension). Fulfill client's demands in a more appropriate way and thus create better quality of life for all stakeholders (social dimension).*"

The tools of the Product-Service System Design for Sustainability are mostly the same as for PSS: diary, empathy, and ecosystem maps, interviews, cards, personas, journey maps, storyboards, stakeholders maps, system maps, synthesis walls, evaluation matrixes, product and service proto-

Figure 2.10. Design knowledge: Systemic Design operates in the fields of humanities and economics, to create valuable solutions. Adapted from *Design as a mediation between areas of knowledge* (p. 25), by F. Celaschi, 2008, Turin, Italy: Allemandi & C. Copyright 2008 by Flaviano Celaschi.



types, business model canvas, value proposition canvas, success metrics.[15] A Sustainability Design-Orienting (SDO) toolkit was developed by Carlo Vezzoli and Ursula Tischner and initially used also for a LeNS EU-funded project, to orient the product-system design process toward sustainable solutions.[16] The toolkit has a modular structure to be adopted in different circumstances. Its purpose is to define the design priorities for the three dimensions of sustainability (see section 2.1), stimulate the generation of ideas, and assess potential improvements of the new concepts compared to existing projects or solutions that were previously envisioned (Vezzoli, Kohtala, & Srinivasan, 2014). The toolkit provides a real-time visual radar chart that is pretty easy to understand. Multidisciplinary teams, rather than single designers alone, are advised to use the toolkit in their projects.

PSSD for Sustainability is a common approach worldwide, which also goes well with cultures other than the Western one. Design Matterology, for example, is a modern design science that emerged in China, and that pushes the boundaries of traditional product design to go beyond its conventional mean-

15 An updated set of Service Design tools is available at https://servicedesigntools.org/ The project started in 2009 with Roberta Tassi's graduation thesis entitled '*Communication tools for Service Design*', in collaboration with Poli.Design and Domus Academy Research Center in Milan. Politecnico di Milano has the first Specializing Master in Service Design in Italy.

16 LeNS (Learning Network on Sustainability) is an EU-supported project involving universities from Europe, Asia, Africa, and the Americas, to foster the transition toward sustainability through the education of aware and competent designers and design educators. More information at http://www.lens-international.org The SDO toolkit is available to use for free at http://www.sdo-lens.polimi.it

ings. It is defined as *"combining traditional Chinese thoughts with modern design ideas and [...] reflects the essence and connotation of sustainable design and sustainable PSS design [...] leading the innovative driving force of those internal factors and creating 'new' species, 'service systems' or Product-Service Systems"* (Guanzhong & Xin, 2014, p. 406).[17]

Most of the methodologies and tools for PSSD for Sustainability described in this paragraph will be widely used in the design phase of this thesis.

2.3.4 Systemic Design

Systemic Design is quite a new discipline. Particularly studied by Politecnico di Torino and few other universities worldwide, it is an approach to design, with particular attention to environmental sustainability. It started to thrive in the early 2000s in Turin, Italy with the first studies on eco-compatible materials and products by Prof. Luigi Bistagnino.[18] As research and practice advanced, in 2014, the name of the M.Sc. course in 'Ecodesign' changed into 'Systemic Design', to make the theoretical inspiration of this course even more recognizable. The course was named in honor of Aurelio Peccei, a visionary businessman and the founder of the Club of Rome. Today, systemic design has analogies with other design approaches and methodologies, including Ecodesign, Product-Service System Design, and Transition Design. It also has many similarities with the 'Blue Economy', an innovative approach to the economy – conceived by Gunter Pauli[19] – that is based on the imitation of the nature to find unconventional production techniques, towards zero emissions (Pauli, 2015).

17 During the literature review in the first year of Ph.D. studies, I had the opportunity to read the essay by Prof. Liu Guanzhong and Prof. Liu Xin. Their studies and the numerous connections with PSSD and Systemic Design fascinated me. I am happy to have had the opportunity to talk about these topics with them during the visiting study period at Tsinghua University in Beijing.

18 The systemic approach is adopted in design practice but even more in design research. Some universities conduct studies on the subject: Politecnico di Torino in Italy is the most prominent, with an entire M.Sc. course dedicated in teaching and researching systemic design, but also the Oslo School of Architecture and Design in Norway, and the OCAD University in Canada run a few courses in systemic design thinking. These institutions have joined up in a non-profit association called 'Systemic Design Association' (SDA) to facilitate the emerging systemic design practice and research community by advancing theoretical and practical knowledge in this field. The studies of Peter Jones (2014) and Birger Sevaldson (2011; 2017), among others, are also relevant and significantly contributing to the advancement of this discipline. More information about SDA at https://systemic-design.net

19 Gunter Pauli is a member of the Club of Rome, a successful entrepreneur, and founder of the Zero Emissions Research Initiative (ZERI). He received an honorary Master's degree in Systemic Design from Politecnico di Torino and works on sustainability projects all over the world. He is the author of a collection of children's stories that teach about sustainability and are translated in many languages.

In a systemic design approach, *"behaviours are the most important area on which we have to operate. Systemic approach positively realizes it impacting profoundly on how to activate new relations between subjects, to manage resources so that output of a system are the inputs of another one"* (Bistagnino, 2016, p. 21). Compared to other design approaches that are more related to fine arts and technology, Systemic Design bridges the fields of humanities and economics, to create valuable and sustainable solutions (Fig. 2.10). Systemic design is based on five fundamental principles which exist in nature, and can also be applied to anthropic systems. The guidelines were defined by Bistagnino (2011) and the Zero Emissions Research Initiative (ZERI). These are:

- **The outputs (waste) of a system become input (resource) for another system:** In nature there is neither trash nor landfill. It is, therefore, essential to get away from the idea of waste and consider it as a low-cost (or free) resource. The waste from industrial or agricultural productions – with due considerations – can be used for other industries and agriculture production. By exchanging a continuous flow of energy and matter between systems, it is possible to generate new production models, foster economies, and secure job opportunities for many. Different systems can interact with each other in a macrosystem.
- **Relations generate the system:** A system without relations would only be a non-functional set of elements. In systemic design, all system components have the same importance and are strategic. The qualitative relationships between parts (individuals, industries, companies, and institutions present on a given territory) provide strength to the system, creating new dynamic relationships both inside and outside it. Each system is unique.
- **Autopoietic systems sustain and reproduce themselves:** Biological systems can dynamically change and co-evolve, supporting each other and

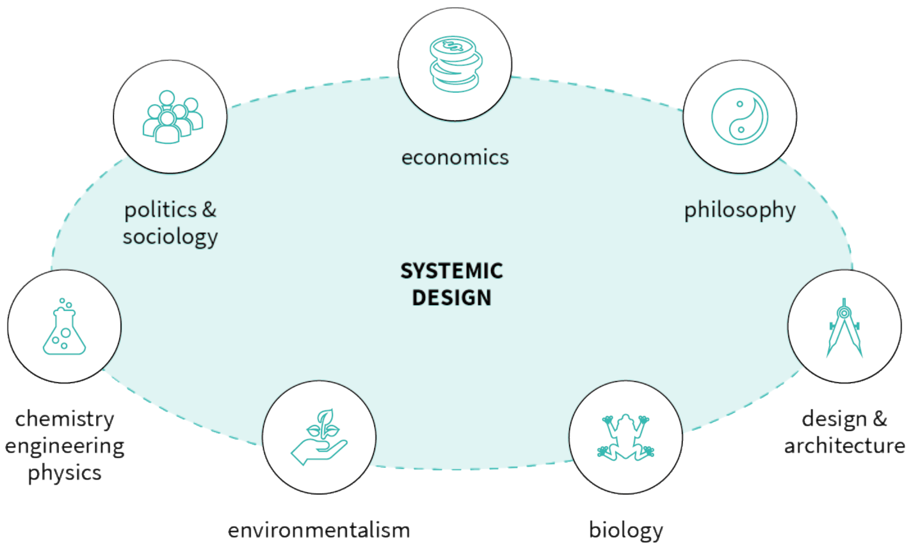


Figure 2.11. A systemic designer plays an interrelational role between disciplines and heterogeneous professionals, fluidifying boundaries while creating new connections. Adapted from "From 'The limits to growth' to systemic design: Envisioning a sustainable future", by Peruccio, P. P., Vrenna, M., Menzardi, P., & Savina, A., 2018, *Cumulus Conference Proceedings Wuxi 2018 - Diffused Transition and Design Opportunities*, p. 755.

reproducing. Similarly to natural systems, manufacturing facilities should cooperate and not compete with each other, to the benefit of all.

- **Act locally:** In an increasingly globalized world, it is of primary importance to act locally in order to scale, replicate, and adapt projects subsequently. The area of interest should be respected and enhanced. The social, cultural, and material resources onsite must be managed wisely to foster social development. These operations make it possible to counteract the decentralization of production, while preserving the tangible and intangible heritage of the area.
- **Humans connected to the environmental, social, cultural, and ethical context:** Systemic design focuses on the real needs of humans, who are firmly integrated within nature and not superior to it. Systemic designers intervene on processes, with particular attention to the relationships between communities and territory, the natural and the artificial, human and ecosystems. The development of products, services, and strategies should always keep the whole system in mind. For these reasons, inclusive and multidisciplinary approaches are necessary.

Addressing a systemic design project requires a certain degree of awareness and knowledge of the basic concepts of environmental sustainability. It also requires designers to make design decisions responsibly, in the interest of an entire community. It is necessary to think critically, casting doubts upon preconceptions and prejudices (Fig. 2.11). Working within multidisciplinary groups is recommended because it develops more ideas and observes the problem from multiple points of view, therefore improving productivity and results. The systemic approach is not complicated, and fledgling designers should not be afraid to try: following simple steps, it is possible to achieve excellent results. The methodology[20] that is suggested to systemic designers involves seven steps and is structured as follows (Battistoni & Barbero, 2017; Bistagnino, 2017):

1. Holistic diagnosis of the geographical area;
2. Analysis of each productive business;
3. Identification of problems;
4. Framing of opportunities;
5. Definition of a new systemic production model (Open system);
6. Definition of relations within a territory (Macrosystem);
7. Review of the outcomes generated.

In the first phase – the holistic diagnosis – a geographical area is chosen. The client, which can be a district, a municipality, a consortium of companies, or

20 Politecnico di Torino adopts this methodology in research and teaching. The students of the M.Sc. in Systemic Design 'Aurelio Peccei' learn it during their studies and put it into practice in real-world projects, Master and Ph.D. theses.

a region, usually makes this choice. Several hours of desk and field research are required to get a precise design scenario and to study the unique features of the territory. These include the total land area and the percentage allocated for agricultural use, the morphology, the number of inhabitants, the types of local flora and fauna, the productive and industrial activities, the traditions, the typical products, the foods, the architecture, and so on. The quality of the analysis must be high and as detailed as possible: while not all the data collected will be directly used in the design phase, these are essential to give significance to the final project. For a better understanding, it is suggested to visualize these data through infographics and collages of pictures like mood boards.

Afterward, the local productive activities are analyzed one by one. The companies can be of various types: factories, farms, cattle breeding, restaurants, markets and supermarkets, bars, bakeries, coffee roasters, distilleries. Each geographical area is unique and will have distinctive businesses, both in number and in typology (an area near the sea will most likely have multiple fish farms and fishmongers, while an inland area perhaps more grain crops). For each productive activity, the relationships that they have with the other activities, in a business-as-usual scenario, are drawn. It soon becomes clear that most suppliers, customers, and partner companies do not have direct relations with the local territory, as the supply of materials is usually coming from delocalized areas – international logistics platforms allow cheap goods to move quickly, despite contributing to emitting large quantities of CO_2 into the atmosphere. This analysis is relatively simple to conduct and permits to conclusively show that, overall, most of the current economic-productive supply chains function badly. With more specific analysis, the primary inputs and outputs for each productive business are outlined. The inputs include energy, water, and all the various resources necessary for the production of the goods; the outputs consist of both waste and the finished products. Waste could become a resource for another business. Considering that, in some cases, the production activities include several subsequent actions, it might be appropriate to analyze the input-outputs of every single step of the process. The same agricultural activities, for example, could have diverse inputs and outputs in different seasons and geographical places. These qualitative analyses, with the support of scientific literature and experts highlight the current problems of the production models. The most common are: the use of energy from non-renewable resources, the supply of material from non-local suppliers (with high environmental costs for transportation), waste of drinking water, use of highly-polluting production techniques, waste material that is not valued, loss of cultural and traditional heritage, but not limited.

The problems identified are opportunities and levers for change. The real systemic design project starts from here. In the design phase, it is essential to consider not only the quantity but also the quality of the inputs and outputs (if contaminated or not treated correctly, the waste from production is, unfortunately, unusable by others). Dynamically, the activities are connected to the others and arranged into an open system, optimizing the flows of matter and energy, and tending to zero waste. The open systems for each productive business are combined in a territorial macrosystem, in which all the activities – previously identified in the holistic diagnosis – are present and interconnected. The macrosystem is a conceptual scheme characterized by a dense network of connections: it does not exclude any activities or individuals. It is very balanced in its parts, which are not hierarchically ordered. The macrosystem is the ideal representation for territories in harmony with the production activities, the community, and nature (Bistagnino, 2016). To assess the validity of this model, the system outcomes are analyzed with the help of an economist. New activities generated are described in detail, and the reverberations on the local economy are traced. A shift from linear to systemic thinking leads to evident long-term benefits both for the individual activities and for the entire territory. A completely fresh and sustainable social, cultural, productive, and economic paradigm is therefore outlined.

2.3.5 The relevance of nature-based solutions

In recent years new sustainable practices linked to biological sciences are emerging in the world of design and architecture. Various interventions have involved the use of living organisms and biomaterials for the realization of projects on different scales, and nature-based solutions are gaining momentum. As discussed in the previous paragraphs, nowadays, design means conceiving products, systems, services, and experiences that lead to a better quality of life. Design should not have an anthropocentric vision anymore, and *"its methods should be aimed at [...] reintegrating our relationship with the environment and with all the species"* (Antonelli, 2019, p. 38).

For the first time, a radical approach to design is emerging. It draws on biological sciences and combines the use of living matter within products, structures, and processes (Myers, 2018): this approach is called Biodesign. Compared to other forms of sustainable design like green design and biomimicry, where the approach and inspiration are mainly form-driven[21], Biodesign implies cross-disciplinary collaborations with scientists, biologists, and engineers, in a way in which the incorporation of microorganisms results in an enhancement of the final work. Biodesign is a discipline that is not yet well

21 Drawing inspiration from nature is not recent. Already in the 19th century, Art Nouveau was breaking down traditional architectural and design canons (as well as graphic art, sculpture, jewelry, and furniture), and was influenced by natural forms such as flowers and plants. The forms were purely decorative and symbolic, with no particular other functions.

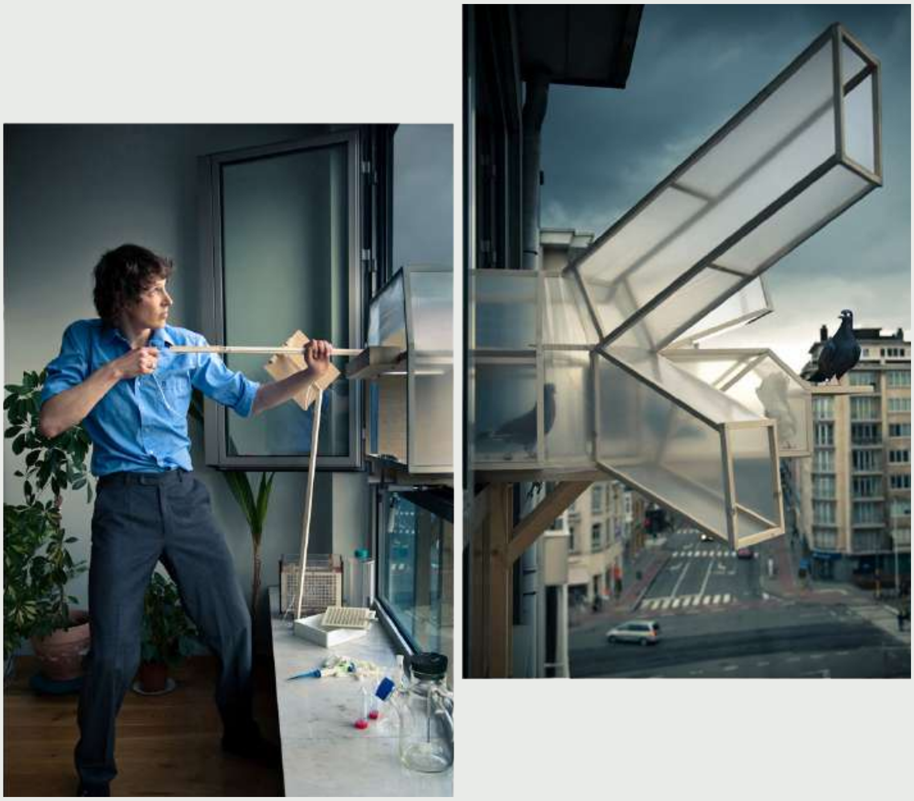


Figure 2.12. One of the installations from the project ‘Pigeon d'Or’. Reprinted from *Revital Cohen & Tuur Van Balen* website, 2010, retrieved from https://www.cohenvanbalen.com/wp-content/uploads/2012/09/pigeon-dor-1-2-full.jpg Copyright 2010 by Revital Cohen & Tuur Van Balen.

Figure 2.13. Local River by Mathieu Lehanneur, is a miniature fish-farm to be placed at home with both functional and decorative aspects. Adapted from *Biodesign: Nature+Science+Creativity* (p. 115), by W. Myers, 2018, New York, NY: MoMA. Copyright 2008 by Mathieu Lehanneur.

Figure 2.14. First generation of the Mycelium Chair, 3D-printed by Dutch designer Eric Klarenbeek. It is now part of the permanent collection of Centre Pompidou in Paris, France. Reprinted from *Eric Klarenbeek* website, 2011, retrieved from https://www.ericklarenbeek.com Copyright 2011 by Eric Klarenbeek.

Figure 2.15. Oyster-tecture by SCAPE Studio envisions the use of a human-made oyster reef to diversify marine life in the New York Harbor while purifying the waters. Reprinted from *Scape Studio* website, 2010, retrieved from https://www.scapestudio.com/projects/oyster-tecture/ Copyright 2010 by SCAPE Studio.

Figure 2.16. Dune project by Magnus Larsson Studio, London, United Kingdom. Adapted from *Biodesign: Nature+Science+Creativity* (p. 43), by W. Myers, 2018, New York: MoMA. Copyright 2010 by Magnus Larsson.

structured and with blurred boundaries by definition; nevertheless, its adoption is following an exponential trend. Not only designers are attracted to it but also scientists, who have the desire to leave their laboratories and have the opportunity to work on real-world projects, where they can apply and experiment with their discoveries and contribute by 'getting their hands dirty'. The impact of Biodesign on our present and future lives could be disruptive, as was mechanization in the 20th century – this is well described by Sigfried Giedion (1948) in the famous book 'Mechanization takes command'. Biodesign will probably be the next paradigm, in which biological processes will replace, at least partly, today's digital processes (Antonelli, 2018).

The approaches to Biodesign are quite different, and there are many overlapping elements, also with other forms of sustainable design. A first, albeit partial, exploration dates back to the 2008 'Design and the Elastic Mind' exhibition curated by Paola Antonelli, Senior Curator of the Department of Architecture & Design at MoMA in New York (Antonelli, 2008). In the following years, there have been several opportunities to discuss this matter, such as the Biodesign Challenge, a university competition for students to envision innovative applications of biotechnology in design practice, which this year celebrates the fifth edition.[22] In the field of research on Biodesign, are noteworthy the advancements of Neri Oxman, an American-Israeli Designer and Associate Professor of Media Arts and Sciences at the MIT Media Lab. Oxman is a curator and author of several publications in refereed journals and books, in which she has been investigating the new features of design at the intersection of technology and biology. Her areas of expertise include product, fashion, and architectural design, as well as technologies for digital fabrication. The most recent and complete publication dealing with themes, ethics, and collecting a wide selection of practical Biodesign projects, is the book 'Biodesign: Nature+Science+Creativity' by Amsterdam-based curator and teacher William Myers.[23] Furthermore, in 2019, the exhibition 'Broken Nature' at the XXII Triennale di Milano was curated by P. Antonelli, which was visited by thousands of people from all over the world.[24]

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22 The Biodesign Challenge (BDC) takes place every year since 2016. Students and mentors all over the world are invited to submit their projects. They gather at MoMA and at the Parsons School of Design in New York to showcase their works. Winners are selected by a panel of experts. The Biodesign Challenge is supported by governmental bodies, private companies, and foundations with interests in the fields of energy, biology, circular economy, and design. More information about BDC at https://biodesignchallenge.org/

23 Myers, W. (2018). *Biodesign: Nature+Science+Creativity*. New York, NY: MoMA.

24 The exhibition celebrated the contributions of architects and designers, at all scales and in all materials, to survive in the Anthropocene - or at least mitigate the risks. The exhibition catalog in Italian is Antonelli, P., & Tannir, A. (Eds.). (2019). *Broken Nature. XXII Milan Triennale*. Milan, Italy: Mondadori Electa.

Nature-based projects are very dissimilar, and cover scales from micro to macro. Although there are still no exhaustive studies on the methodological classification of nature-based solutions, it is good to know that these can be related to biomass, the design of objects, man-made structures, services, and finally, systems. Several designers have already showcased progressive solutions that involved the use of animals, plants, algae, mosses, fungi, bacteria, and other organic materials. Some examples are briefly described below. Pigeon d'Or by Revital Cohen & Tuur Van Balen (Fig. 2.12), is a series of installations that allow feeding the pigeons with a special yogurt, that gives cleansing properties to their feces. By defecating soap, pigeons could become city cleansers, rather than representing a threat, for instance, to historical monuments in city centers. In a domestic environment, instead, Local River by Mathieu Lehanneur (Fig. 2.13) is the provocative response to 'locavorism' (the preference of eating locally-sourced food). In essence, plants and fishes live together in a symbiotic relationship in a miniature aquaponics fish-farm, which could substitute traditional living room furniture. As for biomaterials, the Mycelium Chair by Eric Klarenbeek (Fig. 2.14), 3D-printed with living fungus, is significant. Klarenbeek has been developing this out-of-the-box technique since 2011, and it has been perfected just recently. Once dried, the chair is extremely lightweight, solid, and durable. Studies on Material Driven Design (MDD) can support designers in finding novel solutions for material in development (Karana, Barati, Rognoli, & Zeeuw van der Laan, 2015). MDD can also be applied with excellent results to the design with mycelium-based materials (Karana, Blauwhoff, Hultink, & Camere, 2018).

Designers and architects even addressed urban- and ecosystems- scale problems, such as the Oyster-tecture project (Fig. 2.15), which aims to block wave motion and purify the water of the channels of New York through a human-made reef of oyster colonies, and Dune (Fig. 2.16), a project by Magnus Larsson to transform 6,000 kilometers of Sahara desert into a habitable colony, to protect from desertification while housing thousands of climate change refugees in the future. To do so, the architect has been studying the reaction of a particular bacterium, which could transform sand into structurally-sound sandstone.[25] In the field of architecture, the Biodesign approach has also been used for the realization of biomimetic façades (Dollens, 2009; Marino & Giordano, 2015; Proksch, 2013; Tokuç, Özkaban, & Çakır, 2018). Biodesign has also influenced the world of art (Cogdell, 2011) and fashion (Stabb, 2015), among other fields.

If about ten years ago, researchers were discussing Bio fever experimen-

25 For more information about these projects visit the websites: www.scapestudio.com/projects/oyster-tecture/ and www.designboom.com/architecture/magnus-larsson-sculpts-the-saharan-desert-with-bacteria/

tations and profound changes expected in the way of doing architecture and design (Benjamin, 2011), now it is the time to train designers capable of imagining a more sustainable, fair, and resilient future. Biodesign is continuously evolving, but for the moment with evident limits: nevertheless, these represent enormous design opportunities. Central Saint Martins in London recently inaugurated a Master in Biodesign, as well as the Berlin-based AMD Akademie Mode & Design, which offers sustainability fashion classes with a particular focus on biomaterials (Bianchi, 2019). Other design institutions in Italy, Europe, as well as China, and the Americas, have incorporated innovative sustainability and biodesign courses into their curricula. However, the fundamental pedagogical objectives and methodologies are still to be perfected and deserve further investigation (Roshko, 2010).

Nature-based solutions, which are not only those objects made with biomaterials, are incredibly topical both in research and in practice, and this is not only a temporary trend: it will probably last for the next decades. To conclude, *"using technologies, designs, and models that integrate nature into bio-activity in a way that is beneficial to both ecosystem and humanity, whether by bacteria or by fungi embedded in infrastructures or algae generating our energy, may be considered as the best, smartest, and most applicable way to avoid global ecological ruin"* (Deniz & Keskin-Gundogdu, 2018, p. 73).

2.4 Remarks

This chapter consists of a literature review on the topic of sustainability and the different approaches to sustainable design. This part of the research has been conducted mainly during the first year of the Ph.D., although it was periodically updated also with general news taken from newspapers and websites and not only from academic databases. It is from this chapter that it is possible to deduce the approach to research and the thoughts behind some design and methodological decisions that will be addressed later in the thesis. It is also clear that this research field is and will continue to remain current in the next future.

Today sustainability has become an imperative, not only to reduce waste, pollution, or to safeguard biodiversity, but primarily to mitigate the risks that our societies will be facing. During crisis – such as the recent COVID-19 outbreak but also the climate emergency – radical, innovative, and game-changer solutions are needed. The design community is called to respond with concrete, but at the same time, visionary projects that can be implemented relatively simply and that follow methodological rigor. Academia can – and must – put its scientific research at the service of society. As far as food production is concerned, the food needs of a growing number of people must undoubtedly be met: novel foods, including algae and microalgae, represent viable solutions which, however, will inevitably find resistance to broad adoption.

There are many approaches to sustainable design. The goals, the methodologies, and the methods are, however, similar and, in some cases, identical. Systemic Design, Product-Service System Design for Sustainability, and Biodesign are valid and complementary approaches that are adopted in this research. These approaches do not consist only in the design of products – which is reductive – but also in the design of experiences, services, and innovative complementary systems that can bring real well-being. In the field of sustainable design, microalgae-based solutions are not yet widespread, except for some experimentations. Also, as regards academic research, the contributions are still quite limited.

Sustainability is a broad theme which, in this research, collects the other domains of investigations, of which design is part. The next chapters will deal with the themes of novel foods and superfoods, and cities as places where it is necessary to operate as they are a key to sustainability. Moreover, chapter 6 – Design and microalgae investigates the relationships between the discipline of sustainable design and phycology.

CHAPTER 3

Feeding the world

This chapter presents only the peak of the iceberg of one of the biggest threats to the planet that humanity will face in the decades to come[1]. Nevertheless, it traces the perimeter of this thesis's research, limiting it to the theme of food, but without excluding other possible applications. Today's world is very different from just a hundred years ago, and the environmental challenges posed by agriculture will become more pressing as we try to meet the growing global food demand. As mentioned in chapter 2, the United Nations (2015) have set the Sustainable Development Goals. The goals no. 2 (Zero Hunger), and 3 (Good health and well-being) are critical: a radical change must comply with these guidelines and in a common global interest.

Present-day food systems have multiple shortcomings: millions of people die every year in developing countries due to malnutrition; on the other hand, in the richer countries, obesity is a problem that afflicts an increasing number of patients and a burden for health systems. With the advent of large-scale supermarkets, uncurbed urbanization, and social inequalities, the so-called 'food deserts' – typically urban areas of large cities, inhabited by groups with reduced economic availability, where there is no access to fresh, healthy, and

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1 Part of the work described in this chapter was also previously published in: Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019.

Figure 3.1. One of the original promotional posters for the movie Greenberg, S. R., & Harrison, H. (Writers), & Fleischer, R. (Director). (1973). *Soylent Green* [Motion picture]. United States, CA: Metro-Goldwyn-Mayer. 9 May 1973. Adapted from IMDb website, 2019, retrieved from https://www.imdb.com/title/tt0070723/mediaviewer/rm1286799360 Copyright 1973 by Metro-Goldwyn-Mayer.

nutritious food (Shaw, 2003; 2006) – are present in large numbers in America, Africa, as well as Europe. Furthermore, food waste is not only an economic and ethical problem, but it also depletes natural resources. Feeding the world is a real challenge for this century, but especially ensuring proper nourishment for the exponentially-growing global population. Today, the most recent United Nations reports confirm the population growth trends. *"The world's population reached 7.7 billion in mid-2019, having added one billion people since 2007 and two billion since 1994. The global population is expected to reach 8.5 billion in 2030, 9.7 billion in 2050 and 10.9 billion in 2100"* (United Nations, 2019, p. 5). The regions of Sub-Saharan Africa and Central and Southern Asia will be profoundly affected. Urban areas are – and will continue to be – the most densely populated.

The first essay that suggested the exponential growth of the world population is attributable to Thomas R. Malthus, an influential English economist in the fields of political economy and demography. At the end of the 18th century, Malthus claimed that population and food were growing at a different ratio. When unchecked, the population was increasing geometrically (exponentially), while the subsistence for the man – e.g., food – arithmetically (linearly). If not properly controlled, this mechanism would inevitably have led to poverty and famine (Malthus, 1798). In the last century, there was a neo-Malthusianism revival: for instance, after disclosing the first reports of the Food and

Agriculture Organization of the United Nations in the post-war period, which suggested the need to prepare for harder future decades (FAO, 1947). The publication of best-selling books like ‘The population bomb’ by Stanford University Professor Paul R. Ehrlich (1968) and ‘The limits to growth’ (see paragraph 2.1.2) ignited the debate too.

The governments and academia mainly addressed the problem of ‘how to feed the planet’, but also public opinion. Several journalists and celebrities wrote and talked about this topic: it was also a recurrent theme in film production. For example, in 1973, film director Richard Fleischer presented ‘Soylent Green’, a film that met mixed reactions from critics[2] (Fig. 3.1). This dystopian thriller’s story is set in the year 2022 in New York, an overpopulated city with more than 40 million inhabitants living in deplorable conditions. Homes, water, and food are difficult to find, and the population perpetually organizes riots, which are promptly suppressed by the police. Euthanasia is legal, and temple-like facilities are set up, where the older population is invited to go to die comfortably. The wealthiest can afford to eat fresh meat and fruit only occasionally: for everyone else, the only resource left is Soylent. Soylent is a green and allegedly plankton-based nutritious and high-protein bar, produced by a multinational company and sold to the population at tiered prices. The protagonist of the film will soon realize that Soylent bars are actually made from the remains of human corpses. Although macabre, watching this movie is recommended because it brings out the most ancestral fears of humankind, namely the death and the shortage of basic life needs, including food. Fortunately, the future imagined by the director has not yet arrived.

Figure 3.2. Just close your eyes and chew. An article by Eric Perlman on the San Francisco Examiner. Adapted from *Algae Industry Magazine* website, 2011, retrieved from https://www.algaeindustrymagazine.com/special-report-spirulina-part-2-first-human-consumption-and-cultivation/ Copyright 1977 by Eric Perlman.

Less dystopian, but somewhat provocative, was the article written by journalist Eric Perlman on the San Francisco Examiner in 1977, entitled ‘Just close your eyes and chew’. Dragged by the hype around the novel microalgal research (the first scientific studies on microalgae and their potential in the food and industrial fields began in the 1950s and were widely subsidized by governments), the author hypothesized that microalgae would become the food of the future because they can grow rapidly, produce more food, and purify the human body better than other foods. The illustration on the cover showed a table set with a plate of *Spirulina* strains seen under a microscope (Fig. 3.2): it was a particularly objectionable picture for that time.

3.1 A new green revolution

With the beginning of agriculture and cattle breeding, humanity has started uncontrolled exploitation of natural resources. “*It took almost 10,000 years for*

2 Greenberg, S. R., & Harrison, H. (Writers), & Fleischer, R. (Director). (1973). *Soylent Green* [Motion picture]. United States: Metro-Goldwyn-Mayer. The screenplay was based on the novel ‘Make room! Make room!’ by H. Harrison, published in 1966.

food grain production to reach 1 billion tons, in 1960, and only 40 years to reach 2 billion tons, in 2000. This unprecedented increase [...] has been named the 'green revolution'" (Khush, 2001, p. 815). The beginning of the green revolution occurred between the '40s and '70s of the last century and testified a spectacular increase in the production of some products, including rice, wheat, and corn. The revolution has been possible through the use of new technologies, disruptive agronomic practices, the creation of genetically-improved crop varieties, and the extensive use of fertilizers and pesticides. This 'miracle' permitted to rapidly meet the food needs of a growing population, especially in some of the most impoverished areas of the planet, by lowering the production prices considerably, and we are still benefitting from it today (Fig. 3.3). However, after a few decades, the downsides of this progress are increasingly evident: biodiversity loss; dependence on fossil fuels; contamination of groundwaters, rivers, streams, and lakes; soil degradation; dependence on the use of GMOs; damage to small farmers; centralized seed control by large multinationals. According to many experts, *"it is unclear whether high-intensity agriculture can be sustained, because of the loss of soil fertility, the erosion of soil, the increased incidence of crop and livestock diseases, and the high energy and chemical inputs associated with it. The search is on for practices that can provide sustainable yields, preferably comparable to those of high-intensity agriculture but with fewer environmental costs"* (Tilman, 1998, p. 211).

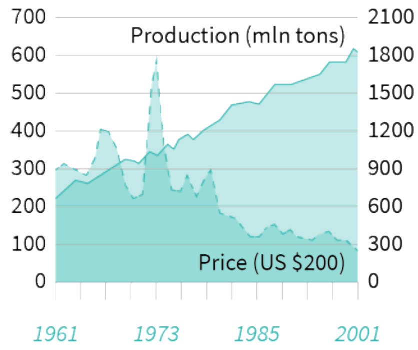

Figure 3.3. The impact of green revolution. Production of unmilled rice (left axis) and its price from 1961 to 2001 (right axis). Adapted from "Green revolution: The way forward", by G. S. Khush, 2001, *Nature*, *2(October)*, p. 816. Copyright 2001 by Gurdev S. Khush.

In light of the problems exposed and for many years, the scientific community has sought alternative solutions to feed the growing world population. A new green revolution is needed now more than ever before. *"Population growth, ongoing soil degradation and increasing costs of chemical fertiliser will make the second Green Revolution a priority [...] in the 21st century"* (Lynch, 2007, p. 493). A new green revolution will feature a fresh approach to problems. It will focus on chemical and technological improvements, but also on supply chains and behavior change, acting on a few points (Foley, 2014):

- **Stop agriculture's footprint:** Avoiding deforestation is a priority. Humanity can no longer afford to expand agricultural areas but has to protect forests and grassland.
- **Increase current productions:** Organic farming, high-tech, and precision farming systems could increase yields in farmlands that are not 100% productive.
- **Use resources efficiently:** In this case, technology helps too. For instance, drones, sensors, and GPS systems could provide data to increase productivity. Practices like subsurface drip irrigation and organic farming are also recommended to reduce waste.
- **Change diets:** A radical change in food habits is needed, especially in wealthier countries. More than 35% of the world's crop calories are used to feed livestock, but only a small fraction of these calories make their way in

our bodies. Consuming chicken rather than beef would notably reduce the amount of land and water needed for animals to grow. Adopting a vegetarian/vegan lifestyle could ultimately enhance food availability for all.

- **Reduce waste:** It is estimated that 50% of the total food weight is wasted (or lost) before being consumed. Food waste happens in homes, restaurants, and supermarkets, but also due to deficiencies in the supply chains, even in developing countries. Simple actions like serving smaller portions or providing 'doggy bags' for leftovers to clients could have a significant impact.

Producing qualitatively nutritious food in sufficient quantities for humankind is a tremendous challenge. Changing the eating habits and traditions of billions of people is even more demanding. This issue was discussed during EXPO 2015 'Feeding the Planet, Energy for Life' in Milan, Italy (May 1-October 31, 2015). In the light of a new global scenario and emerging trials, the exposition developed a few sub-themes, including science for food safety, innovation in the agro-food supply chain, healthy food for better lifestyles, and technology for agriculture and biodiversity, among others. The participating countries have selected contributions from various experts in biology, agronomy, nutrition, economics, medicine, engineering, and design, producing futuristic exhibition pavilions, and showing radically innovative solutions. The universal exhibition was a moment of exchange, spreading of knowledge, and a vector of innovation, which planted the seeds for a new sustainable food revolution. To date, governments, private research institutes, and venture capitalists are investing money and resources also in research and development for the production and marketing of healthy, tasty, low environmental impact novel foods that are easy-to-eat and to introducing in our diets. Novel foods are part of a fascinating field of study that deserves to be explored.

3.2 Future food today

Distinguished journalist, author, and professor Michael Pollan (2008) in his book 'In defense of food' explored the socio-cultural impacts of food in relation to modern industrial chains and agribusiness. The author asserts that we should be skeptical of certain foods – especially those produced industrially – and eat only those that our grandmothers would recognize as such. This statement is reasonable considering that our relationship with food has changed considerably over the millennia, but mainly in recent decades.

However, a scientific debate has recently started, which has also aroused a great interest in public opinion: food futurologists are convinced that the food we will eat in the coming years will be very different from what we have been used to until now. Novel foods will become part of our diets, replacing, at least in part, some of the most common ingredients. "*'Novel foods' constitute a food regulatory construct employed in many countries […] and are referred to as 'new*

Figure 3.4. A California-based startup created an hydroponic farm run entirely by robots. Adapted from *Iron Ox* website, 2019, retrieved from https://ironox.com Copyright 2018 by Iron Ox.

Figure 3.5. Beyond Meat plant-based burger: the patty is made up with a mixture of legumes and rice. Adapted from *Usa Today* website, 2019, retrieved from https://eu.usatoday.com/story/money/2019/06/11/beyond-meat-launches-new-meatier-version-plant-based-burger/1426235001/ Copyright 2019 by Beyond Meat.

Figure 3.6. A wide range of meal replacements offered by Soylent Nutrition. Adapted from *Soylent Nutrition* website, 2019, retrieved from https://soylent.com Copyright 2019 by Soylent Nutrition.

dietary ingredients' in the United States. Novel foods include foods and ingredients that have not been used to any significant extent in a particular country prior to a specific date specified in a food regulation. Novel foods include pure chemicals, genetically modified foods, cloned animals, whole foods new to a particular world region, and foods processed by a new technology. Assurance of safety and nutritional quality of the food supply are key reasons for the regulation of novel foods" (Hendrich, 2016, p. 79).

This paragraph illustrates some of the most relevant and innovative production techniques and novel foods: algae and microalgae will have a dedicated paragraph. Hydroponic farming, for example – a method of soilless farming using mineral nutrient solutions in water – is a real revolution. This method is not so new and permits to save a high percentage of water, which would be dispersed with traditional cultivation methods. It also permits to minimize the space needed for production, because many types of plants can be grown on multiple levels on shelves. The most hydroponically grown plants for food use are lettuces, peppers, tomatoes, and cucumbers. The global hydroponics market is forecast to grow multifold in the next few years, especially for the advancement of technologies and automation. The growth is also attributed to the increasing population and growing demand for sustainably-produced foods (Statistics Market Research Consulting, 2017). Among the companies that grow in hydroponics, Iron Ox stands out, a Californian startup that has created a fully-autonomous farm run by robots (Fig. 3.4). The robots use Artificial Intelligence to remove infected plants and optimize productive cycles while controlling nutrients. The startup grows non-GMO, pesticide-free fresh produces, and managed to raise more than $ 6 million in seed funding in 2018 (Brigham, 2018). Hydroponics farming is an excellent opportunity for food production in urban areas, as well as community gardens, vertical farms, and farmers' markets because spaces are limited, and the local production can meet the needs of the neighboring population – or at least part of it.

With a growing number of people interested in reducing or eliminating meat consumption – for health, nutritional, or ethical reasons – many consumers have started eating substitutes. The plant-based meat market is, therefore, also booming. Plant-based meat is created to mimic the properties found in natural meat: color, consistency, taste (Fig. 3.5). The main ingredients of these products are highly nutritious, i.e., legumes (mainly soybeans and lentils), wheat gluten, and tofu. Plant-based meat is less input-intensive than traditional meat and requires minimum water for its production. The best-known brands are the Americans 'Impossible Meat' and 'Beyond Meat', and 'OmniPork' (新猪肉) that recently entered the Chinese market (Schmidt, 2020). Their products are quite successful and attracted the curiosity of both meat-eaters and flexitarians.[3] The leading fast-food companies are also interested in adding some of these products to their menus, and, in the last year, tests and partnerships have been made with Burger King, KFC, and Taco Bell (Carman, 2019; Lamb, 2019; Villas-Boas, 2019).

Food supplements and meal replacements (drinks, tablets, or soups intended as a substitute for a solid meal, usually with controlled quantities and nutrients) are also particularly appreciated by consumers who are more attentive to a balanced diet. Many companies are offering this type of product, but Soylent Nutrition stands out in a crowd.[4] The company started in 2014 after a successful crowdfunding campaign, and it is named after the 1973 movie 'Soylent Green'. The company offers meticulously-blended drinks and foods with complete nutritional values, which are particularly appreciated by athletes and health-conscious people. The company claims that its drinks host health benefits because of the perfect nutrient balance, providing greater control over people's nutrition. The wide range of products are packaged in eye-catching and convenient formats (Fig. 3.6): products are ready-to-drink or eat, use plant-based protein, do not require refrigeration, and are highly customizable. The company also collaborates with local NGOs to distribute meals to people in need.

There are many other novel foods, including insects. Certain insects are considered a delicacy in some Asian countries, and due to their high protein content, they may be integrated into more familiar products such as flours and snacks. "*Insects represent an edible material of great potential interest for food scientists. They are able to convert in a very efficient way waste biomasses into proteins, lipids and polysaccharides. Despite the cultural barriers related to their consumption, scientists and policy makers concurred in considering insects as one of the best opportunities to cope with the need of feeding humanity in the future*" (Fogliano, 2014, p. 11). Several studies are also being conducted on lab-grown meat, a promising form of cellular agriculture for producing meat in vitro, rather than slaughtering animals. The price of this meat is still high – despite a quick price fall in recent years – and its production still raises several ethical issues. However, this trend is gaining momentum, and it may be better for the environment, also improving on several health aspects of conventional meat (Wiley, 2019). The production of highly-nutritive mushrooms and other microorganisms is another hot topic.

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3 I had the chance to taste some of these products for the first time during the event Veggieworld Beijing at Beijing International Convention Center on November 8, 2019. I was particularly impressed with the consistency and flavor of plant-based burgers and nuggets, almost indistinguishable from that of the animal-based ones.

4 Up to now, products are available to purchase only in the United States, Canada, and the United Kingdom. For more information visit Soylent website: https://soylent.com

3.2.1 Superfoods and novel foods

What are superfoods? The thesis raises this question, and so far, superfoods were only mentioned in the introductory chapter. Superfoods are foods that stand out more than others for their exceptional nutritional profiles. The term 'superfood' is on everyone's lips: magazines, television, advertising, and online blogs. However, there is no universally recognized legal or scientific definition for it (CBI, 2015). *"Superfood is a marketing term promoting certain foods that are associated with high concentrations of vitamins, minerals, fibers, essential fatty acids, or antioxidants [...] which '[Westerners] are having a wild love affair with'"* (Schiemer et al. , 2018, p. 218). For these reasons, it is a word that does not seem to be going anywhere anytime soon.

The list of superfood-labeled food items is long, but keep in mind that there is a 'superfoodization' redundancy, especially in Western markets. Many of the superfoods we hear about do not have 'super' properties, and experts even argue that there are no superfoods at all because real whole foods are the only superfoods per se. Besides, single superfoods cannot replace a well-balanced diet. Shopping locally-produced, seasonal products, and cooking at home using less oil and salt is eventually the only way to eat real superfoods (Kay, 2017). For reference, some of the most popular and recognized superfoods and their properties are reported here: blueberries (rich in vitamins, soluble fibers, and phytochemicals); kale (loaded with vitamins A, C, and K, and many other minerals); nuts (high levels of minerals and healthy fats); salmon (rich in omega-3 fatty acids); avocado (rich of healthy monounsaturated fats, it protects against metabolic disorders); goji berries (low in calories, help reduce the oxidative stress in our bodies); quinoa (a pseudo-grain that helps improving blood lipid profile and prevent weight gain), among many others. Some other products are claimed to be superfoods but are not. For instance, coconut oil (its consumption may raise total cholesterol levels); almond milk (a lot of the nutrients are lost during processing); honey (overeating sugar is not suitable for a healthy diet); wheatgrass (no scientific studies showed its ability to prevent or treat cancer); etc. So, superfoods not only come with a biased public perception, but a general criticism is that even if the food itself is healthy, its processing might not be (Kay, 2017).

Among the many superfoods, some have already been used in local/traditional diets, while others are entirely novel. As mentioned in the previous paragraph, novel foods are particular because they are innovative from a production/nutritional perspective and never (or rarely) used in the cuisine. Some novel foods are going to be the foods we will eat daily in a few years. The most promising future novel superfoods are meal replacements, plant-based meat, lab-grown meat, insects, mushrooms, seaweed, and microalgae. Table 3.1 shows a comparison between them and underlines why this thesis focuses on microalgae, an up-and-coming ingredient. Different parameters were taken

	Meal replacements	Plant-based meat	Lab-grown meat	Insects	Mushrooms	Seaweed	Microalgae
							
Type	synthetic	synthetic	synthetic	natural	natural	natural	natural
Presence in diets	yes	partly	no	partly	yes	yes	partly
Nutritional value	●●●	●●●	●●	●●●	●●●	●●●	●●●●
Acceptance	●●●	●●●	●●	●	●●●●	●●●	●●●
Palatability	●●●●	●●●	●●●	●●	●●●●	●●	●●
Ethical/Cultural issues	no	no	yes	yes	no	no	no
Production price	●●●	●●●	●	●●●	●●●	●●●	●●●
Consumer price	●●	●●	●	●●●●	●●●	●●●	●●●
Processing difficulty	●●	●●	●	●●●	●●●	●●●●	●●●●
Sustainability	●●	●●	●●	●●●	●●●●	●●●●	●●●●
Chance of diffusion	●●●●	●●●●	●●	●●	●●●●	●●●●	●●●

Table 3.1. The most promising future novel superfoods: a comparison.

● = very poor ●●●● = very good

into consideration for this comparison. Some have been quantified on a scale of 1-4, where 1 is generally very poor, while 4 is very good.

- Type: synthetic or natural;
- Presence in diets: if the food is already present in today's diets or not and if so, its degree of diffusion;
- Nutritional value: the amount of protein in percentage (compared to microalgae that have the highest protein value)
- Acceptance: the degree of acceptability. For example, the appearance of insects could be a barrier to adoption in Western countries, as well as the atypical color of microalgae;
- Palatability: if the food taste is overall pleasant (or if the palatability may be an obstacle to the diffusion);
- Ethical/Cultural issues: the production or consumption of particular foods could be taboo in some cultures and also carry ethical implications (e.g., consumption of lab-grown meat);
- Production price: current production price, ranging from affordable to very expensive (where 1 = very expensive and 4 = affordable). This data does not refer to a particular regional area, but it is quite generic;
- Consumer price: current consumer retail price, ranging from affordable to very expensive (where 1 = very expensive and 4 = affordable). Also, this data does not refer to a particular regional area;
- Processing difficulty: the number of operations needed and their complexity, ranging from very easy to very difficult (where 1 = very difficult and 4 = very easy);
- Sustainability: generally speaking, it includes the environmental sustainability of production and processing (including industrial processing), or any benefits and downsides;
- Chance of diffusion: the possibility that the product will become part of our daily diets in the coming years, based on current scientific research, perception, current market dynamics, and forecasts.

Based on the considerations in Table 3.1 – which has a purely demonstrative purpose – it is clear that microalgae are an extremely promising superfood because it is a natural and sustainable product already partially used in our diets (and with a diversified use throughout history). Their nutritional value is high in the face of limited production costs. Although palatability could be a barrier to adoption, microalgae consumption does not imply ethical-cultural issues and can, therefore, be consumed anywhere in the world. The chances of microalgae becoming part of our diets in the coming years are pretty high.

3.3 Algae and microalgae: Solutions to food shortage

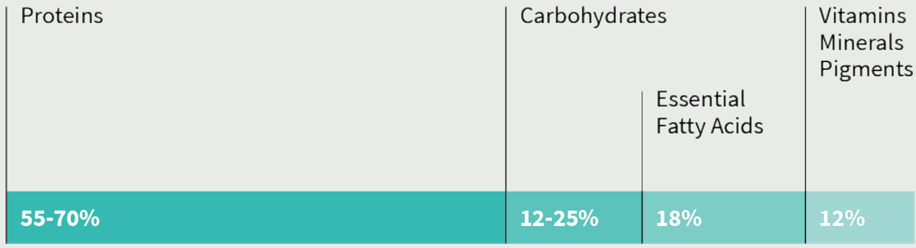
Algae are excellent natural resources, with a potential that is still mostly underused in several fields.[5] *"It may still be a long way for seaweed enthusiasts [...] to fundamentally change the way we eat. And whether seaweed will become the bread and butter of our children, or the biofuel of our future, we are not able to predict. But one way or another, seaweed will one day change the way we live"* (Thies, 2013, 19:45). There are many edible algae: Kelp, Kombu, and Nori are the most widely used, especially in Asian cuisine.

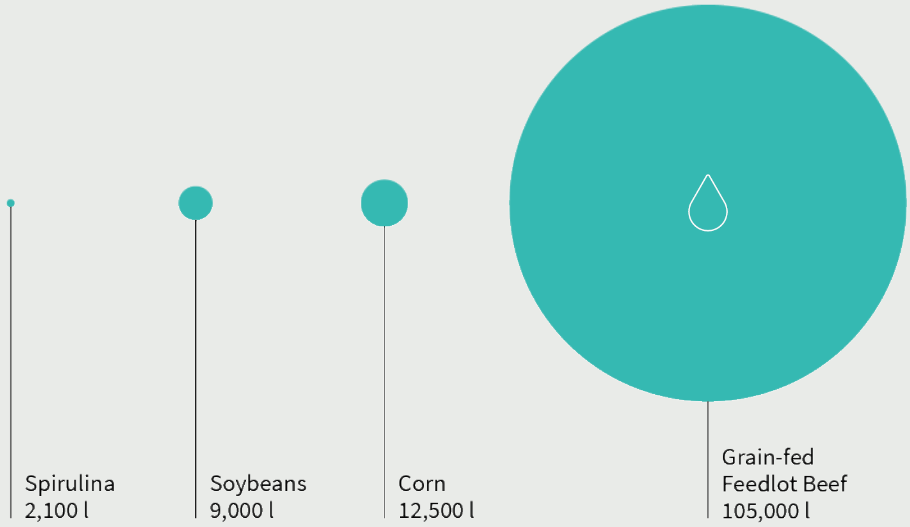
Some of these are considered real 'superfoods', used in many recipes, and natural remedies in holistic medicine (Arndt, 2014). Algae and microalgae are considered the future foods even by expert chefs and nutritionists who work with the UN (see Appendix: A chat with Lee Yi-Wen). Given the unique nutritional properties of algae for human consumption – but not only – seaweed production is undergoing rapid expansion, raising new challenges for producers and the environment. *"Global seaweed cultivation industry has been driven by the growing demand for contaminant-free seaweed and by the commercial sector requiring seaweed-derived products for biotechnological, and medical applications in countries with little traditional interest in seaweed aquaculture or consumption"* (Cottier-Cook et al., 2016, p. 3). The world production of marine seaweed has more than tripled since 2000 (FAO, 2020). Although production occurs mainly in Asia, particularly in China, the interest in this novel food is high even in Western countries – where algae are not yet widely used in traditional recipes. For example, *"the Dutch government prefers to grow it [algae] in its own sea. It is convinced that investing in seaweed can ultimately be a good deal for the environment, and therefore also for health"* (Giannini, 2017, 07:31). Small and large companies worldwide are at the forefront of algae cultivation for the most diverse purposes. Marine algae agriculture – even in 3D on multiple levels – could be a solution to food shortage. Cultivations of highly nutritious and proteinic algae could replace soybean crops and ultimately contribute to the ocean ecosystem's recovery. This practice could guarantee astounding effects with tangible results, allowing millions of people to escape poverty and hunger, even in a relatively short time (Pauli, 2017).

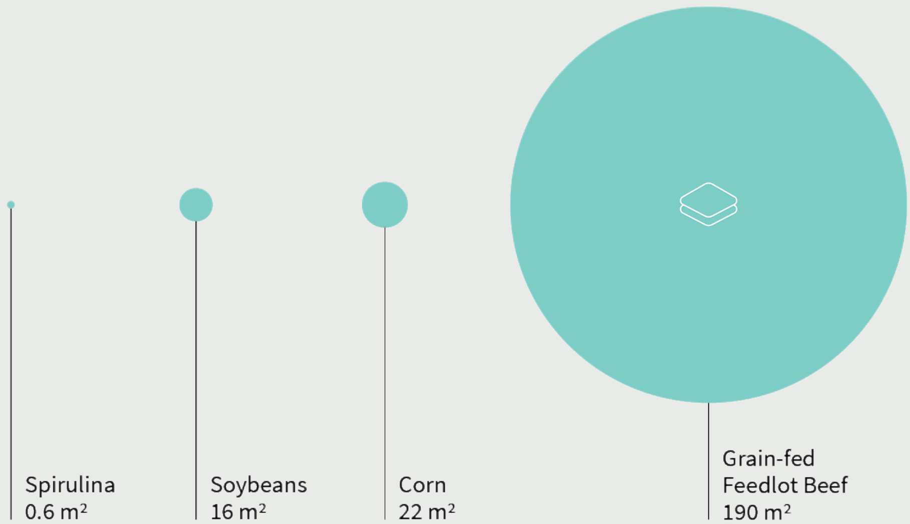
Figure 3.7. A filament of *Arthrospira platensis*, also known as *Spirulina*, under microscopic view. The name derives from its unique form. Retrieved from https://www.shutterstock.com/es/image-photo/spirulina-sp-algae-under-microscopic-view-1289107543?src=CuUVt0FWc5jBr9BvqPFt1Q-1-48
Copyright 2018 by Elif Bayraktar.

Among the algae already widely used for food, there are also microalgae. Unlike macroalgae and seaweed, microalgae have microscopic dimensions, high morphological and metabolic biodiversity, and account for about 40% of the primary production of the food chain (Chini Zittelli, 2018). Microalgae have enormous commercial success, especially among vegetarians, vegans, and sportspeople, who use them as food supplements. This research focuses only on microalgae because of their exceptional versatility and high acceptance rate. Furthermore, as seen in the second part of this thesis, there are al-

5 Seaweed and microalgae are incredibly versatile because, in addition to being a very nutrient-rich food, they can also be used to produce biofuels, biopolymers, purify wastewater, and even for sustainable fabrics, among other uses.


Proteins
Carbohydrates
Essential
Fatty Acids
Vitamins
Minerals
Pigments
55-70%
12-25%
18%
12%


Spirulina
2,100 l
Soybeans
9,000 l
Corn
12,500 l
Grain-fed
Feedlot Beef
105,000 l


Spirulina
0.6 m²
Soybeans
16 m²
Corn
22 m²
Grain-fed
Feedlot Beef
190 m²

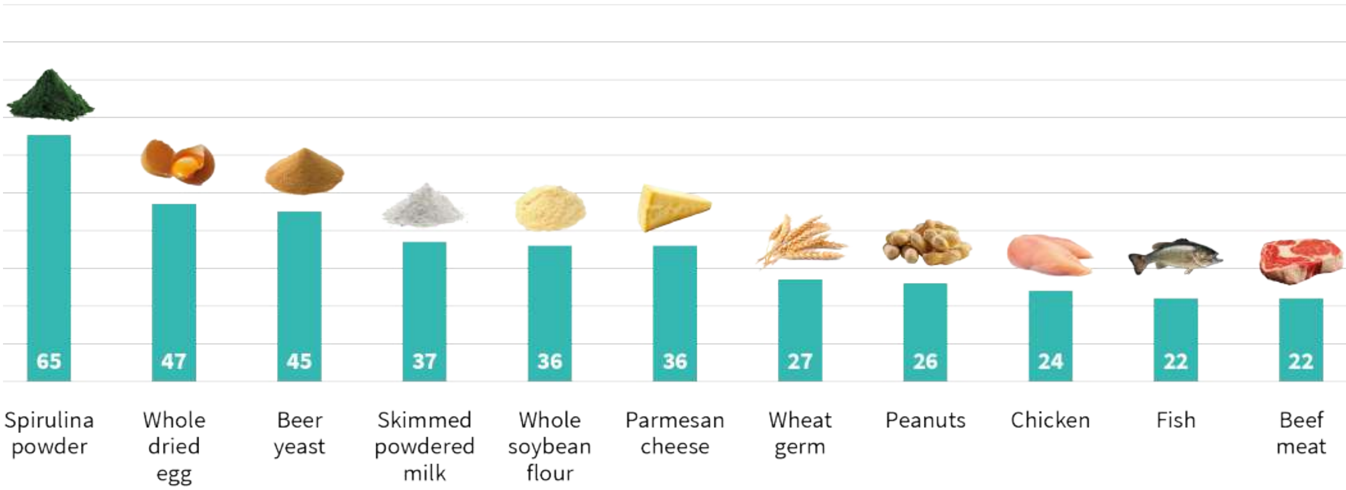


Figure 3.10. Quantity of *Spirulina* proteins and other foods. Crude protein percentage. Adapted from "Spirulina (*Arthrospira*): An edible microorganism: A review", by Sánchez et al., 2003, *Universitas Scientiarum*, *8*(1), p. 12. Copyright 1994 by R. Henrikson.

ready many projects in the fields of food, architecture, and design that have involved these particular types of algae. The next paragraph introduces *Spirulina*, the most commonly consumed microalga. Properties and methods of cultivation of microalgae, as well as more information on the taxonomy and evolution of algae and microalgae, are described in detail in chapter 5.

3.4 Superfood Spirulina

Among the thousands of species of microalgae, *Spirulina* (*Arthrospira platensis*) is the best known and most used, especially as a food and nutraceutical. It is a blue-green microalga, a multicellular filamentous cyanobacterium, with a particular spiral shape, 300-500 microns in length, a size that can barely be detected by the naked eye (Ciferri, 1983) (Fig. 3.7). Although cyanobacteria can live in very different habitats (in water, on rocks, on plants), *Spirulina* has been growing spontaneously for millions of years in some African and Mexican salt lakes and in some freshwater lakes (among these the Lake Kossorom in Chad, Lake Rudolf in Kenya, Lake Natron in Tanzania, Lake Chiltu in Ethiopia, Lake Texcoco in Mexico, and Lake Huaca-china in Peru) (Henrikson, 2010). *Spirulina* is sold fresh and dried in powder form all over the world, where health bodies and public administrations have approved its use as a food. It is consumed by sportsmen, vegetarians, children, and the elderly as an essential protein supplement.

Spirulina is considered a 'superfood' because of its chemical composition (Jung, 2019) (Fig. 3.8). It has a high content of high-quality proteins, equal to about 60-70% of its dry weight, and it contains a balanced dose of carbohydrates (12-25%), lipids, and essential amino acids (18%). It is also a rich source of vitamins (Vitamin E, Vitamin B12) and pigments (Carotenoids, Chlorophyll a, Phycocyanin). *Spirulina* contains many minerals, including calcium, magnesium, phosphorus, sodium, potassium, and iron, which are more easily absorbed by the body (Sánchez, Bernal-Castillo, Rozo, & Rodríguez, 2003). Com-

Figure 3.8 (Facing page – Top). Chemical composition of *Spirulina* (Sánchez et al., 2003).

Figure 3.9 (Facing page – Bottom). Water and land area needed to produce one kilogram of protein. Comparison with *Spirulina*, soybeans, corn and beef. Adapted from *Algae microfarms* (p. 17) by Henrikson, R., 2013, Richmond, VA: Ronore Enterprises. Copyright 2013 by R. Henrikson.

pared to other foods, a handful of *Spirulina* has as much iron as three portions of spinach, the same Beta-carotene as around 18 carrots, the same amount of potassium as a banana, and as much calcium as three glasses of milk. The protein content (60-70%) is much higher than other foods, including dry eggs (47%), parmesan cheese (36%), peanuts (26%), chicken (24%), fish and beef meat (22%) (Sánchez, Bernal-Castillo, Rozo, & Rodríguez, 2003) (Fig. 3.10). *Spirulina "can be cultivated on marginal, unusable and non-fertile land. Its rapid growth means spirulina protein needs 20 times less land than soybeans, 40 times less than corn, and 200 times less than beef cattle. Spirulina offers more nutrition per acre than any other food, but does not require fertile soil; [moreover] Spirulina proteins uses 1/3 the water as soy, 1/5 as corn, and only 1/50 the water needed for beef protein"* (Henrikson, 2013, p. 17) (Fig. 3.9). *Spirulina* can be produced at relatively low costs than other food products (e.g., beef meet). For this reason, many experts believe that *Spirulina* may be the perfect food to sustain a world in crisis (Ponce López, 2013).

Spirulina is, in most cases, added as an ingredient to other foods, and a multitude of *Spirulina* products can be found on the market. Among these: dry and fresh pasta, croissants, crackers, and other baked goods, hamburger and hot dog buns, seasoning, chips, cheese, chocolate, ice-creams, candies, honey. *Spirulina* is also added to many drinks, including bubble tea, smoothies, juices, milkshakes, beer, energy drinks (Figg. 3.11–3.22). The palatability of *Spirulina* is particular: it has a delicate sea-taste similar to the one of seaweed, with a slightly sulfuric edge. These characteristics may change according to where and how it grows. Some people love it, and some people hate it. Various cookbooks are suggesting recipes[6] and chefs are experimenting all over the world to enhance the flavor of *Spirulina*.

Due to these properties and uses, in this thesis, particular attention is paid to *Spirulina*, which will also be used in the design part. It is believed that *Spirulina* may be among the best microalgae for urban production because it is already known by a large number of people and, therefore, more easily adaptable in design and food-related projects.

3.4.1 Food safety aspects

The classification of microalgae is still under debate among international scientists, as well as countries. For this reason, there are no universal and valid food safety regulations. Consumption of any food is not without risk, and even microalgae could cause harm. However, studies on the risks of microalgae are quite recent. *"Although there has been no conclusive evidence [...] only*

6 To know more about recipes with *Spirulina*, it is recommended to read: Arndt, U. (2014). *Le alghe della salute. Spirulina, Clorella, Klamath. Superfoods naturali di forza, bellezza e benessere*. Torino: L'Età dell'Acquario.

products from Arthrospira platensis [Spirulina] have so far been cleared for consumption (United States of America, Australia, Canada and probably EC), under specific conditions, by public health authorities" (Habib, Parvin, Huntington, & Hasan, 2008, p. 19). If not adequately grown, *Spirulina* could be contaminated with toxic metals and other harmful bacteria, causing allergies, liver damage, nausea, thirst, vomiting, weakness, rapid heartbeat, and even death. Thus, it is recommended researching the source of *Spirulina* in supplements to ensure it is safe for consumption (Cox, 2018). If consuming *Spirulina* regularly, it is important to seek medical advice and not to abuse it, because prolonged exposure to heavy metals is toxic. Fortunately, recent studies have shown that the vast majority of *Spirulina* on the market contains heavy metal levels within the daily intake levels and are, therefore, considered to be safe food (Al-Dhabi, 2013).

Figure 3.11. Fresh *Spirulina* tagliatelle. Retrieved from https://caffeinforchetta.wordpress.com/2013/05/31/pasta-fresca-allalga-spirulina/

Figure 3.12. Mermaid croissant. Retrieved from https://loves.cucchiaio.it/pasticceria-croissant-blu-allalga/

Figure 3.13. The Algae Factory. Milk Chocolate 70% and *Spirulina*. Retrieved from http://www.designhub.it/smartdesign/2018/10/08/algae-factory-superfood-con-spirulina-e-cioccolato_gruppo-7/

Figure 3.14. Blue *Spirulina* cheese. Retrieved from http://rawchefyin.com/post/170414834005/blue-spirulina-cheese-raw-vegan-my-plantlab

Figure 3.15. Gluten-free vegan ice-cream with *Spirulina*. Retrieved from https://blog.nuts.com/spirulina-ice-cream-recipe-gluten-free-vegan/

Figure 3.16. Chips with kale and *Spirulina*. Retrieved from https://2.bp.blogspot.com/-XjaDonnAd64/WNRI27svdZI/AAAAAAAAFlU/nO5D0jo0aWiRQRs0jKkNKTcODzgCLcB/s1600/IMG_4475.JPG

Figure 3.17. Chocolate-dipped *Spirulina* shortbread. Retrieved from https://www.alive.com/recipe/chocolate-dipped-spirulina-shortbread/

Figure 3.18. Focaccia with *Spirulina*. Retrieved from https://insta-stalker.com/post/BlkthidA8t7/


Fig. 3.11


Fig. 3.12


Fig. 3.15


Fig. 3.16


Fig. 3.19

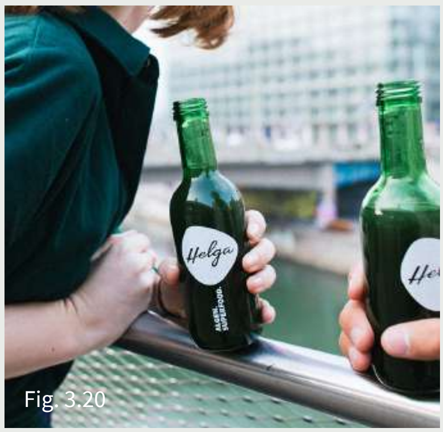


Fig. 3.20

Fig. 3.13


Fig. 3.14


Fig. 3.17


Fig. 3.18

Fig. 3.21

Fig. 3.22

Figure 3.19. Blue *Spirulina* smoothie with phycocyanin. Retrieved from https://thefeedfeed.com/briewilly/blue-spirulina-smoothie

Figure 3.20. Hello Helga *Spirulina* energy drink. Retrieved from https://hellohelga.com

Figure 3.21. *Spirulina* anti-aging beer. Retrieved from https://matadornetwork.com/read/drink-anti-aging-beer-myanmar/w

Figure 3.22. B-Blue, Elixir de la Mer. Retrieved from https://deskgram.net/p/1835543355686626457_4877363017

CHAPTER 4

Making cities resilient

Cities are places in which cultures are born, ideas are developed, and economic-productive systems flourish and thrive (Braudel, 1984): they are centers of innovation, education, and wealth.[1] Cities attract talents offering them career opportunities and well-being. A large part of the world's population now lives in urban agglomerations, and except for major disruptive events that could change our lives, the number of urban dwellers is expected to increase in the next years. The dimensional and demographic expansion of the cities will take place differently, depending on the geographic macro areas and socio-cultural contexts, confirming a common global trend that seems unstoppable. Therefore, studying urban contexts and designing solutions for making them more resilient is essential. This thesis considers urban areas in an attempt to bring well-being for a greater number of people in the present and future perspectives. Microalgae are one of the many pretexts for activating processes and projects that are virtuous and sustainable, to contribute to the resilience of

1 Part of the work described in this chapter was also previously published in: Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019; Vrenna, M. (2016). *The system design of Caijia from the consumer's point of view* (Master's thesis, Politecnico di Torino, Italy); Vrenna, M., Crétier, M., & Landén, S. N. (2019). Participative urban air quality monitoring using open source devices. *Agathón*, *2019*(5), 167–174. doi:10.19229/2464-9309/5192019.

artificial and complex urban environments.

Each city is quite different from the others and has unique characteristics. Some are small and medium-sized urban realities; others are megacities and capitals of populous countries. For urban and city contexts, the studies of Dijkstra and Poelman (2014), and Dijkstra, Poelman, and Veneri (2019) are taken as reference. These studies open up a new definition of degree of urbanization: the authors developed and perfected a methodology to define the functional and economic extent of cities beyond the traditional concepts of population size and density. This methodology is based on a grid cell system of 1 km^2. In short, an urban center is a set of contiguous cells, with a population of a minimum of 50,000 people and 1,500 residents per km^2. A city is composed of one or more clusters, with at least 50% of the people living inside the city center. The peri-urban areas (also called the 'commuting zone') are proximal to the city center and is where at least 15% of the working population in the city lives. The city and the commuting zone define an urban functional area. The densely-populated areas have an extension that can vary in size. They also have a close relationship with neighboring rural areas, with which they connect through numerous physical, social, and cultural infrastructures. Urban and rural areas should not be treated as distinct and unrelated spaces, and urban-rural links must be solid.

The living standard of developed urban areas is desired by many, who are attracted by the glitz of cities, higher wages, and multiple services: this has caused an unprecedented exodus from rural areas in recent decades, which impoverished them even more. Connecting to quote of Shakespeare (1964), who wrote in the 16th-century play 'The merchant of Venice': *"All that glisters is not gold"*, cities also have great problems to face. Italian writer Italo Calvino in the 70s described an imaginary city called Leonia. *"The city of Leonia refashions itself every day: every morning the people wake between fresh sheets, wash with just-unwrapped cakes of soap, wear brand-new clothing, take from the latest model refrigerator still unopened tins, listening to the last-minute jingles from the most up-to-date radio. On the sidewalks, encased in spotless plastic bags, the*

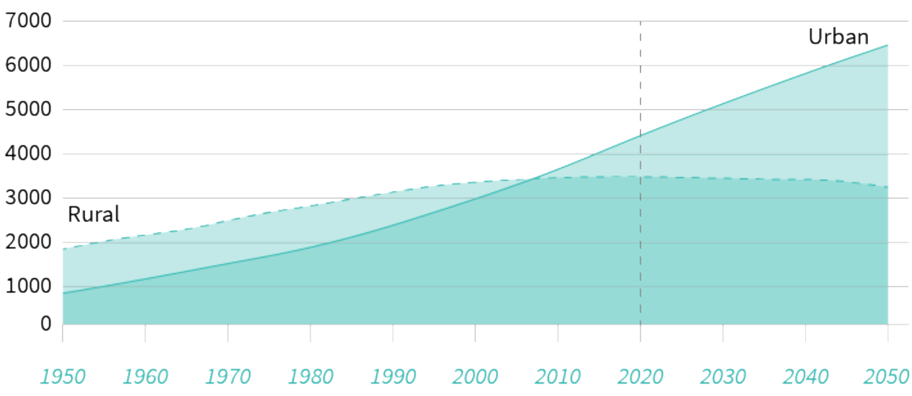


Figure 4.1. World urban and rural population, 1950-2050. Globally, more people are currently living in urban agglomerates rather than in rural areas. This number is expected to rise exponentially. Adapted from *World urbanization prospects* (p. 7), by United Nations, Department of Economic and Social Affairs, Population Division, 2015.

Figure 4.2. Rapid urbanization taking over the agricultural land in Chongqing, China. Adapted from *LensCulture* website, 2016, retrieved from https://www.lensculture.com/2016-lensculture-portrait-award-winners Copyright 2016 by Tim Franco.

remains of yesterday's Leonia await the garbage truck. Not only squeezed tubes of toothpaste, blown-out light bulbs, newspapers, containers, wrappings, but also boilers, encyclopedias, pianos, porcelain dinner services. It is not so much by the things that each day are manufactured, sold, bought that you can measure Leonia's opulence, but rather by the things that each day are thrown out to make room for the new. So you begin to wonder if Leonia's true passion is really, as they say, the enjoyment of new and different things, and not, instead, the joy of expelling, discarding, cleansing itself of a recurrent impurity" (Calvino, 1974, p. 114). Calvino had described a future city, a city of our present. However, today the problems are not only related to waste management but are even more complex and include an enlarged dimension of sustainability. Among the many challenges, resilient cities should be able to cope with air pollution, to plan water and food supply systems in the event of scarcity of agricultural areas, find new uses for abandoned or degraded zones, while supporting disadvantaged groups of the population. This is not only to mitigate damages but, primarily, to adapt new project proposals to a radical and irreversible change. Operating on cities could, therefore, be the key to reach sustainability.

This chapter offers an overview of the countless studies in the field of architecture, sociology, technology, and design for the development of cities. It shows only the tip of the iceberg in this field of knowledge, with notions that support the theoretical and practical research of this doctoral thesis. The chapter analyzes the urbanization forecasts and the different types of city domains, with particular reference to the relationship between public and private spaces. Some best practices are also illustrated. The discipline of design has a lot to offer cities. In these contexts, new solutions are adopted, and innovative projects are being developed, which also involve the use of microalgae.

Urban areas, therefore, deserve to be studied and analyzed as potential areas of intervention.

4.1 Urbanization forecasts

Urbanization began thousands of years BC when nomadic populations settled down in small villages. This process was stimulated by technological innovations, social and economic changes, and also by environmental phenomena. From small settlements, our ancestors moved to modest-sized towns with more complex systems for their management. The creation of large ancient cities started, which became the cradle of culture and civilization. It is estimated that by the time of Christ, the global population accounted for around 256 million people. By the first years of 1900, this number reached 1.6 billion, and by 1975 – only 75 years later – it reached almost 4 billion, following an exponential growth pattern (Durand, 1977).

The world has changed dramatically in just over two thousand years: as of 2020, the world population accounts for 7.8 billion, with most of the population living in Asia. The world population prospects of the United Nations (2019) estimates that the Earth will be inhabited by 8.5 billion people in 2030, 9.7 billion in 2050, and 10.9 billion in 2100. Most of us will be living in urban agglomerations, which are expected to see a strong demographic and dimensional development. In 1950, around 70% of the world population lived in rural settlements, while less than a third in cities. As of the years 2000, the share of the urban population outpaced the rural one. By 2050, the urban population will account for around 70% of the global one. This is an outstanding change in only one hundred years of history (Fig. 4.1) (United Nations, 2015). Economic activities are mainly concentrated in urban regions: in recent years in Europe, for example, activities in cities accounted for 53% of all gross domestic product (European Union, 2016). With due considerations for some countries, this figure is quite similar to the global data.

The development of cities has led to the emergence of so-called 'megacities', urban areas notable for their size, population, and concentration of economic activities. At the end of the last century, there were only ten cities with more than 10 million people: these included New York and Tokyo. As of 2014, the number had risen to 28, providing a home to approximately 10% of the world's population. The list of megacities includes Tokyo, Seoul, Jakarta, Delhi, Shanghai, Karachi, Beijing, Moscow, Istanbul, as well as Mexico City, New York, London, and Paris. Megacities are mostly located in the global south, mainly in Asia. Considering the growth rate of some cities in South America and Africa, the number of megacities is supposed to increase in the near future (United Nations, 2015).

"Rapid urbanization will generate substantial economic growth. It will favor entrepreneurs, economies of scale and agglomerations, social networks of creativity

Figure 4.3 (Facing page). A simplified illustration of the domains of a city and their elements (Harrison & Donnelly, 2011).

and collaboration, specialization, and lower transaction costs will generate huge increases in productivity. [...] Melting of ice, scarcity of freshwater, drought, poor harvests, rising sea levels, tropical cyclones, forest fires, seasonal floods, and extreme temperatures will cause massive migration of people [...]. By 2052, our species will truly be Homo sapiens urbanis" (Gladwin, 2013, pp. 135-136).

We are already observing the effects of uncontrolled urban development, which brings with it many problems, primarily the loss of areas initially used for agriculture (Fig. 4.2). Life in urban environments has tremendous consequences on the political agenda (as well as the economic and the design agendas), which will have to focus more on the problems of the inhabitants. These include poverty, crime, air quality, food supply, water, sewage, traffic, noise, waste disposal, and energy (Randers, 2012). Given these circumstances and the urbanization forecasts – which portray a sad but plausible future – designing for the development of cities is imperative. By operating on different levels, many goals can be achieved. It makes sense to focus on smaller cities (or districts), and then try to adapt, decline, and scale the results in larger cities. Alternatively, try experimenting directly in megacities.[2]

4.2 The domains of a city

Influential environmental scientist and expert in system dynamics Donella Meadows (2008, p. 11) defined the city as a complex system that is *"an interconnected set of elements that is coherently organized in a way that achieves something"*. A system includes elements, interconnections, and a common function (or purpose): it is much more than the sum of its single parts. The elements of a city are the streets, the buildings, the citizens, to name a few. Interconnections are relationships between people, commercial exchanges, social mechanisms. One of the many purposes of a city could be, for example, providing the necessary infrastructures and possibilities for people to live, work, and prosper with a meaningful lifestyle.

"The city [...] is something more than a congeries of individual men and of social conveniences—streets, buildings, electric lights, tramways, and telephones, etc. [...] The city is, rather, a state of mind, a body of customs and traditions, and of the organized attitudes and sentiments that inhere in these customs and are transmitted with this tradition. The city is not, in other words, merely a physical mechanism and an artificial construction. [...] The city is, finally, the natural habitat of civilized man" (Park, Burgess, & McKenzie, 1967, pp. 1-2). Cities are therefore physi-

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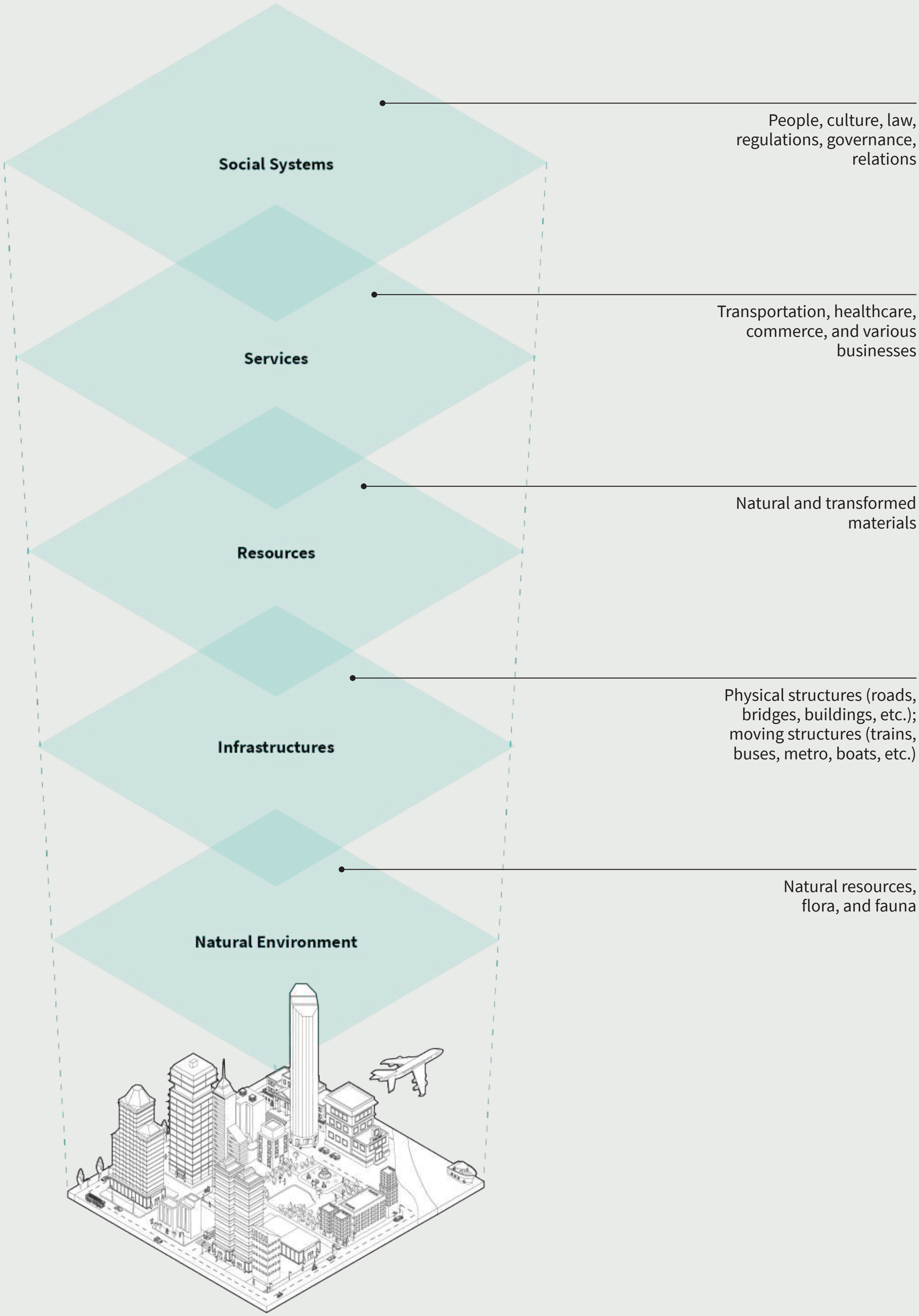
2 The visiting research period in Beijing was useful for experiencing the dynamics of a big city firsthand. Daily observations allowed me to understand better the actions, behaviors, and mentality of urban dwellers. This was a constant daily first-person, and unstructured ethnographic/phenomenological research, from which I drew valuable qualitative considerations which were fundamental for the development of a product/service design project.


Social Systems
People, culture, law, regulations, governance, relations
Services
Transportation, healthcare, commerce, and various businesses
Resources
Natural and transformed materials
Infrastructures
Physical structures (roads, bridges, buildings, etc.); moving structures (trains, buses, metro, boats, etc.)
Natural Environment
Natural resources, flora, and fauna

cal and metaphysical places with innumerable facets: as clearly described by Lynch (1960) in the book 'The image of the city', the result of a five-year study of Boston, Jersey City and Los Angeles, the perception of a city varies from person to person. For a geographer or demographer, a city represents a place with a large number of people concentrated in a small space; for a politician a unique administrative district; for a sociologist a place with certain cultural features and particular values. For most of the citizens, a city is just the place where they live: a place with traffic, pollution, a high density of people, as well as events, job opportunities, and leisure activities. For centuries, cities were built to reunite people, sharing skills and goods, and thrive prosperous civilities. In ancient Greece, all the activities of the city were organized around the 'agora'. The literal meaning of the word is 'gathering place' or 'assembly'. "*The agora was the center of athletic, artistic, spiritual and political life of the city*" (Ring, 1996, p. 66), and served as a marketplace where merchants kept stalls and shops. In ancient China, houses were built in a way to facilitate interactions between neighbors, and gardens were the places for meditation, exchange of opinions, and playful activities. Meeting points and common areas have always and everywhere been important for the development of the cities and for establishing interactions among people.

For understanding cities, it is relevant to divide their innumerable and multifaceted physical and immaterial domains. The levels identified by the studies of Harrison and Donnelly (2011) are taken as reference. The authors consider the city as an information model that can be represented in some two-dimensional layers. Below is a list and a brief description of them:

- **Natural environment:** natural resources, flora, and fauna;
- **Infrastructures:** physical structures including the built environment like roads, bridges, buildings, electrical communication lines and pipes, as well as moving structures (trains, buses, metro, boats, etc.);
- **Resources:** natural materials that originate in the natural environment and eventually return to it, after being metabolized by the city;
- **Services:** many kinds of services, including transportation, healthcare, commerce, and various businesses. Services may imply the consumption or transformation of resources;
- **Social systems:** culture, law, regulations, governance. This layer affects people directly and is therefore very dynamic.

Figure 4.3 illustrates the above-mentioned domains, which are directly related to the economic, social, and environmental issues of the city. The social space of cities is interesting, and many researchers have analyzed it already. It is a widely acknowledged fact that human behaviors are the product of the context they live in. The physical context in which one grows up and the places in which one lives are every bit as important as one's genetic endowment or social class in determining behavior (Krupat, 1985). With the rapid growth

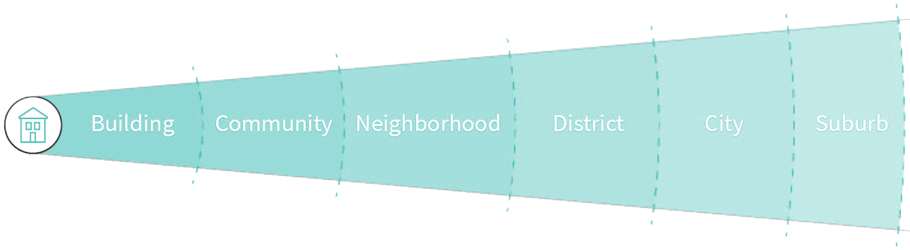


Figure 4.4. Public and private spaces of a city. The intimate domestic context is related to its surroundings, at different levels.

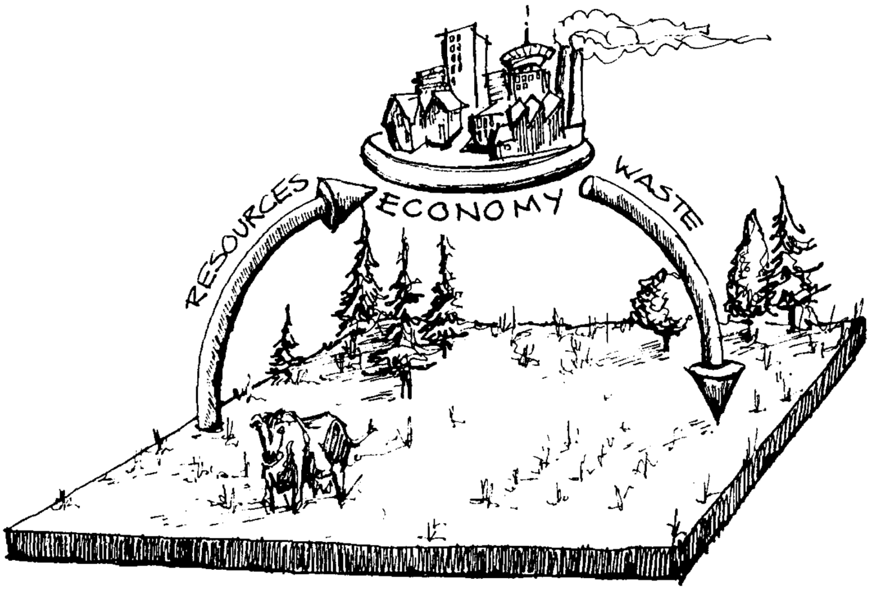
and development of urban areas, the way of living cities changed dramatically. In the book 'The death and life of great American cities', Jane Jacobs (1961), journalist, activist, and author, criticizes the methods of planning and urban renewal of cities of her time. This classical book about urban sociology investigates the need for a better urban development not to lose identities and human relationships.

Nowadays, the current urban trend is the spectacularization and artificialization of the metropolitan areas. At the same time, the patterns of cities changed dramatically. If in the past blocks and streets were narrower, facilitating social interactions and making encounters more frequent and easier, larger streets are now instead designed and built for cars and trucks. Although this is a theory developed several years ago for the urban development of the American cities, it is still topical. It can be easily applied to most of the modern cities, where traditional houses have been torn down for the construction of skyscrapers and residential high-rise buildings, and highways and elevated roads are connecting the city, often without taking into account the real needs of its inhabitants.

To these domains of action, it is relevant to consider also that the way of living the city changes considerably depending on whether people are in public or private spaces. *"This is almost a universal feature of cities, as cities of all cultures, at all historical periods, are organized along some form of public-private lines, although the nature of this division, the meaning of and relationship between public and private spheres vary widely"* (Madanipour, 2003, p. 1).[3] When it comes to housing, the apartment – the private and intimate space par excellence – denotes a physical space that is, however in close relationship with the surrounding environment. The geographical, social, and cultural context in which people reside cannot, therefore, be excluded: this characterizes direct and indirect multi-scale tensions with the building, the residential community, the neighborhood, the district, up to the city, including its suburbs (Fig.

3 The book Madanipour, A. (2003). *Public and private spaces of the city*. London, United Kingdom: Routledge is an exhaustive study on the relationship between the public and private sphere, that is one of the main concern of modern urban societies. It is recommended to read this book to learn more about the topic.

Figure 4.5. Industrial metabolism of a city. Reprinted from "Urban ecological footprints: Why cities cannot be sustainable—and why they are a key to sustainability", by Rees, W., & Wackernagel, M., 1996, *Environmental Impact Assessment Review*, *16*, p. 228. Copyright 1995 by William Rees and Mathis Wackernagel.



4.4). Designing for the city is a complex job and means taking into account all the domains, including the private domestic sphere and the public one. The design part of this thesis will try to operate in both these contexts, leveraging economic, social, and environmental processes. For this reason, this paragraph is relevant for the comprehension of the next research steps and some design choices.

4.3 Cities: A key to sustainability?

Non-anthropomorphized ecosystems are sustainable by definition because they are regulated by natural mechanisms perfected over millions of years and have not undergone human intervention – which is, in many cases, destructive. Virgin environments are increasingly rare, and cities – entirely artificial – are probably the least sustainable ecosystems ever created. The ecological footprint – formally defined as *"the total area of productive land and water required continuously to produce all the resources consumed and to assimilate all the wastes produced, by a defined population, wherever on Earth that land is located"* (Rees & Wackernagel, 1996, pp. 228-229) – of a city, is very high. Present-day cities are not self-sufficient but depend mainly on resources coming from outside, which are avidly consumed. For producing enough food to feed a city, it is necessary to have large agricultural fields in the surroundings, or to import products from other areas, with evident environmental downsides. The same goes for other resources, such as water essential to life, but also wood and other building materials. Urban and rural areas are diametrically different, but strongly connected. Cities usually overexploit the natural capital stocks of the surrounding land for thriving their economies. They also release

Impacts	Mitigation strategies
High traffic density	Efficient public transport; Compact city design
High amount of waste	Recycling
Urban warming	Increasing green space; Using reflective materials
Increasing air pollution	CO_2 capture; Air filtration; Increasing efficiency of vehicles
Increasing consumption	Using renewable sources; Achieving low energy buildings
Lack of biodiversity	Increasing green spaces; Animal/plant protection areas
Sinking water resources	Water purification; Desalination; Rainwater harvesting
Rising food demand	Vertical farming; Artificial food production; Greening deserts
Land shortage for housing	Multifunctional buildings; Creative architectural designs
Weak social cohesion	Improving sociocultural environment; Bring people together

Table 4.1. Strategies adopted for mitigating the impacts of global urbanization. Adapted from "Future cities and environmental sustainability", by Riffat, S., Powell, R., & Aydin, D., 2016, *Future Cities and Environment*, *2*(1), p. 2. Copyright 2016 by Saffa Riffat, Richard Powell, and Devrim Aydin.

waste in the environment. Cities, therefore, have an 'industrial metabolism' and can be compared to large animals grazing in pastures (Fig. 4.5). The space that the animals need for their subsistence is much larger than the animals themselves (Wackernagel & Rees, 1995).

Talking about sustainable cities is an oxymoron (Rees, 1997), at least as they are currently intended. However, considering that urban areas will be housing most of the world's population in the coming decades and that they face great challenges, operating on their sustainability is imperative, entailing difficulties but also unique opportunities. Building resilient cities could be the key to achieving global sustainability, and projects in this direction are required. Sustainability should not only be related to the environmental aspect but also economic and social, as described in paragraph 2.1.

Cities are facing a new future. As identified by Roseland (1997) in a still current and highly cited paper, sustainable eco-cities are an extensive theme that encompasses various objectives, namely: sustainable urban development, sustainable communities, bioregionalism, community economic development, appropriate technology, social ecology, green movements and communities. Today, sustainable cities must ensure the well-being of citizens, creating jobs, and safe and affordable housing. They must also support the link between urban and rural areas, reducing per capita and overall city environmental impact by building resilient communities. These goals are in line with the 11th Sustainable Development Goal of the United Nations (2015). The cities of the future will be much different from the present ones. Now, strategies are already being adopted for mitigating the impacts of the global urbanization, including waste recycling, CO_2 capture, and urban farming, among others (Table 4.1). "*The 'Future Cities' topic employs a multidisciplinary approach to address the urban development challenges facing emerging cities. […] Nevertheless, simply applying innovative technologies alone will not guarantee the combination of sustainability and acceptable living standards for future cities*" (Riffat, Powell, &

Aydin, 2016, p. 20). The following paragraphs briefly describe some urban best practices, including smart cities and urban food systems, which are also useful for understanding the design approach to this thesis, which is partly technical, as well as humanistic.

4.4 Urban best practices

Investigating best practices is important to get an overview of the most remarkable results obtained in one or more particular action domains. As anticipated, many cities around the world are carrying out innovative and game-changing projects to achieve sustainability. Urban best practices are ranging from urban planning projects to policymaking. In an attempt to make cities more livable and safe for citizens, recent sustainable urban development projects have focused on contribution to global climate change, local mobility, traffic congestion, air quality, noise pollution, waste production and management, water consumption, wastewater management, as well as sustainable land use (European Green Capital, 2013). Professionals from different fields, including designers and architects, have collaborated for the realization of these projects – which involve not only the construction of physical structures but also the creation of services and the implementation of rules for behavior change.

Urban best practices are numerous and continuously emerging: researchers are trying to map and catalog them utilizing precise indicators. This paragraph only briefly illustrates some practices related to the so-called 'smart cities' and the creation of urban food systems. These examples underline how important it is to operate both on a technical and humanistic level while providing essential insights for the design part of this dissertation, which exploits microalgae as a vector of environmental, social, and economic sustainability.

4.4.1 Smart cities

"Future cities are neither the invisible ones of Italo Calvino nor the visionary ones of Fritz Lang[4]. They are the present ones, seen and inhabited with a more efficient, at the same time technological and creative – but especially participatory – perspective" (Mattei, 2014, p. 9). A smart city can be defined as an urban area that utilizes internet-connected electronics to get data, and then use these data to manage resources, assets, and services efficiently. Smart cities can save energy, optimize vehicle traffic flows, decrease crime, offer better services and infrastructures, among several other functions. As defined by the European Commission (2007), a smart city is based on six axes (or dimensions), which

4 Fritz Lang was a famous Austrian naturalized American film director who directed Metropolis (1927), which is regarded as a pioneering science-fiction movie and a masterpiece of film history.

are:

- Smart governance: correct administration that acts in the interest of the entire community, and enhances human capital.
- Smart economy: an economy seeking innovation and collaboration for the creation of jobs and increased productivity.
- Smart living: guaranteeing citizens a high standard of living, taking into consideration aspects of primary importance such as education, health, and safety.
- Smart people: involve citizens in bottom-up decision-making processes and make them aware of the problems and changes in the city.
- Smart environment: sustainable development of the city, with respect and protection of the environment.
- Smart mobility: reduction of costs – including the environmental ones – and optimization of movement flow in the city, and with peripheral areas.

Even though the topic of smart cities is pretty recent, it is raising interest among researchers, practitioners, policymakers, and even citizens. Technology, on several levels, can enormously help to tackle the problems of cities also, and above all, "*to improve their environmental effectiveness in the context of connected societies, global competitiveness, economic development, climate change, and demographic shifts*" (Mitchell & Casalegno, 2008, p. 8). In this short paragraph, the multifold themes that can be connected to the smart city are not going to be covered. Nevertheless, it should be noted that modern smart cities are embracing solutions from disparate fronts and not only that of technology: urban street furniture is one of them. Visionary architects have created, for instance, structures for air purification, such as the Smog free tower by Studio Roosegaarde (Fig. 4.6). Furthermore, a smart city can only exist with smart citizens (Ratti, 2014): social participation allows citizens to become co-designers through participatory design processes, which shape projects that respond to real needs, as in the case of the High Line in New York (Fig. 4.7). Designing for smart cities opens up a multitude of possibilities that deserve to be explored. It is, therefore, important to take inspiration and learn from the projects that have already been done to implement strategies that can also lead to a behavioral change.

Figure 4.8. Elements of an urban food system (Pothukuchi & Kaufman, 2000).

4.4.2 Urban food systems

Cities, like people, are what they eat (Steel, 2013). Considering that every day, each city in the world has to provide at least three meals per citizen, enough food must be produced, imported, distributed, sold, cooked, eaten, and eventually dumped. These quantities are enormous and, remarkably, most of us can eat properly. Feeding cities takes enormous efforts and has a massive impact on societies, lives, and the planet. People rarely wonder how the food they eat might have got there. Carolyn Steel (2006) wrote the book 'Hungry city:


Fig. 4.6

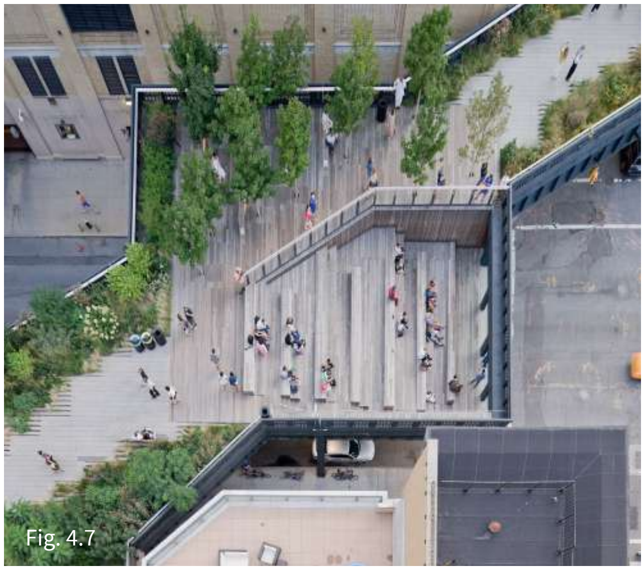


Fig. 4.7


Fig. 4.9


Fig. 4.10

How food shapes our lives', a publication about food geography[5] in which she has also introduced the case study of the city of London. The attitudes toward food shaped the form of the city itself. In John Ogilby's map of London – dated 1676 – it is possible to see how streets were connected with food because

5 Food geography is a discipline that deals with the relationship between food, space, and territory, including issues like sustainability, resilience, public health, and access to food. Food, because of its intrinsic connections with the original geographical areas, models the landscapes creating the so-called 'foodscapes' (Morgan & Sonnino, 2010). Food geography aims to create 'sitopias' (from the Greek words 'sitos', meaning food, and 'topos', place). Sitopia is a term used to describe a community affected by the relationship with food.

they were named after the foods that were sold in. For instance, sheep and cattle coming from Scotland and Ireland were giving the name to the streets of the Northern-East area of the city. At that time, food was a matter of public domain: it was not sold in shops but open-air markets. The whole process of food transformation was visible. This process changed with industrialization: in London, as well as other cities, high streets and private shops have taken the place of local markets. At the beginning of the 20th century, the first supermarkets opened, and nowadays, only a few corporates are controlling the food industry, monopolizing the entire sector. Food became agro-industrialized and globalized, losing its identity.

The food issue has been absent from urban agendas for a long time, because it has been misunderstood, or thought of as something just regarding rural areas (Pothukuchi & Kaufman, 1999). Because of that, the profit-oriented free market has been ruling the distribution of food in cities. This trend is changing because feeding cities is not anymore a private question, but an issue that needs to be addressed publicly and at city-scale. Thus, urban food planning (Morgan, 2009) and urban food strategies are necessary and challenging. An urban food system is characterized by the connection of all the activities related to production, processing, distribution, consumption, and post-consumption of food, as well as the related institutions and regulatory activities (Pothukuchi & Kaufman, 2000) (Fig. 4.8). Urban food strategies consist of real-world projects for healthy communities and resilient local food systems: for example urban farming and shared gardens, guerrilla gardening, alternative food networks (farmer-to-consumer, farmer's market, community-supported agriculture, collective buying), street vendors, educational food programs, as well as economic initiatives.

The practice of urban agriculture, for instance, demonstrated being a source of healthful sustenance and contributing to a household's income through the creation of jobs. Garden or rooftop farming can get people together, also enhancing the cultural and social identity for city residents (Ackerman, Conard, Culligan, Plunz, Sutto, & Whittinghill, 2014). *"The implementation of productive green roofs should be considered and actively pursued wherever possible, due to their vital contribution to the advancement of urban agriculture, social and economic gains and potential job creation, which all strengthen our urban environments and communities"* (Proksch, 2011, p. 497). This practice is spread all over the world (Fig. 4.9). Citizens worldwide are also rediscovering traditional markets, revisited in a modern key, as a place of aggregation, culture, and purchase of fresh local products (Fig. 4.10). Much can be learned from these best practices: new models of urban food systems could include the cultivation and distribution of microalgae while stimulating connections between stakeholders that have never been explored so far.

Figure 4.6. Smog free tower by Studio Roosegaarde in Beijing, 2016. Adapted from *Studio Roosegarde* website, 2016, retrieved from https://www.studioroosegaarde.net/data/images/2019/10/2029/143142/smogfreetowerkorea5.jpg Copyright 2016 by Studio Roosegaarde.

Figure 4.7. An aerial view of the High Line in New York: a great example of participatory design. Adapted from *High Line* website, 2020, retrieved from https://www.thehighline.org/photos/at-a-glance/ Copyright 2015 by Iwan Baan.

Figure 4.9. ØsterGRO, the first Danish rooftop farm located in the heart of Copenhagen. Adapted from *Anders Husa & Kaitlin Orr* website, 2016, retrieved from https://andershusa.com/stedsans-at-ostergro-clean-simple-local-rooftop-restaurant-urban-farm-mette-helbak-flemming-hansen/ Copyright 2016 by Anders Husa.

Figure 4.10. The Markthal in Rotterdam is a well-known and unusual residential and office building with a market hall underneath. Adapted from *Gizmodo* website, 2014, retrieved from https://gizmodo.com/rotterdams-new-farmers-market-looks-like-the-inside-of-1644347328 Copyright 2014 by MVRDV.

4.5 Shaping cities through design

There is no doubt that institutions, governments, and policymakers are essential for the development of cities, services, and the whole society. Until now, public opinion has been little aware that architecture and design also play a significant function. However, as already seen in chapter 2.3.1, the role of present-day designers is changing. Designers and architects contribute to shaping cities with transversal interventions, no longer barely linked to the built environment or the creation of new products. Such an approach also permits determining new actions and behaviors. In the famous slogan 'From the spoon to the city' (Rogers, Sert, & Tyrwhitt, 1952), the Italian Ernesto Nathan Rogers underlined the typical approach of the architect of the time, who was able to design at all scales: from the product to the building, up to the urban plan. In order to interpret Rogers' thinking, the domains of the project can be related to the internal or external environment, to product or service/system, or the private and public spheres. What changes is only the scale of the project, while the approach and methodology remain the same with due, but rather minimal, considerations.

Already several years ago, Margolin (1998) argued that in order to become leading advocates of sustainable development, designers had to change their mentality and practice, collaborating with other professionals – including architects – in solving the big problems of cities. More recently, Margolin adopted a holistic and systemic approach that could be the basis of a new theory of sustainable urban planning, taking into account factors including food production and distribution, waste collection and recycling, elimination of homelessness, micro-lending and cooperative business, and alternative energy sources. According to Margolin (2015, p. 34) "*designers can contribute solutions. Action can take place at three levels: the micro level, that of individual action; the meso level is the level of groups where the individual may still have some influence; and the macro level includes governments, international organizations, and large companies. At the outer limits of the meso level is the city, which is still potentially capable of adopting coherent policies for change*".

Fortunately, the role of design in shaping cities is more widely recognized today. The World Design Organization, starting in 2008, launched the World Design Capital program, to encourage research and practice of design to further the development of cities while showcasing the best projects. Through the World Design Capital designation, a city can join a network of innovative cities, and become an international design hub.[6] In light of these considerations,

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6 The first design capital was Torino, Italy, in 2008. Lille Metropole in France holds the title for 2020, and Valencia, Spain, has been nominated for 2022. More information about the program can be found on WDO website at https://wdo.org/programmes/wdc/

it is clear that design is a powerful tool – at the service of citizens – to address the urban challenges we are facing, and shaping the present and future cities through a strong multidisciplinary top-down, as well as boom-up, approach.

4.6 Reflections

The battle against global challenges will be lost or won in cities. Decisions we make now will significantly influence the lives of the next generations. Among the various problems of cities, air pollution needs cumbersome interventions. The World Health Organization (2016), has reported that air pollutants are responsible for about one in nine deaths every year. Economic, social, and environmental costs are destined to surge in the upcoming decades (European Environment Agency, 2018), while pollution peaks are becoming increasingly common. Many cities are a victim of the same problem, in Europe, as in Asia, Africa and America. Considering the unprecedented urban sprawl, projects and research aimed at mitigating this phenomenon are particularly relevant (Keivani, 2010). At the same time, meeting the rising food demand in cities will be increasingly problematic. Current harvesting and distribution methods are not efficient, and it is estimated that *"cities still thriving in the late 21st and early twenty-second century will [...] provide most of their food [...]. They will also have solved the problem of getting food and other resources into and around the city without fossil fuels-powered trucks"* (Lang, 2018, p. 17).

According to expert Marco Poletto (TEDx Talks, 2018), urban microbiology could be the key to build resilient future cities and mitigate, at least partly, these problems. As analyzed later in this thesis, it is in cities that microalgae are finding innovative and successful applications, for example, vertical green walls, installations, and photobioreactors for CO_2 capture and food production. Technical and social similarities with traditional urban gardens are manifold, and this research field is undoubtedly relevant. A change of paradigm, characterized by targeted actions from a wide variety of disciplinary fields, is therefore of primary necessity. It is in this context that design must grasp the possibility of becoming a promoter of innovative practices through the design of products, services and systems, to achieve shared well-being. Besides, the active participation of citizens could become the driving force for raising awareness and achieve goals.

In conclusion, it is good to keep in mind that urban spaces are incredibly different from each other and particularly diversified, even internally. Public spaces such as squares, parks, schools, as well as airports, shopping centers, abandoned industrial areas, could be places of intervention. Domestic spaces – especially during and after the 2020 COVID-19 pandemic – also deserves special attention. We could, therefore, hypothesize solutions to produce microalgae safely, even directly at home.

CHAPTER 5

Toward microalgal studies

Algae are organisms lacking stems, roots or leaves, called thallophytes.[1, 2] These are photosynthetic organisms with chlorophyll as the main pigment. This definition includes a variety of other life forms that are not necessarily connected, like cyanobacteria. Around 50,000 species of algae are present, but only 30,000 have been analyzed (Richmond, 2004). Algae mainly live in water (both marine and freshwater), but they can also survive in desert soils, hot springs or on rocks (Lee, 2008). They grow rapidly and in large quantities, and in a broad range of temperatures. The branch of botany concerned with the study of seaweeds and other algae is called phycology.[3] Virtually, all aquatic organisms are dependent on algae, not only at the ecological level but also phylogenetically. It is actually thought that the major groups of animals

1 Part of the work described in this chapter was also previously published in: Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019

2 From the greek word θαλλός, thallos, meaning 'green shoot'. A thallus lacks true roots and a vascular system. Thalli are typical of algae, fungi, and lichens (Oxford Dictionary of English).

3 'Phycology' derives from the ancient Greek word φῦκος, phykos, (seaweed) and -λογία, -logia (a branch of learning) (Oxford Dictionary of English). This name is preferred to 'algology' since it reminds of the medical term 'algogenic' which means 'producing pain' (Lee, 2008).

and plants originated from the sea, and this is where the most representative evolutionary lineages can be found. Thus, investigating the evolution of algae is of utmost importance (van den Hoeck, Mann, & Jahns, 1995).

5.1 Taxonomy and evolution

The first attempts of distinguishing algae from plants dates back to ancient Chinese literature. But it was only in 1753 that the Swedish botanist, physician, and zoologist Carl Linnaeus published 'Species Plantarum' and classified algae. Several other attempts and proposals occurred in the last centuries. The most recent classification has been advanced by Robert Edward Lee[4] in 2008 (Baweja & Dinabandhu, 2015) and includes two main groups: prokaryotic algae and eukaryotic[5] algae.

The group of prokaryotic algae only include *Cyanophyta* (cyanobacteria). Cyanobacteria are a division of bacteria characterized by a blue-green color, able to manufacture their own food and to produce oxygen through photosynthesis (University of California Museum of Paleontology, 2012). The group that comprehends the eukaryotic algae is instead divided into three subgroups. The first subgroup includes *Glaucophyta* (an intermediate evolutionary position between bacteria and algae with chloroplasts), *Rhodophyta* (red algae), and *Chlorophyta* (green algae). The second subgroup includes *Euglenophyta*, *Dinophyta* (dinoflagellates, mostly marine plankton, some of them can exhibit bioluminescence) and *Apicompexa*, while the third subgroup includes *Chrysophyceae* (golden-brown algae), *Bacillariophyceae* (diatoms) and *Phaeophyceae* (brown algae), among many others.

With regards to the several efforts of algal classification, we may thus recognize two main kinds of algae, that are the macroalgae and the microalgae. Macroalgae are represented by diverse groups of photosynthetic marine, eukaryotic, multicellular organisms (e.g., seaweed). Microalgae are instead mostly single-celled organisms. *"In applied phycology the term microalgae refers to the microscopic algae sensu stricto, and the oxygenic photosynthetic bacteria, i.e. the cyanobacteria"* (Tomaselli, 2004, p. 3). Microalgae have many similarities with phytoplankton: most microalgae live as phytoplankton and most phytoplankton is microalgae, with the remainder consisting of cyanobacteria and dinoflagellates. Nevertheless, the taxonomic classification of phytoplankton

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4 R. E. Lee is Teaching Coordinator in the Department of Biomedical Sciences at Colorado State University, USA and author of the book *Phycology* (1st edition: 1981; 4th edition: 2008).

5 In biology, prokaryotes are a single-celled organisms (usually bacteria and cyanobacteria) without a distinct nucleus and that lack a bounding membrane and specialised organelles. The first living organisms were supposed to be prokaryotes. See: Fuerst, J. A. (2010). Beyond prokaryotes and eukaryotes: Planctomycetes and cell organization. *Nature Education*, *3*(9).

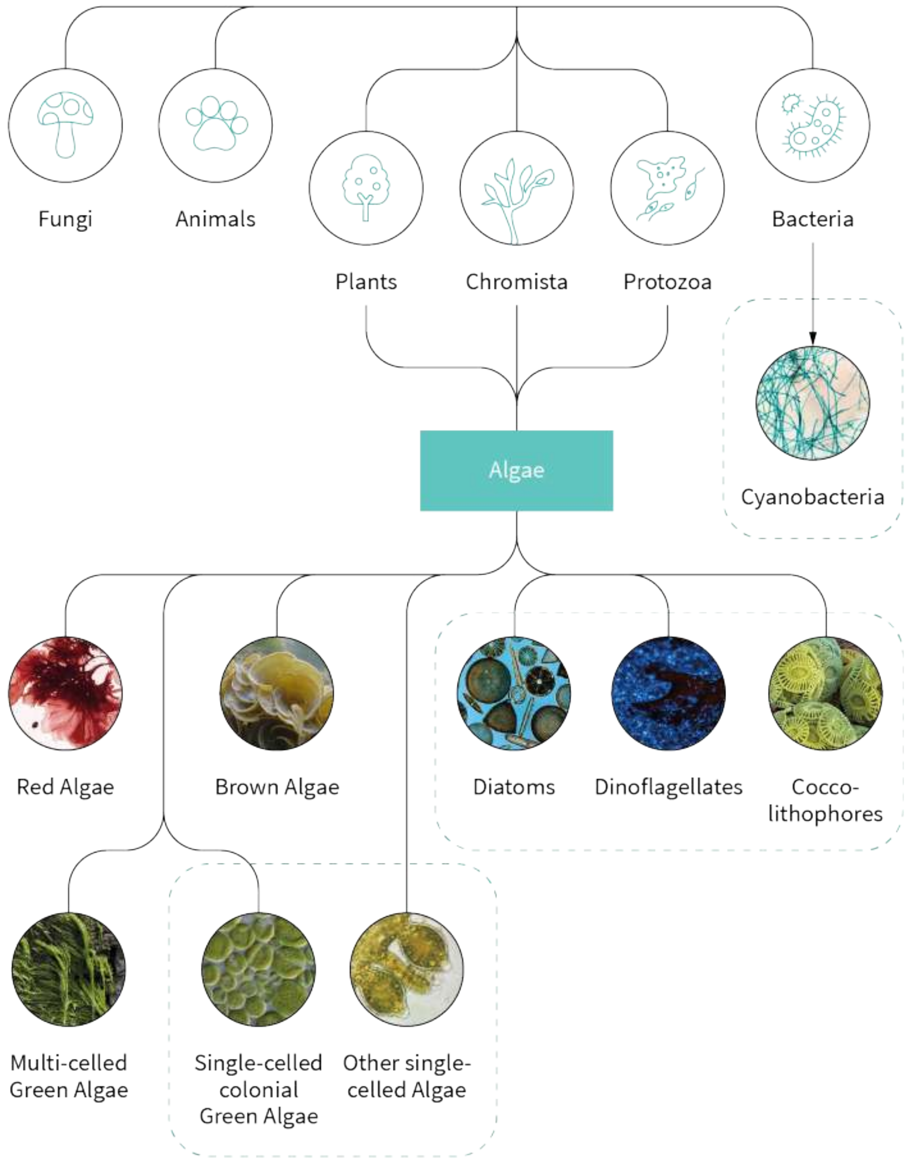

Figure 5.1. Simplified taxonomic classification of phytoplankton. Those highlighted are considered phytoplankton. Adapted from "Phytoplankton communities of polar regions—Diversity depending on environmental conditions and chemical anthropopressure", by Kosek et al., 2016, *Journal of Environmental Management*, *171*, p. 244. Copyright 2016 by Kosek et al.

and microalgae is still under debate (Fig. 5.1), with disagreement on their belonging kingdom (Kosek, Polkowska, Zyszka, & Lipok, 2016).

Microalgae have a long evolutionary path and originated well before several other organisms. Earth formed around 4.5 billion years (Ga) ago, while the evidence suggests that the first life forms, that were basically prokaryotes cells without a nucleus, emerged around 3.7 Ga ago (Pearce, Tupper, Pudritz, & Higgs, 2018). Approximately 2.6 Ga ago cyanobacteria started to spread in different areas all over the Earth. Their massive photosynthetic activity, together with other phototroph organisms, caused an uninterrupted increase in oxygen levels. From an evolutionary point of view, this was a catastrophe that lasted for more than 2 billion years.[6] The several other organisms, in fact, had to deal with the toxic effects of the increased partial pressure of the oxygen, which they were not used to. Then and surprisingly, around 550 million years ago, a moment called 'Cambrian Explosion' took place. Rich fauna and flora developed, including mollusks and early vertebrates. The first fishes appeared 450 million years ago; amphibians around 350 million years ago; reptiles, who were the first vertebrates that were living out of the water, appeared around 270 million years ago (Gunga, 2015). Our human presence on Earth is instead infinitesimally short: if the first primates can be dated back to 70 million years ago, the first hominids appeared only 25 million years ago, while our species, the Homo Sapiens Sapiens, is living on Earth since only 25.000 years.

Considering such a long and complex evolution of life, it is worth noting the pivotal role of cyanobacteria and algae in this context. Cyanobacteria initiated the oxygenic age on Earth, while algae are instead to be accounted for the initiation of the evolution of land plants (Prasad, 2011). Algae and microalgae are thus important organisms that paved the way, and are still shaping, our Earth's evolutive direction. They have devastating powers but at the same time are essential for the life of billions of creatures – including us – that rely on their photosynthetic action to breathe and live.

5.2 Algae uses in history

The great availability of both seaweed and microalgae in marine and freshwater permitted several experimentations in the domains of food and medicine – but not limited – during the centuries, and all over the world. These paragraphs review the main contributions coming from Africa, America, Asia, and Europe. Algae have been used as means of subsistence when food supplies were scarce, or as novel remedies to everyday problems. Initially, people were harvesting algae that were naturally growing in water basins. Subsequently, they started to produce and cultivate them systematically with man-made solutions.

5.2.1 Algae as food

Algae benefitted humankind since ancient times. Already in 800 B.C., pond weeds were used by Chinese as edible delicacies. It is also recorded that in 1660, Chinese were utilizing some transparent and tasteless algal extracts to produce jelly, various desserts, and candies. They were also using them as a base for soups. The same was happening in the Region of Armonica (now Brittany), where locals were baking a seaweed bread called 'pain des algues'. Between the 18th and the 19th century, seaweed was used for feeding livestock in

6 Experts refer to this period as the Great Oxidation Event (GOE). It also called 'Oxygen Crisis', 'Oxygen Holocaust', and 'Oxygen Revolution'.

Northern British Islands and Yugoslavia. On the Pacific American coast, it was fried in fat and eaten for breakfast, while in Northeast America it was chewed fresh. Algae were also widely exploited during the World War I and World War II in several ways: as food for troops, as fodder in case of scarcity of supplies, i.e. grain, but also to mitigate the irritative effects of gases on the throat (Maryam, Salman, & Hasan, 2017). Some soldiers were also chewing them in the attempt of relieving their thirst (Schwimmer & Schwimmer, 1955).

As regards microalgae, it is not exactly known when people started to use them. It is thus reported in 1521 by Bernal Díaz del Castillo, member of Hernán Cortez's troops, that *Spirulina maxima* (a blue-green microalga that grows in both fresh and saltwater), was used as a food in Mexico during the Aztec civilization (Fig. 5.2). The historical literature revealed that locals were harvesting fresh *Spirulina* from Lake Texcoco, sun drying it, and then selling the produce in the form of small cakes called 'Tecuitlatl'[7], in the local markets of Tenochtitlán (now Mexico City) (Sánchez, Bernal-Castillo, Rozo, & Rodríguez, 2003).

A very similar way of harvesting *Spirulina* was also described in 1940 by the French phycologist Dangeard, who studied a sample obtained from Lake Chad, in the Sahelian zone of west-central Africa. The scientist communicated in a letter to the Linnean Society of Bordeaux that the natives of the village of Massakory (from the Kanembu tribe) were eating a food called 'dihé'. These cakes were the result of the collection and the drying of the *Spirulina* biomass on the sandy shores of the lake. The hardened cakes were broken into pieces and sold in local markets without any further treatments (Ciferri, 1983). Dangeard studies unfortunately failed to capture the attention of the scientific community due to the war. Only a few decades later, in 1966, the Belgian botanist Jean Léonard reported finding Dihé sold as dry cakes in the capital city (Koru, 2012). This traditional practice is still common in the region and its local trading represents an important contribution to the economy of the area (Abdulqader, Barsanti, & Tredici, 2000).

In 1967 *Spirulina* was recognized as a 'wonderful future food source' by the International Association of Applied Microbiology (Sasson, 1997), and it is now widely harvested all over the world. It is commonly used as food (it is estimated that more than 70% of the global *Spirulina* market is for human consumption), dietary supplement, and cattle feed supplement (Wikfors & Ohno, 2001).

5.2.2 Algae as medecine

Algae played an important role also in past medicine. Romans were treating

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7 Tecuitlatl literally means 'stone excrement' since in the 16th century the 'breeding' of minerals was still considered possible. The practice of making Tecuitlatl disappeared soon after the Spanish conquest. See Farrar, W. V. (1966). Tecuitlatl; a glimpse of Aztec food technology. *Nature*, *1966*(211), 341–342.

joint pain by applying Kelp poultice; other marine algae served as remedies for burns, diarrhea, skin abrasions and heartburn (Schwimmer & Schwimmer, 1955). Chinese recommended the use of some of them for curing goiter, colicky pains, and flatulence (Zhenguo, Ping, & Peiping, 1999), and in recent times dried red algae were sold in Oriental apothecaries for treating various infections of the intestine. It is reported that different species of algae were employed for similar uses also in Russia, Brasil, Japan, Greece, Turkey, and in the Hawaiian Islands in the twentieth century (Maryam et al., 2017). The Kanembu tribe in Chad was avoiding vitamin A deficiency by adding one tablespoon of *Spirulina* to their daily meals (Gough, 2013).

Figure 5.2. Aztecs harvesting blue-green algae from lakes in the valley of Mexico. Reprinted from "Spirulina, a nutritious alga, once a staple of Aztec diets, could feed many of the world's hungry people", by Furst, P. T., 1978, March, *Human Nature*, p. 60. Copyright 1978 by Peter T. Furst.

Present-day medicine is also benefitting from algae. Contemporary studies in the fields of toxicology and microbiology discovered that particular microalgae are excellent sources of phenolic and biologically active compounds such as carotenoids, polysaccharides, sterols, and fatty acids (Raposo, Morais, & Morais, 2013). Microalgal-derived extracts also possess anti-inflammatory, anticancer, antioxidant, and antiviral properties. They are thus used by the pharmaceutical industry for the production of specific drugs and medicines (De La Noue & De Pauw, 1988), and may even possess a neuroprotective potential that could be effective for the treatment of Alzheimer's disease (Olasehinde, Olaniran, Okoh, & Koulen, 2017). In addition to that, algae are currently marketed as 'nutraceuticals' or 'functional foods'[8] in many countries, implying a benefit for health that is far beyond the traditional nutrition (Wells et al., 2017).

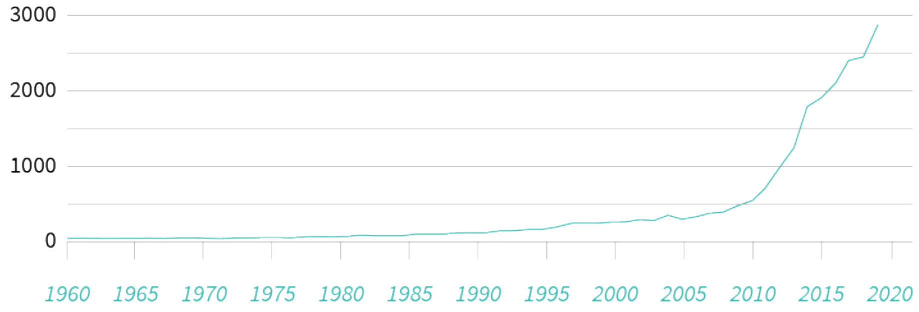
5.3 The rising interest in microalgae research

Although the properties of microalgae were already known for some time, the first modern scientific studies were conducted only between the late 19th century and the early decades of the 20th century. These studies demonstrated the effectiveness of microalgae in wastewater treatments (Bischoff & Knauff, 1883; Cotton, 1910). Since the '50s and after World War II, the research in many scientific fields surged, including phycology. Among the factors that most influenced the study of microalgae were the fear of food insecurity, the housing boom, and the rise of environmentalist movements in America (Paddock, 2019).

In 1947, a report from the Food and Agriculture Organization of the United Nations suggested the need for agricultural development to cope with an increase in the world population in the following decades (FAO, 1947). "*The food policy establishment was quite taken with algae. With half of the people of*

8 These words have no legal status in most of the nations where functional foods are marketed. Nevertheless, nutraceuticals show health benefits both in physical and mental terms.

Figure 5.3. Scopus database. Documents by year – 1960 to 2018 – mentioning the word 'microalgae' in title, abstract, and keywords (21,115 documents).

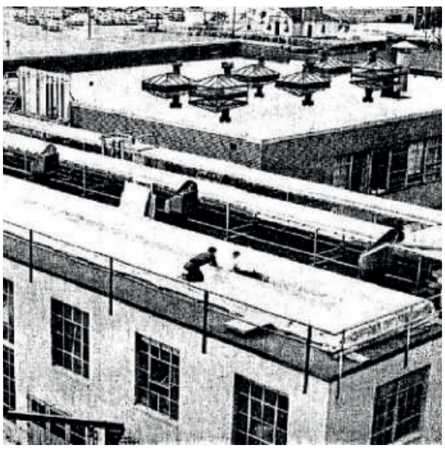


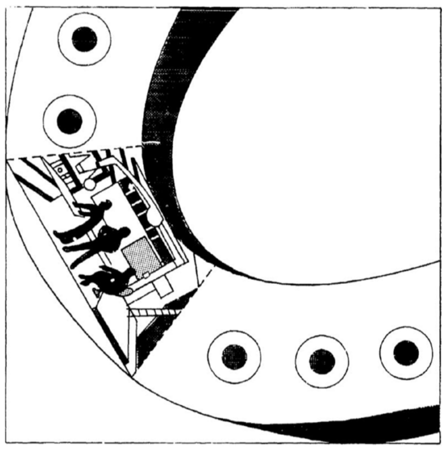
the world hungry, [...] and farmers already struggling to grow enough food, significant doubts began to emerge about the ability of conventional agriculture to stave off catastrophe. Scientists believed that they would have to develop radically unorthodox food sources to feed a much more crowded world" (Belasco, 1997, p. 608). Thus, experts considered algae as a possible remedy to a Malthusian catastrophe and a promising solution for the upcoming years. Major research institutes have funded ambitious studies, and cultivations under controlled conditions have started, aimed at investigating the potential of microalgae in various fields (Garrido-Cardenas, Manzano-Agugliaro, Acien-Fernandez, & Molina-Grima, 2018).

In 1951 at the Massachusetts Institute of Technology, for example, the first experiments included the mass cultivation of microalgae on a rooftop, in raceway ponds, photobioreactors, and plastic bags (Burlew, 1953) (Fig. 5.4). Other major research institutions all over the world, supported by governments, led similar research. By the mid-'60s, the Green Revolution (or Third Agricultural Revolution) and the adoption of new technologies and chemical fertilizers, dismissed the necessity of finding novel food sources. Also, the development of birth control helped to curb population growth. The results of research during the last years were remarkable: in the following decade, during the Cold War and the nuclear arms race, both the US and the USSR began investigating new methods to sustain humans in controlled environments like vessels and

Figure 5.4 (Left). First microalgae mass culture experiments on a rooftop at MIT, Massachusetts. Adapted from "*Algal culture: From laboratory to pilot plant*, by J. S. Burlew, 1953, Washington, D.C.: Carnegie Institution of Washington Publication 600. Copyright 1953 by John S. Burlew.

Figure 5.5 (Right). Artist's conception of incorporation of Algatrons into a space station. Reprinted from "*Microalgae wastewater treatment: A brief history*, by Paddock, M. B., 2019, Preprints, p. 9. Copyright 1966 by Air Force Research Laboratories, United States Airforce.





submarines. "*Microalgae showed the potential to close the loop for life-support systems*" (Paddock, 2019, p. 7). Studies even envisioned innovative devices for microalgae production called 'Algatrons', to be placed in space stations (Shelef, Golueke, Oswald, & Gee, 1966) (Fig. 5.5). With the end of the Cold War, interest in microalgal studies has grown slowly. It started in the 2000s with the energy crisis driven by the rising oil prices and then rose again with the world economic crisis of 2008. Many experts have been attracted by the numerous possibilities of using microalgae, especially for the production of biofuels (Fig. 5.3).

Nowadays, the interest in microalgae is very high, not only for researchers but also for a wider audience. The use of microalgae-based biofuels has not yet been adopted on a large scale due to the production costs, which are still not competitive compared to fossil fuels. The dream of feeding the world with microalgae-based proteins vanished because the market prices of microalgae for food use are too high and affordable only by a few wealthier people – except for some practices in developing countries. However, to face the present and future problems of contemporary global societies, including population growth, air pollution, and food production, a new way of thinking and acting is needed. Research in this field continues to be essential for leading the next sustainable green revolution.

5.4 Properties and applications

Microalgae have a wide range of commercial and industrial applications that attracted the interest of entrepreneurs and researchers from various fields of study. Research over the past few decades has made it possible to advance knowledge in this field significantly. Recent research has shown that microalgae can be used as human food and animal feed, to extract added value components, but also for phyto-purification, the production of biofuels, and organic fertilizers (Khan, Shin, & Kim, 2018). Besides, because of their photosynthetic efficiency (Fig. 5.6), microalgae represent a promising tool for mitigating carbon dioxide in the atmosphere (Singh & Ahluwalia, 2013). Therefore, considering the different fields of application and the relative ease of cultivation, microalgae could play an important role in pioneering solutions in different contexts. This paragraph reviews the principal commercial and industrial applications of microalgae, ultimately focusing on the specific properties of *Spirulina*, one of the best-known microalgae for food use, that is already marketed all over the world.

5.4.1 Commercial applications

The global microalgae market is thriving: in 2018, it was valued at $ 54.64 million, and it is expected to reach around $ 76 million in the next five years (Brand Essence Market Research and Consulting, 2019). This surge is due to improvements in cultivation technologies and the growing demand for nutritional supplements. Commercial applications are manifold. Here are some of the best known (Priyadarshani & Rath, 2012).

- **Human food:** As we have already seen, the use of microalgae as food has not been uncommon throughout history. Due to their nutritional properties, including the abundance of carbohydrates, proteins, vitamins, and minerals, different types of microalgae are currently used for food use. Among these types, *Chlorella vulgaris* and *Spirulina platensis* are dominating the market (Becker, 2004), also because of the relative ease of cultivation. The products found on the market can be fresh or dry. Biomass can be marketed in capsules, tablets, and even liquids. It can be added to many products: pasta, biscuits, crackers, chocolate, drinks, to name a few. These products are generally characterized by a bright green or, in some cases, blue-cyan color.
- **Cosmetics:** Microalgae extracts from *Nannochloropsis oculata*, *Dunaliella salina*, *Arthrospira*, and *Chlorella* are rich in water-binding agents and antioxidants. These extracts are used in the cosmetic industry mainly for skin-care products, anti-aging creams, face masks, and emollients (Stolz & Obermayer, 2005). They can also be used in sun protection and hair-care products because of the UV screening capabilities.

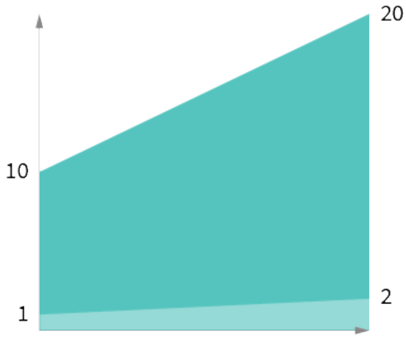


Figure 5.6. Photosynthetic efficiency of microalgae ranges 10–20% in comparison with 1–2% of most terrestrial plants (Singh & Ahluwalia, 2013).

- **Food colorants:** Food pigments are widely used in the industry. Microalgae pigments are natural dyes, an excellent alternative to the artificial ones. From *Spirulina*, for instance, it is possible to extract phycocyanin, a bright blue pigment-protein which is also used in smoothies and other baked products. Because of their eye-catching color, phycocyanin-based foods and drinks are highly appreciated on social media. *Dunaliella salina* is instead grown for Carotene and natural Beta Carotene extraction, which is known to be a superior anticarcinogen and anti heart disease agent. It is also used to improve the color of the flesh of fish and egg yolks.
- **High-value molecules:** High-value molecules are compounds with high concentrations of lipids, proteins, and pigments. Microalgae have a great taxonomic variety that cannot be found in other organisms: therefore, they produce a great variety of biologically active metabolites. Some of the high-value bioproducts extracted from microalgae are phycocyanin, Beta carotene, and astaxanthin, used in cosmetics and for pigmentation; various polyunsaturated fatty acids (PUFAs) used in nutraceuticals; various vitamins, including vitamin C (Li, Wu, Lan, & Dubois-Calero, 2008). Each microalga has unique characteristics and differs significantly from the others.
- **Oil and alcohol:** Many studies recognize that microalgae can be used for producing biofuels because of their high content in oil. Compared to biofuels made from soybeans and other oil crops, microalgae cultivation leads

to higher yields; they do not compete with traditional agriculture because they can be cultivated even on non-arable lands, can grow on wastewater, and sequester CO_2 (Brennan & Owende, 2010; Benemann, 2013). Even if the technology and the facilities do exist, until now, microalgal biofuels still have higher production costs that limit the adoption. Nevertheless, microalgae still appear to be a potential replacement for fossil fuels (Chisti, 2007, 2008). *"The biggest challenge over the next few years in the microalgal biofuel field will be to reduce costs of cultivation and to further improve the biology of biofuel production"* (Singh & Dhar, 2011, p. 622).

5.4.2 Industrial applications

Various industrial applications use microalgae. The production in large quantities usually takes place in artificial basins in rural areas or city outskirts. The largest manufacturers are located in the USA, China, and India.

- **Biofertilizers:** The majority of cyanobacteria can be employed in agriculture as soil additives, soil conditioners, and as feed supplements. They are mainly used in lowlands for rice cultivation (Vaishampayan et al., 2001). Studies have shown a significant increase in root volumes, plant height, and chlorophyll formation, also resulting in improved germination. Using microalgae as a soil additive in agriculture is economically convenient and environmentally safe (Odjadjare, Mutanda, & Olaniran, 2017).
- **Pharmaceuticals:** *"Algae are increasingly being consumed for functional benefits beyond the traditional considerations of nutrition and health. There is substantial evidence for the health benefits of algal-derived food products"* (Wells et al., 2017, p. 949). Pharmaceuticals utilize the bioactive compounds present in algae because they have been proved to have antibacterial activity. A number of blue-green microalgae produce toxins that may have potential pharmaceutical applications (Katircioglu, Aslim, Yuksekdag, & Atici, 2006). Currently, it is possible to buy pills and tablets of microalgae powder, which are marketed as a panacea against many diseases (Buono, Langellotti, Martello, Rinna, & Fogliano, 2014).
- **Aquaculture feed:** Aquaculture and animal feed: *"The popularity of microalgae as aquaculture feed is increasing day by day due to their appropriate size, high nutritional value, high growth rate, antioxidant property, disease resistance power etc."* (Roy & Pal, 2015, p. 2). Microalgae can be used to feed larvae, as well as raising zooplankton and for the production of bivalve mollusks. *Spirulina* and *Chlorella* are also used as feed for other domestic animals like cats, dogs, and ornamental birds, but also poultry, horses, and cows. *Spirulina*, *Dunaliella*, and *Haematococcus pluvialis* are a great source of proteins and a natural pigment for prawns and salmons.
- **CO_2 capture:** Microalgae are single-celled photosynthetic organisms. Photosynthesis is a vital biochemical process that consists in capturing solar

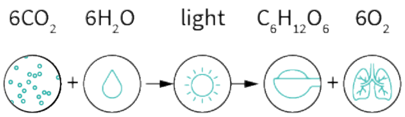


Figure 5.7. Overall balanced chemical equation of photosynthesis, where: CO_2 is carbon dioxide, H_2O is water, $C_6H_{12}O_6$ is glucose and O_2 is oxygen. Light energy is required for the process.

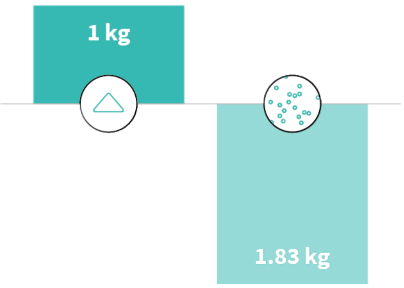


Figure 5.8. Carbon dioxide fixation capacity of microalgae biomass. 1 kg is able to fix around 1.83 kg of CO_2 (Jiang et al., 2011; Gendy & El-Temtamy, 2013).

energy and transforming it into chemical energy. The energy produced serves to convert the carbon dioxide absorbed by the air into sugars, nourishment for the microalga. The waste of this process is oxygen, which is essential for life on Earth (Fig. 5.7). The photosynthetic activity of microalgae is much higher than that of plants, with faster growth and CO_2 fixation rates between 10 and 50 times higher (Bhola, Swalaha, Ranjith Kumar, Singh, & Bux, 2014). "*There is growing recognition that microalgae are among the most productive biological systems for generating biomass and capturing carbon*" (Sayre, 2010, p. 722). In fact, several studies have quantified the carbon dioxide fixation capacity of microalgae biomass. 1 kg of dry biomass is able to fix around 1.83 kg of CO_2 (Jiang et al., 2011; Gendy & El-Temtamy, 2013) (Fig. 5.8). Thus, microalgae cultivation can be a promising tool for carbon sequestration as a response to mitigate climate change (Singh & Ahluwalia, 2013).

5.5 Cultivation techniques

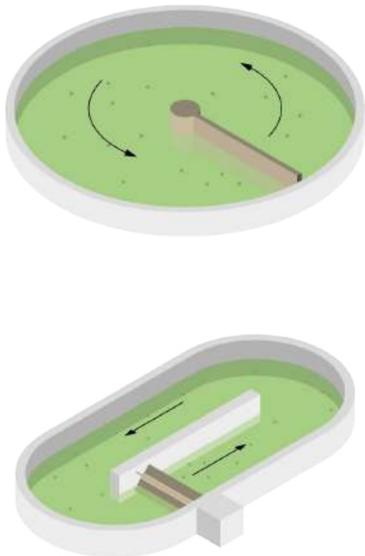


Figure 5.9. Graphic representations of 'Circular open pond' and of a 'Raceway pond'.

Harvesting microalgae for human consumption and medical treatments have been a normal practice in history. Microalgae were spontaneously growing in natural settings like ponds, lakes, and the sea. Around 300 years ago, people started to cultivate them by recreating artificial, low-tech environments for their production (Tseng, 1981). In the '50s, the first scientific studies aimed at investigating the potentials of microalgae took place, and during the decades several new industrial and commercial application were discovered. Novel ways of mass-producing microalgae became necessary especially to optimize their growth, control their chemical composition, and increase yields.

Microalgae are currently harvested with various techniques (Singh & Patidar, 2018), but grown in two main different ways. In ponds, natural or artificial basins that usually occupy large areas of land (Fig. 5.9), and photobioreactors (PBR), aquarium-like closed systems designed and engineered to achieve the maximum photosynthetic activity. Different algal streams require distinct techniques, nutrients, and methods for their cultivation. This section reviews and compare the most diffused farming techniques, with a particular focus on the various typology of photobioreactors.

5.5.1 Open ponds

Cultivating microalgae in open ponds is a very common and diffused method. Ponds can be found in the wild, but in most of the cases the tanks are man-made to replicate and enhance natural growth conditions. Some ponds are unstirred, nevertheless is it highly recommended to agitate the water to avoid stagnation. Unstirred ponds are not common when it comes to the cultivation for industrial applications. They were instead more diffused in developing countries, and even in Europe during World War II to produce algae to be

Figure 5.10. Cyanotech facility at Kailua-Kona, Hawaii harvests several algal strains in open raceway ponds. Copyright 2012 by Cyanotech.

used as a food supplement. Ponds may be built in several shapes, but mainly in circular or elongated ones (e.g., raceway ponds), to allow better water circulation. Circular ponds are characterised by a central agitation system and a water depth of around cm 70; they are the oldest systems for cultivating microalgae on a larger scale, and draw inspiration on similar pools for wastewater treatments (Vieira Costa & de Morais, 2013) (Fig. 5.10). Compared to other cultivation methods, open ponds are quite cheap to build and operate, but they are also subjected to the contamination by external factors, including rain and wind (Fig. 5.11).

5.5.2 Raceway ponds

Raceway ponds are closed-loop, artificial open ponds with semicircular or oval-shaped circulation channels. They are also called 'high-rate algal ponds' and are used for the commercial production of microalgae. *"Raceway tanks are the most widely used artificial systems of microalgal cultivation"* (Vieira Costa & de Morais, 2013, p. 3). The water flow is continuously guaranteed by the use of slowly rotating paddle wheels. They are pretty shallow, with a depth between cm 20 and cm 50, in order to have a greater photosynthetic surface in relation to the total volume of water (the culture depth is no more than cm 20-30). Raceway ponds can be constructed with concrete, bricks, and glass fiber (Brennan and Owende, 2010), covered with long-lasting and resistant plastic membranes (usually PVC liners). Raceway ponds are cheap methods of producing microalgae on a large-scale (Chisti, 2008): *"the surface area of a single pond does not usually exceed 0.5 ha, but can be larger"* (Chisti, 2016, p. 23).

5.5.3 Closed ponds

Algal cultures in open ponds (unstirring, circular, and raceway) are usually threatened by atmospheric elements, dust, or insects, and can be possibly contaminated by other algal streams. When the temperature increases, the water evaporates and a refill is necessary. In this case, rain is beneficial to overcome the loss, but it could overflow the pond if precipitations are excessive. To tackle these issues and to have relatively better control over the growth environment, ponds can be enclosed in glass houses or plastic greenhouses (Chisti, 2012), or just covered with a transparent layer. Covering ponds come at a cost and these solutions are indicated especially for high-value and low volume products, i.e. nutraceuticals (Becker, 1994).

5.5.4 Photobioreactors

A photobioreactor is a closed system for the aquaculture of phototropic organisms like microalgae and cyanobacteria. This aquarium-like apparatus is *"an enclosed, illuminated culture vessel designed for controlled biomass production"* (Singh & Sharma, 2012, p. 2349). Photobioreactors present several advantages over the cultivation in ponds: these include better control of the culture parameters, reduced water evaporation, and minimization of contamination by external factors, among others (Fig. 5.12). Nevertheless, their setup costs are much higher, and only a small part of the total global production of microalgae is produced in closed photobioreactors (Posten, 2009). This part of the production is especially addressed to the pharmaceutical and nutraceutical sectors, that have higher margins of profit. A detailed comparison of the main differences between the cultivation in open or closed systems is found at paragraph 5.5.6.

Photobioreactors have been designed and engineered in several shapes, dimensions, and structures, not only with the aim of maximizing the algal production, but also to optimize spaces, reduce overall costs, and increase their user-friendliness. According to a recent review, photobioreactors can be currently found as vertical or horizontal tubular PBRs, flat panel PBRs, helical type PBRs, stirred tank PBRs, and even as plastic bags (Huang, Jiang, Wang, & Yang, 2017), but researchers are experimenting novel solutions on a regular basis. All PBRs are constructed with similar components and these are a tank (glass or plastic), a lighting mechanism (natural and/or artificial), an agitation system, an aerator to provide CO_2, and a feeding pump.

- **Tubular photobioreactors**: The cultivation of the microalgal biomass takes place inside transparent tubes with a minimum diameter of generally mm 10 to a maximum of mm 60, to maximize the surface area for illumination. Their length can be up to several hundred meters and according to the way they are arranged. Different patterns and orientations can be used: horizontal arranged in a plane, stacked vertically in a fence-like system, or inclined. Vertical PBRs are promising for the production of microalgae on a large scale, even if they still have some limitations (Vree, Bosma, Janssen, Barbosa, & Wijffels, 2015). According to Vasumathi, Premalatha, and Subramanian (2012), some of the main problems related with the uses of tubular PBRs for large-scale production are the photolimitation, the accumulation of oxygen, the CO_2 depletion, and the high temperatures that the systems may reach.

- **Flat panel photobioreactors**: A flat panel bioreactor assumes the form of a parallelepiped. Its sides are typically composed by transparent surfaces made of glass, polycarbonate or plexiglass, and framed within a sealed, usually metallic, structure. The agitation of the cultivation is provided by a bubbling mechanism or through a rotating internal motor. Flat panel photobioreactors are characterized by high surface/volume ratio, and the literature suggests that in particular conditions higher volumetric mass productivity has been reached, compared to similar bubble column reactors (Singh & Sharma, 2012). In the attempts of making the sunlight utilization more efficient, several experimentations have been conducted. For example, Tredici and Zittelli (1998), subdivided the internal volume between the panels into five different channels, resulting in promising yields. The different angles of incidence of the sunlight also affect the cultures: panels PBRs can thus be lying on flat surfaces, be placed vertically, or inclined at a particular slant facing the sun. The temperature of this kind of PBRs

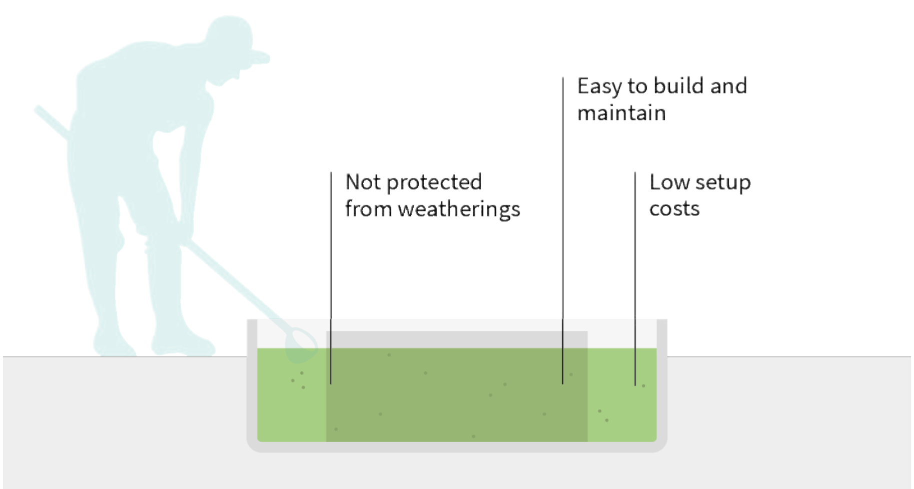


Figure 5.11. Graphic representation of an open pond.

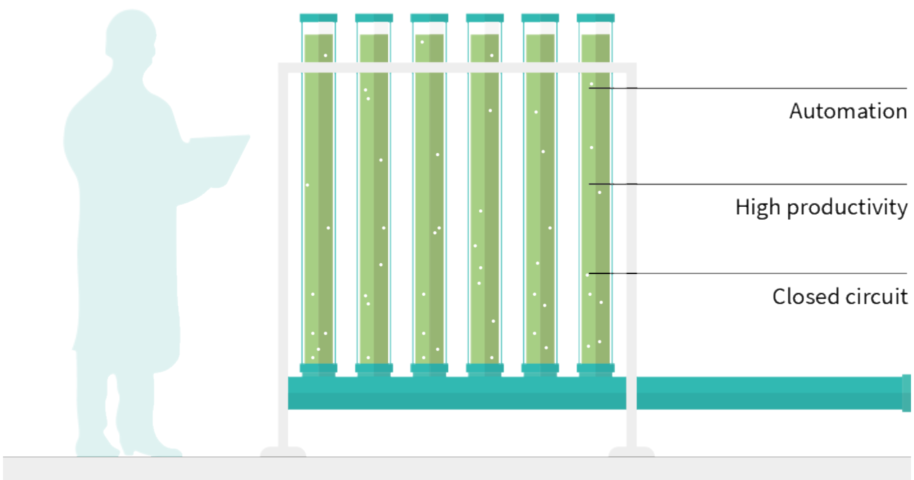


Figure 5.12. Graphic representation of a tubular photobioreactor.

can be easily adjusted by sprinkling water on their surfaces (Dasgupta, et al., 2010), or by submerging them partially in cooler tanks. Conversely, flat panel photobioreactors cannot resist to very high pressures, that could also negatively influence the growth of microalgae (Elrayes, 2018). Because of their limited thickness and the relatively easy possibility of assembling them modularly, flat panel photobioreactors have been also used in several architectural integrations within 'green façades' (Bastanfard, 2018; Elrayes, 2018; Kyoung-Hee, 2013; Marino & Giordano, 2015; Proksch, 2013).

- **Helical type photobioreactors**: This kind of PBRs is made by arranging flexible plastic tubes in a 3D helix-shaped structure, at different inclinations. According to the angle, the photobioreactor may assume a conical shape. It was reported that the best inclination to achieve maximal photosynthetic efficiency is 60° (Morita, Watanable, & Saiki, 2000). Helical tubular photobioreactors have a good surface/volume ratio and it is not difficult to scale up the production by increasing the number of units. Nevertheless helical PBRs also present difficulties in terms of maintenance and regular operations (Dasgupta et al., 2010).
- **Plastic bag photobioreactors**: Cultivating microalgae in plastic bags is gaining popularity in the last years, especially because of their reduced costs (Wang, Lan, & Horsman, 2012). Bags are usually surrounded by an external supporting frame, and because of their adaptability, they can be placed in various patterns with regard to the available space. The volume of the bags ranges from around 20 l up to more than 250 l. The research demonstrated that is also possible to immerse high-volume plastic bags in water pools to mitigate the overall culture temperature and reduce production costs to a greater extent (Huang et al., 2017). Plastic bag PBRs are used both for smaller- and larger-scale solutions. Zittelli, Biondi, Rodolfi, and Tredici (2013) claimed that the productivity of these systems can be very high (productivity still rely on various parameters (e.g., temperature), location, the dimension of the bag, etc.). Even if the plastic bags are less expensive than other materials, their replacement rate is a significant cost driver (Zhu, Anderson, & Jones, 2018). Bags are fragile and can be easily broken, resulting in substantial leakages. Their life-span is also short compared to high-quality glass or even thick PVC panels/pipes, and the final disposal presents potential problems for the environment (Wang et al., 2012).

5.5.5 Hybrid systems

From the research and the practice it is clear that ponds and photobioreactors have great potentials but at the same time limitations (refer to Table 5.1 and the paragraph 5.5.6). Combined systems for algal production may overcome them, by exploiting the best features of both techniques. These systems are called ‘Hybrid Algae Production Systems’ (HAPS). HAPS are engineered pond systems for the production of microalgae biomass that combine the commercially scalable advantages of ponds with the added benefits of photobioreactors without their high costs (Idaho Sustainable Energy, 2013). In this two-stage hybrid system, firstly a continuous inoculum is produced by the PBRs in a closed, uncontaminated environment and at an economical price compared with short-period batch cultures in open ponds (Huntley & Redalje, 2007). The inoculum is subsequently poured into the ponds (open or closed) and is grown with regular techniques.

This type of system is used both on large and small scale plants and is widely adopted. Studies demonstrated that hybrid cultivation is resulting in superior production of lipid-rich microalgae, with significantly higher growth rates (Narala et al., 2016).

5.5.6 Ponds vs. photobioreactors: A comparison

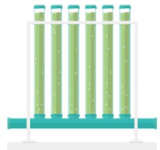
As seen in the previous paragraphs, microalgae cultivation techniques are diverse and vary according to the algal streams, the productivity goals, and mostly the economic constraints. It is hard to reply to the question ‘Are photobioreactors better than ponds?’. A universal optimal solution does not exist yet – and probably will never – but each production should be tailor-made with respect to its different characteristics. Undoubtedly, ponds require more land for their installation, since they can absorb light only from a flat 2D surface. Their photoactive volume is thus quite limited, and this has repercussions also on the volumetric and areal productivity. Ponds are also subjected to various kind of contaminations (conflicting algae, dust, insects, etc.), and to greater water evaporation. If not properly closed, productions in ponds are heavily dependent on weather conditions.

Photobioreactors require limited land for their installation: this might be practical when the price of soil is high. Since cultivations grow within a closed environment, PBRs are not vulnerable to atmospheric events and are facing very low contamination risks. The parameters of the cultivation can be also controlled more easily, resulting in many cases in improved biomass quality. PBRs, in general, are characterized by a considerable photoactive surface-to-volume ratio and the production is more reliable. An interesting feature of PBRs is their flexibility. The tanks can be drained and filled again in a limited time and with easy operations, to keep pace with market needs and sudden client requirements. By connecting more pipes or modular panels, it is possible to scale them up and reach higher production volumes.

The major weaknesses of photobioreactors are their setup and operational costs. The structures are fixed and bulky and need expert workers for their assembly. To guarantee a high refraction index and durability, special glasses need to be used (it is also possible to utilize plexiglass or polycarbonate panels, but their quality over time gets lower and replacements are necessary). Some photobioreactors require artificial light to operate. The energy input to keep the lights on and for mixing the biomass is high, and in several places, electricity is expensive as well. Expert personnel should supervise the performances of the photobioreactors, together with some other people in charge of the harvesting. For all the above-mentioned reasons, nowadays open ponds and two-stages hybrid systems pond/PBR are recommended for large-scale production of microalgae (Narala et al., 2016). Nevertheless, each kind of production is characterized by unique features and specific solutions need to be adopted. Table 5.1 visually compares the pros and cons of the two main cultivation techniques, rating them on a qualitative scale ranging from 'very poor' to 'very good', as an adapted result of the analysis made by Narala et al. (2016).

Table 5.1. Comparison of microalgae cultivation in open ponds and photobioreactors. Adapted from "Comparison of microalgae cultivation in photobioreactor, open raceway pond, and a two-stage hybrid system", by Narala, R. R. et al., 2016, *Frontiers in Energy Research*, *4*(29), p. 8. Copyright 2016 by R. R. Narala.

+ Good
− Poor

		
Space required	−	+
Contamination risk	−	+ +
Water consumption	−	+ +
Photoactive volume	− −	+ +
Volumetric productivity	−	+ +
Areal productivity	−	+ +
Biomass quality	−	+ +
Flexibility	−	+
Production reliability	−	+ +
Setup costs	+	−
Production costs	+	−
Weather dependance	−	+
Harvesting costs	−	+
Process control	−	+ +

5.6 Harvesting process and nutrients

For the cultivation of microalgae at both artisanal and industrial levels, particular techniques and processes are necessary for optimizing the harvest. The following paragraphs briefly analyze the main processes and culture media.

5.6.1 How to harvest Spirulina

Regardless of the technique used for cultivation (pond, photobioreactor, hybrid systems), biomass is ready for harvesting when its density is adequately high. Its readiness can be noticed from the color: if the shade is dark green, then it means that there is a large concentration of algae.

There are reliable analog and digital tools for measuring this. The Secchi disk[9], for instance, is a plain black and white circular disk, mounted on a pole or line, which can be immersed in water to measure its turbidity/transparency and, in this case, the density of the cultivation. Microalgae need light, heat, and other nutrients to grow: if the density of the culture is high, it is very likely that a limit level has been reached that does not allow light to penetrate completely, thus limiting photosynthetic activity (Fig. 5.14). *"If the light intensity is above a critical value and reaches the saturation level, the growth will be inhibited by the light (photoinhibition) and the light will be wasted [...]. On the other hand, if the light intensity is below the level that is necessary to balance the maintenance, the growth will be limited by the light (photolimitation) and the culture will collapse"* (Huang, Jiang, Wang, Yang, 2017, p. 319).

Harvesting microalgae means the separation of algae from their growth medium. *"The harvesting method intensely depends on the physiognomies of the micro algae chosen, density and size of the microalgal cell, specifications of the final product and on allowability for reuse of the culture medium [...]. Regardless of the objective of harvesting process [...] their high growth rates which needs frequent harvesting compared to land crops make harvesting process a challenging task"* (Singh & Patidar, 2018, p. 500). There is no universal harvesting technique: filtration, centrifugation, and flocculation are the most used. The simplest of these is filtration, which usually takes place employing filter cloths with small meshes. This operation is mainly carried out by artisanal growers for pond cultivations. Filtration provides wet biomass. The excess water, still rich in nutrients, is returned to the culture tank. Biomass can be eaten fresh within 2-3 days or frozen. This very malleable paste can be extruded in '*Spirulina* spaghetti' and laid on a microperforated tray to dry. Once dry, the *Spirulina* nibs are ready to be packed and sold. They can also be grounded in powder. By drying the *Spirulina* directly on a flat tray – without extruding it – *Spirulina* petals can be obtained. Figure 5.13 describes this process.

5.6.2 Growth media

Spirulina can live in a wide range of waters. Nonetheless, it prefers an alkaline environment to grow (pH 8-10). Like any other living organism, it needs mi-

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9 The name comes from its inventor Angelo Secchi, an Italian Jesuit Father who lived in the 19th century. He is considered as a pioneer of astronomical spectroscopy and was active in oceanography, meteorology, and physics.

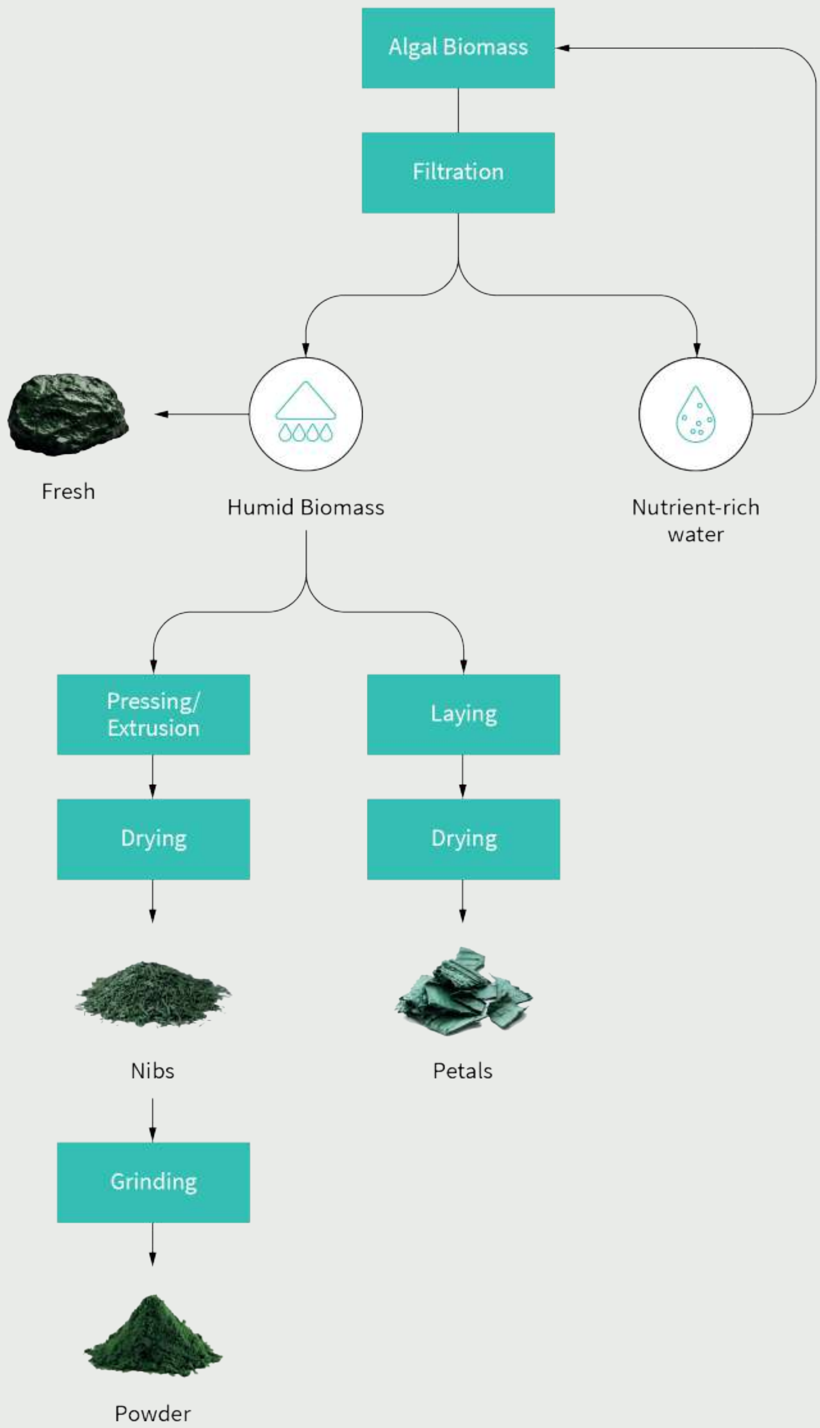


Figure 5.13. Spirulina harvesting process and primary products obtained: fresh biomass, nibs, petals, and powder.

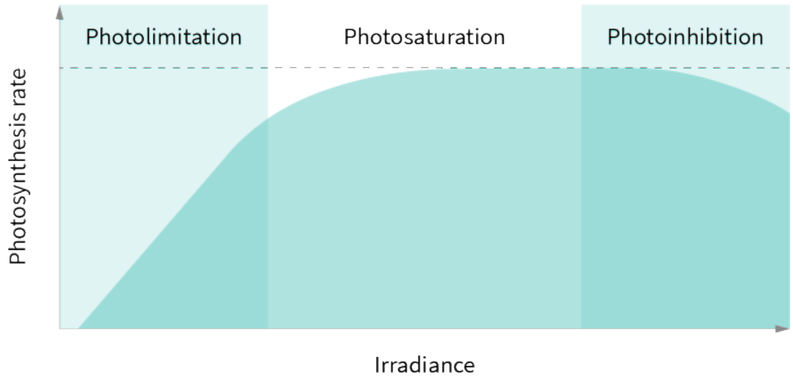


Figure 5.14. PI-curve that relates photosynthesis rate to irradiance. Adapted from "Photobiology of microalgae mass cultures: understanding the tools for the next green revolution", by M. Tredici, 2010, *Biofuels*, *1*(1), p. 146. Copyright 2010 by M. Tredici.

cronutrients, and if they are not sufficiently present in water in nature, it is necessary to integrate them. Generally, *Spirulina* demands nitrogen, phosphorus, and potassium, the main ingredients of fertilizers. Thanks to scientific research, various culture mediums have been perfected. The most used is the 'Zarrouk medium', which has successfully served as the standard medium for many years (Zarrouk, 1966). Dr. Zarrouk prepared this medium from distilled water, adding baking soda, potassium phosphate, sodium nitrate, potassium sulfate, sodium chloride, magnesium sulfate, calcium chloride, ferrous sulfate, edetic acid (Fig. 5.15). Table 5.2 describes its chemical composition. By changing the proportions of nutrients, it is possible to experiment and modify some growth parameters: this technique is widely used, especially for laboratory studies.

Table 5.2. Zarrouk culture medium composition (Zarrouk, 1966).

Reagents	**Amount (g L^{-1})**
$NaHCO_3$	16.8
K_2HPO_4	0.50
$NaNO_3$	2.50
K_2SO_4	1.00
NaCl	1.00
$MgSO_4$. $7H_2O$	0.20
$CaCl_2$	0.04
$FeSO_4$. $7H_2O$	0.01
EDTA	0.08

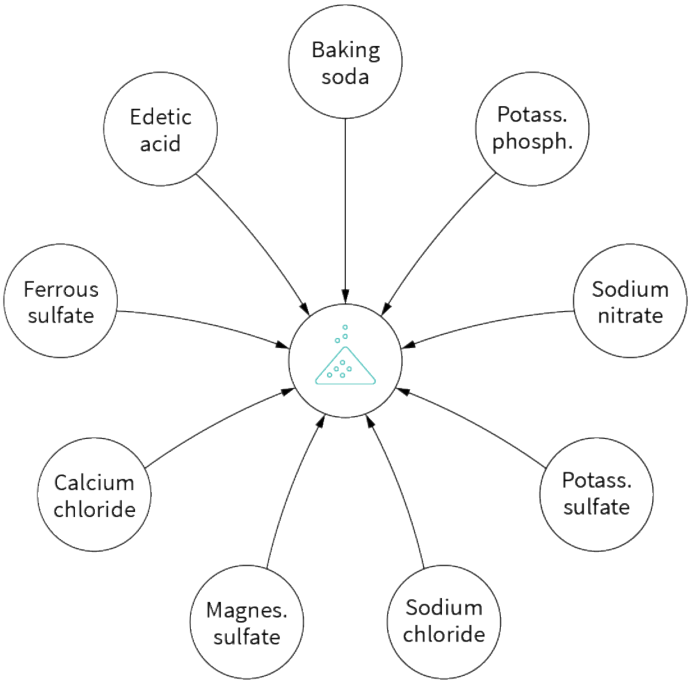
The cost of the culture media, especially for large plants but also for small productions, can be high. Certified and synthesized products are used in large-scale cultivations. Small local producers, however, can extract the nutrients autonomously: a sustainable practice that requires a certain degree of attention and experience.[10] To prepare an organic and cheap culture medium, it is possible to use Natron (a natural mixture of sodium carbonate and sodium bicarbonate) or wood ash lye. Everything else can be replaced by 4 ml of urine per liter and, if necessary, iron. Phosphoric acid extracted from calcined bone powder, Chili's nitrate, leaves from edible plants are also possible substitutes and sources of carbon and minerals, necessary for the abundant growth of the culture (Jourdan, 2001, 2006, 2018).

5.7 Microalgae wordwide

Microalgae are studied, produced, and marketed all over the world. This paragraph reviews the major research centers, universities, and manufacturers,

10 Some of these practices are not allowed for the production of commercial *Spirulina*, as there may be hygiene problems. Urine may contain pathogens if the subject is not healthy. The extraction of phosphoric acid from bones is a risky operation that requires precautions and expertise.

Figure 5.15. The main reagents of the Zarrouk culture medium.



highlighting their specific characteristics. Developed countries have invested substantial economic resources in public research and the realization of sizeable private production plants. In some villages in developing countries, alternately, there is a thriving economy based on the production of *Spirulina* in small farms. It is interesting to note that both production models are valid but, above all, how traditional farming techniques have also been adopted in western countries by small independent growers. The paragraph also briefly analyzes the international microalgae market and the primary sales methods, with a particular focus on the Italian context.

5.7.1 Research centers and main producers

Internationally recognized centers are conducting cutting-edge studies on microalgae worldwide. Public and private research institutions mainly subsidize their studies. Among these, Wageningen University & Research, a university and research center in the Netherlands where the AlgaePARC was set up, has become very important. The AlgaePARC is a place where lab- and pilot-scale projects are developed to deliver fundamental research and bring applications in the market.

At the European level, the studies of University College London in the United Kingdom are also critical, as well as the well-established Italian University of Florence. Like many other universities, the Department of Agricultural Sciences and Technologies has also created a private spin-off company that deals with consulting, evaluation, design, training, installation, and start-up of specific solutions for the pilot to large scale algae plants. The company offers its customers proprietary patented photobioreactor technologies and a collection of more than 1,200 microalgal and cyanobacterial strains, which can be used for a multitude of applications. Several European institutions, scientists, industrialists, and decision-makers are joining up in EABA – European Algae Biomass Association, with the intent of promoting cooperation and interchange in the field of algal biomass for all the uses.[11] Annual conferences such as AlgaEurope and Aquafarm, offer a unique opportunity for the exchange of knowledge and practice between academia and industry, with international speakers and attendees. Similarly, in the USA, the Phycological Society of America organizes conferences, workshops, courses and publishes periodical publications on internationally-renowned scientific journals.[12] Especially in recent years, an increasing number of researches are coming from India and China, which are investing countless human and economic resources in this field. Notable are the studies of the Chinese Academy of Sciences in Beijing and the work of the Chinese Microalgae Industry Alliance (CMIA), intending to improve the microalgae food standard system and lower production costs to meet market requirements (Chen, Wang, Benemann, Zhang, Hu, & Qin, 2016).

Microalgae are mainly mass-produced in large plants outside inhabited areas. *"Some of the best worldwide known Spirulina producing companies are: Earthrise Farms (USA), Cyanotech (USA), Hainan DIC Microalgae Co., Ltd (China), Murugappa Chettiar Research Center (India), Genix (Cuba) and Solarium Biotechnology (Chile)"* (Koru, 2012, p. 194). The plants are usually hybrid systems, characterized by large raceway ponds. These large productions satisfy a large part of the world market needs but do not fully cover it.

Large plants have also recently been opened in Europe, with microalgal production in photobioreactors. The Buggypower group, in collaboration with Electricidade da Madeira, inaugurated in 2011 a pioneering plant for the production of microalgae for biofuels – but not only – in Porto Santo, a Portuguese island off the coast of Morocco. The production of microalgae has been an economic engine and source of employment for the island (Varela, 2017). In March 2018, Ecoduna celebrated the grand opening of a 1-hectare sized plant in Bruck an der Leitha, a city in Lower Austria (Fig. 5.17). To date, this plant is the largest photobioreactor plant for the cultivation of microalgae in Europe, with a total volume of 780 m^3 and around km 230 of self-cleaning glass tubing (Schott, 2018). Ecoduna produces GMO-free *Spirulina* and Chlorella and offers its microalgae as raw material or final product in the form of powder, capsules, tables or extracts both for private customers and the industry. The plant produces about kg 160 of dry biomass daily, but the company is working toward reaching an annual production of t 100. The company's

11 More information at https://www.eaba-association.org/en

12 More information at https://www.psaalgae.org

Figure 5.16. The main microalgae producers and research centers worldwide (Belay, 1997; Benemann, 2013, 2015; Priyadarshani & Rath, 2012).

Ecoduna
Gemeinde Bruck an der Leitha (Austria)
Sun Chlorella Corporation
Ashoro (Japan)
Algatechnologies
Ketura (Israel)
Hainan-DIC Microalgae
Hainan (China)
Energaia
Bangkok (Thailand)
Betatene (Cognis)
Whyalla (Australia)
Murugappa Chettiar Research Centre
Chennai (India)

Figure 5.17. Interior view of Ecoduna's Parella plant in Austria. Retrieved from https://www.facebook.com/ecoduna/photos/a.2387265021289816/2387275537955431/?type=3&theater Copyright 2018 by Ecoduna AG.

mission is to lead the European market by collaborating with universities and governments, while educating businesses and final customers on the benefits of microalgae (S. Fluch, personal communication, February 13, 2019). Smaller production plants, such as Archimede Ricerche in Camporosso in the Liguria region (Italy), produce particular species of microalgae to be used in natural cosmetics (oils, pigments), in aquaculture and as a food supplement (nutraceuticals). The map (Fig. 5.16) shows the major research centers and relevant production plants worldwide.

5.7.2 Global Spirulina market

The global microalgae market is expanding. *Spirulina* and *Chlorella* are expected to lead the market from 2017 to 2026 and account for over 80% market revenue share. Over $ 75,000,000 are estimated to be procured from sales of microalgae across the globe (Persistence Market Research, 2018). Their countless possibilities attract an increasing number of scientists and investors. At the same time, consumers are increasingly looking for healthy and nutritious products. Consumers – and especially young urbanites – are seeing healthy living as an ongoing trend as self-care continues to increase. Sustainability has become a primary element, along with nutritional values and convenience (Resvey Research Services, 2019). Currently, *"as per the survey conducted by Spirulina.Company, the annual production of Spirulina platensis is 5,000 tons. It is difficult to determine the exact production because of the many relatively small producers in Asia, but the capacity exists to expand production of Spirulina platensis to meet any growing market demand"* (Sharma, Kaur, & Marwaha, 2019, p. 435). *"Data understate the real scale of world microalgae farming because of unavailable data from important producers such as Australia, Czechia, France, Iceland, India, Israel, Italy, Japan, Malaysia, Myanmar and the United States of America"*

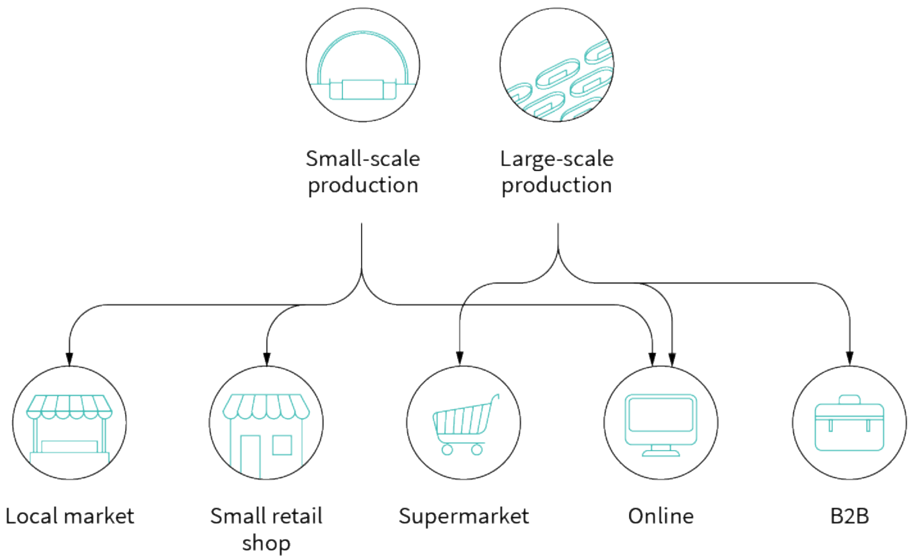


Figure 5.18. Microalgae sales channels.

(FAO, 2020, p. 32). The average wholesale and retail selling price varies considerably, especially in different geographical areas. In western countries, the selling price to the end customer can go up to $ 600.00 per kg. In Asia, this price is significantly lower. In China, for example, it is possible to buy 1 kg of dry *Spirulina* online at around ¥ 100.00 (€ 13.17). In India the market price for 1 kg of *Spirulina platensis* is around ₹ 1,200-1,500 (€ 14.43-18.04) (Sharma et al., 2019).

As regards the sales channels (Fig. 5.18), large producers prefer the sale of dry biomass through traditional retail channels, especially in supermarkets, or the B2B sale in large quantities (in many cases, production happens based on client requests). Small producers, on the other hand, prefer selling fresh and dry biomass in local markets and small shops. Online sale is a growing trend. Positive results are expected in the coming years to come for the global microalgae market.

5.7.3 Spirulina farms in developing countries

For centuries, local tribes have been harvesting *Spirulina* from Mexican and African lakes, where it grows spontaneously. This practice is still in use on the shores of Lake Chad, in the Sahelian zone of West-central Africa (Fig. 5.19). *Spirulina* helps to restore the intestinal flora while strengthening the immune system. Moreover, it "*is considered as an excellent food, lacking toxicity and having corrective properties against viral attacks, anemia, tumor growth and malnutrition*" (Sánchez et al., 2003, p. 7). Recognizing this, over the past 40 years, numerous humanitarian and commercial projects which involved the cultivation of *Spirulina* have been implemented in many countries, including Mexico, Myanmar, Thailand, India, Cambodia, Costa Rica, Ecuador, Togo, Chad, Madagascar, Niger, and Burkina Faso. These are regions between the Tropic of

Cancer and the Tropic of Capricorn that have a suitable temperature range for *Spirulina* production. *"There are many areas on the earth that [...] have an annual productivity potential of 200 tons per hectare"* (Tredici, 2010, p. 153).

The cultivation of *Spirulina* is an effective remedy against chronic malnutrition and permits the creation of numerous jobs. *Spirulina* in developing countries is cultivated in small algae farms (Fig. 5.20). The first experiments started already in the 70s, thanks to Denise and Ripley Fox, devoted pioneers of village-scale integrated systems for *Spirulina* production (Henrikson, 2013). These projects are very similar to the ones realized with the 'systemic design approach' and 'circular economy' in mind. The Swiss NGO Antenna Foundation has also been contributing to charitable activities in Africa, Asia, and South America, and is still currently engaged in research and dissemination of technologies to meet the basic needs of the poor in developing countries.[13] The functioning schema of an integrated algae farm is simple: the natural resources of the local context are used and integrated, if necessary, with human-made elements. Latrines waste and livestock waste are placed in a biogas biodigester that produces compost; The latter is used in field crops; The methane generated by the biodigester is used as fuel; The exceeding CO_2 is pumped into a *Spirulina* algae pond where the microalgae grow abundantly, thanks also to the nutrients provided (partly coming from the sterilized biomass from the biodigester). *Spirulina* is then used for breeding fishes in a fish and waterweed pond (Fig. 5.21).

13 More information about Antenna Foundation at: www.antenna.ch/en/

Figure 5.19 (left). Dihé (*Spirulina*) grows in the water pools that form to the northeast of Lake Chad. The harvesting requires skill and expertise, which has been passed down from mother to daughter. Reprinted from FAO website, 2010, retrieved from http://www.fao.org/agriculture/crops/thematic-sitemap/theme/spi/photogallery/en/ Copyright 2010 by Marzio Marzot.

Figure 5.20 (right). *Spirulina* harvesting at Dogondoutchi Farm, Niger. Reprinted from Antenna France website, 2007, retrieved from https://www.antenna-france.org/projet/dogondoutchi/ Copyright 2007 by Antenna France.

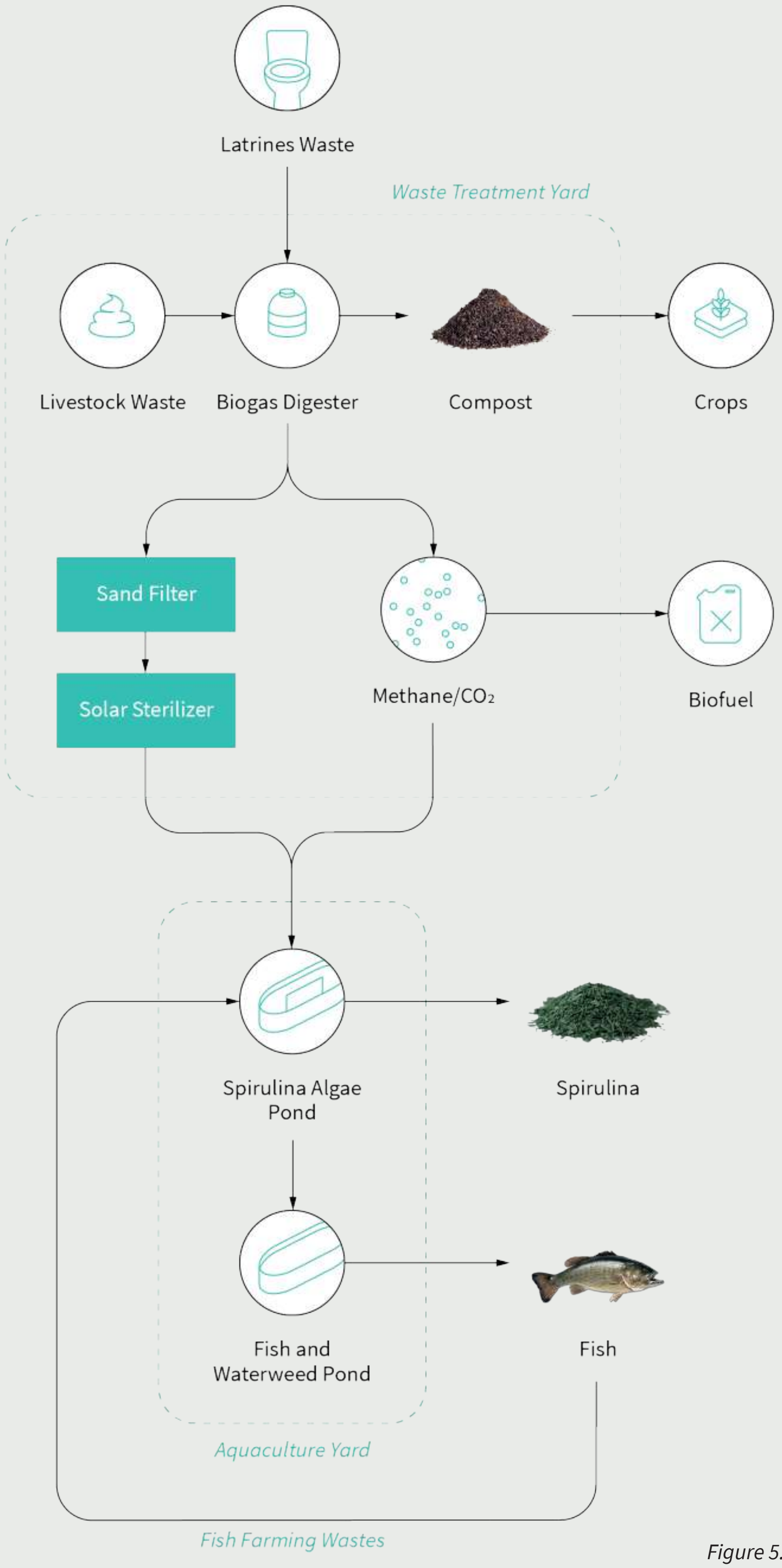


Figure 5.21. Layout of an integrated health and energy system. Adapted from *Algae microfarms* (p. 21), by Henrikson, R., 2013, Richmond, VA: Ronore Enterprises. Copyright 1994 by R. Henrikson.

Few simple elements are required to set up a *Spirulina* culture. Without going into technical details, the most economical ponds – in the medium-long terms – are the ones made of polished cement. They are usually covered with a greenhouse to minimize evaporation and contamination. The water in the tank is moved manually or with a paddle wheel. Solar panels can be installed in the village, to provide electricity when absent. This kind of project has also aroused the interest of FAO, which has long been monitoring the investments required, the methods of communication, and the possibility of creating additional pilot projects in connected communities in the various villages in developing countries (Piccolo, 2011).

There is no doubt that *Spirulina* farms in these contexts are not only used for the production of biomass but they extremely useful also for other reasons. Economically, new jobs are created, together with a modest market for new products. Commercial distribution allows people to be financially self-sufficient. At the environmental level, the production of organic *Spirulina* also promotes biodiversity and helps capturing CO_2. Water and waste systems are also better managed. The use of photovoltaic panels excludes the use of fossil fuels. On a social level, local know-how is valued, local populations are educated, and it is possible to fight malnutrition. Women are empowered because they manage to create their own economic independence. To lower costs, it is possible to extract proteins whose market value is high or to use the surplus of CO_2 from neighboring industrial plants. Hot water could come directly from geothermal stations. This model, therefore, requires some improvements. Nonetheless, this model has also been adopted in other countries: for instance, there is a vast network of producers in France called 'Fédération des Spiruliniers de France' who grows *Spirulina* with artisanal practices. The following paragraph describes this in detail.

Figure 5.22. *Spirulina* producers in France. 101 algaepreneurs are part of the network 'Fédération des Spiruliniers de France'. Data as at 16 April 2019. Adapted and retrieved from: http://www.spiruliniersdefrance.fr

5.7.4 The algaepreneurs

As we have seen, *Spirulina* production is relatively simple. With rudimentary methods, it is possible to produce high-quality biomass: a source of nutrients for the eaters, and income for farmers. The experience gained by NGOs in developing countries since the 1980s has also served in other countries. Upon returning to France, some technicians became experts in *Spirulina* production and started cultivating it in small-scale plants at home. Family and communities are running the so-called 'algae microfarms' with simple production systems, usually in low-cost ponds. This practice has spread widely throughout France. To date, there are about 100 artisanal *Spirulina* producers there, mainly in the south-east area (Fig. 5.22). This number is continuously growing. The producers joined up in an association called 'Fédération des Spiruliniers de France', to agree on quality control guidelines and business practices. The farmers help each other by exchanging valuable tips on how to optimize production, create culture mediums with waste and organic nutrients, and exchanging inocula to restart the cultivations in case of contaminations or death. They also meet periodically in informal symposia.

Spiruliniers are self-made entrepreneurs and deserve the title of 'algaepreneurs' (Fig. 5.23). Their *Spirulina* is produced and sold locally, usually in markets, small shops, or pharmacies. Some farmers also have rudimentary e-commerce websites for online sales. Usually, there is never an excess of unsold products. Although small-scale productions have higher costs than large producers who enjoy economies of scale, micro farmers can capture the full retail value chain by selling directly to customers. *"Big producers get only 10% of the retail price selling bulk Spirulina in quantity to manufacturers. They may capture 35% off the retail price when they tablet, bottle, label, package and market branded finished products and sell through the typical wholesale and retail distribution system that takes 65% of the retail value. Microfarmers [...] can capture 100% of the retail value"* (Henrikson, 2013, p. 39). By going fresh, micro farmers can guarantee frequent rebuys. French Spiruliniers produce almost exclusively in ponds up to a maximum of about 300 m^2. They can guarantee direct sales prices to the consumer of around € 150.00 per kg.

In 2001 the first version of 'Cultivez votre Spiruline. Manuel de culture artisanale pour la production de Spiruline' (Grow your own Spirulina. Manual for artisanal Spirulina production) was published by chemist Jean-Paul Jourdan.[14] The manual teaches the basics of *Spirulina*, the methods of culture, and how to create biological media cultures, starting from the other waste. The manual is available for free and is used by most of the Spiruliniers.

The business model of the Spiruliniers de France is also adopted in other countries, by individual producers who, however, are not part of a shared network. There are also cases in Italy. One of these is the Spirulina G farm by Nuccio Garoscio, in the inner Liguria region. Thanks to his wife, Garoscio came into contact with the French Spiruliniers and, once he learned that there were no such activities in Italy, he decided to start this new adventure. Garoscio has reconverted part of his flower business into microalgae production (Novello, 2018). According to Garoscio, there is a keen interest in the product, and people willingly buyback: for him, the taste of the final product, the quality of water, and nutrients are way more important than marketing. The cultivation takes place in a pond of 42x4 meters (around 170 m^2). A few months after starting the business, the first test cultivation in a 50 m^2 tank produced about 20 kg of dry *Spirulina*. The retail price, in local markets, is around € 200.00 per kg. Its customers are adults around 40-50 years old, medium-spending. Interested

14 The latest updated version available dates back to February 2018. It is available at the following link: http://spirulinefrance.free.fr/Resources/Manuel%20du%202%20fevrier%202018.pdf

Figure 5.23. Estelle Calamand harvesting fresh *Spirulina* form the sieve at Spiruline La Capitelle, in Villecun, South France. Retrieved from http://www.spirulinelacapitelle.com/docs/brochure_lacapitelle.pdf

younger people are rising in number (N. Garoscio, personal communication, January 22, 2019).

The production and business model of the algaepreneurs is undoubtedly uncomplicated and effective and deserves to be taken into consideration. It guarantees a considerable income to many families and communities. For this reason, with due considerations, it could also be adopted in other contexts, such as the urban ones.

5.7.5 Spirulina in Italy

In Italy, the microalgae scenario is quite multifaceted. As far as research is concerned, many Italian universities have biology, chemistry, and botany departments that carry out studies in this field. The University of Florence has taken on particular international relevance because it has been collaborating for many years on academic and commercial projects. In recent years it has also worked with some designers and engineers. In South Italy, the University of Naples primarily leads the research.

As for production, there are about twenty-four companies that cultivate microalgae throughout the national territory (Fig. 5.24). Most of these are small and medium-sized family-owned businesses, such as Spirulina G in Liguria, Prato della Voja in Lombardy, and Biospira in Campania. There are also bigger companies, such as Archimede Ricerche, which produce high-quality microalgae for pharmaceutical, cosmetic and nutraceutical use, and Severino Becagli – Tenuta San Lorenzo and Agriturismo Biologico Sant'Egle which have more considerable productions in terms of quantity. Apuliakundi and the Social Cooperative Malgrado Tutto in Apulia and Calabria are small associations that collaborate with people in need. Some of these activities receive government subsidies as an incentive for agricultural practices. Spirulina Microfarm's work is interesting, because it collaborates with Oil Fox Italia, a multinational company producing biofuels, to create a zero-impact plant and train staff who can then start productive activities in Africa (Bagnato, 2018). Alghitaly, in the province of Verona, grows *Spirulina* with an innovative patented system made of flexible tubes. The pipes contain water and nutrients and are placed on flat ground, even on non-arable lands (Messa, 2016). Alghitaly offers a franchise system to interested *Spirulina* growers, who can buy the tubes at a discounted price. Alghitealy then guarantees that the *Spirulina* produced is bought. In Sardinia, a disused coal mine has been reconverted into a production site for *Spirulina*. Through a patented system, hot water from the soil is used to heat the culture in order to guarantee a continuous production cycle, 24/24h, and 365 days a year and without the use of greenhouses (Madeddu, 2019). The project created several jobs and aroused the interest of potential investors. ENEL Green Power – the most significant Italian energy manager and distributor – is also investing resources in these kinds of projects. In 2017, the first plant in the world for the cultivation of *Spirulina* in Chiusdino in Tuscany was inaugurated, which uses the heat and carbon-free CO_2 of a neighboring geothermal power plant. The pilot plant is small in size and produces *Spirulina* with a hybrid system of raceway ponds and photobioreactors (Enel Italia, 2017). In Turin, the intervention company TNE – Torino Nuova Economia[15], is considering the start-up of a *Spirulina* production in an abandoned factory of approximately 15,000 m^2. Production would take place inside ponds or photobioreactors and would be managed by a local cooperative (Luise, 2019). The municipality of Milan has also shown interest in this approach.

15 TNE is a mainly publicly owned company established by the Piedmont Region, the Province of Turin, the City of Turin, and Fiat aimed at maintaining a pole of production activities in the Mirafiori area – a district in the southern area of Turin. More information at http://www.torinonuovaeconomia.it/index_eng.php

Table 5.3. Spirulina powder or spaghetti. Consumer price of the main Italian producers/sellers per kg of dry product. Data as at 25 January 2019. Retrieved from https://www.agriturismobiologicotoscana.it/index.php/it/ordina-prodotti-biologici-agriturismo-biologico-sant-egle/2-contenuti-vari/67-spirulina-pura-al-100-la-fonte-naturale-piu-ricca-di-proteine-e-ferro; https://www.alghitaly.it/store/spirulina-per-alimentazione/spirulina-in-polvere/; https://www.apuliakundi.it/it/shop/sticks-di-spirulinak-bio-50gr/; https://www.bertolinifarm.it/negozio-online-comprare-alga-spirulina-in-spaghettini-scaglie-polvere/; https://www.biospira.it/shop/; https://livegreen.bio/collections/la-spirulina-italiana; https://www.pratodellavoja.it/collections/all; https://www.spirulinag.it/acquista-online-la-spirulina-g

Producer	**Package (g)**	**Price (€)**	**Price/kg (€)**
Agriturismo Biologico Sant'Egle	50	17.00	340.00
Alghitaly	100	32.00	320.00
ApuliaKundi	50	26.00	520.00
Bertolini Farm	50	20.00	400.00
Biospira	50	25.00	500.00
Livegreen	50	22.00	440.00
Prato della Voja	100	30.00	300.00
Spirulina G	100	22.00	220.00
Average			*380.00*

Figure 5.24. An overview of the main Italian *Spirulina* producers.

The average retail price of *Spirulina* powder in Italy is around € 380.00 per kg, therefore relatively high. This number is obtained from the arithmetic average of the selling prices of eight among the best-known sellers (Table 5.3). The average B2B price of Italian organic *Spirulina* is instead around € 60.00. Large customers purchase quintals of *Spirulina* in bulk at even lower prices (M. Boselli, personal communication, March 5, 2019), preferring local *Spirulina* rather than the imported ones.

The microalgae market in Italy, as well as in Europe and in the rest of the world, is particularly thriving and has seen growth trends and interest for even a young audience. In the wake of the French producers – and to compensate for unsold *Spirulina* in some cases – several producers are gathering in USBI – Unione Spirulina Biologica Italiana.[16] Through USBI, producers can test and certify the biomass they produce, as well as enter in contact with many other processors and producers of different foods (A. Algerio, personal communication, March 12, 2019).

16 More information about USBI at at https://unionespirulina.it

CHAPTER 6

Design and microalgae

This chapter delves into the relationship between the disciplines of design and phycology – the study of algae.[1] To date, there is no word to define the investigation area between these two fields that are so far apart, but it is more a research and practice niche within sustainable design, in particular biodesign. Among the several nature-based solutions that have been identified and adopted so far (bacteria, fungi, animals, etc.), algae are particularly attractive. As seen previously in this thesis, the literature has shown that algae have great potential, and are in many ways already used in industrial and commercial applications, but utterly unexplored in other sectors.

The chapter is fundamental as it broadly describes how algae and microalgae have been integrated into design projects, introducing the next section, which includes an exhaustive collection of cataloged and analyzed case studies. The chapter also describes the research trends and the reasons why microalgae were selected for this study. Finally, the first research question will be answered, that is: 'How can design researchers contribute to microalgal

1 Part of the work described in this chapter was also previously published in: Peruccio, P. P., Menzardi, P., & Vrenna, M. (2019). Transdisciplinary knowledge: A systemic approach to design education. In N. A. G. Z. Börekçi, D. Ö. Koçyıldırım, F. Korkut, & D. Jones (Eds.), *Proceedings of DRS Learn X Design 2019: Insider Knowledge* (pp. 17–23). Ankara: METU Department of Industrial Design. doi:10.21606/learnxdesign.2019.13064

studies?'. The importance of adopting a methodology in research and practice to approach projects of this type is also underlined.

6.1 Algae in design: An overview

Artists, architects, and designers are continuously up to date with the latest technologies and innovations, and over the decades, they challenged the limits with their works. Today, designers are increasingly experimenting with algae and – as seen in previous chapters – when it comes to algae, a multifaceted research domain opens up. Below are some projects that have involved both the use of macroalgae (seaweed) and microalgae, in different fields of design: installations, product, fashion, to name a few. Although microalgae and macroalgae have different characteristics and properties, they have many things in common. Both are aquatic organisms that perform photosynthesis, are common in nature, and highly versatile. These characteristics make them perfect 'materials' for experimentation. To discuss design projects that involve the use of microalgae, it is necessary to have a broader vision and a basic knowledge of those projects that have included the use of macroalgae and seaweed too.

Figure 6.1. William Kilburn's printed fabrics include detailed depictions of marine seaweeds (end of eighteenth century). Victoria and Albert Museum, London. Copyright 1991 by Victoria and Albert Museum.

In general, the interest of design for algae can be traced back to the end of the eighteenth century, with the typical approach of the graphic arts of the time. The Irish entrepreneur and designer William Kilburn was one of the first botanical illustrators that included depictions of seaweeds and other marine organisms in his watercolor designs (Fig. 6.1). These printed pieces of cotton were produced in large quantities and were particularly appreciated (Christie, 2011). Much more recently, seaweed has been used by London-based multidisciplinary designer Julia Lohmann in the large-scale installation entitled 'Oki Naganode' (Fig. 6.2). The designer used Japanese Naga seaweed to create a translucent coating to be applied to a modular structure. The installation celebrates the potential of seaweed as a versatile and sustainable building material for the future (Antonelli & Tannir, 2019), and has been exhibited in several exhibitions. Lohmann has also used seaweed (Kelp seaweed[2]) for the creation of particular laser-cut lampshades and other objects, in an attempt to replace commonly used materials such as paper, leather, and plastic. Also interesting is the work of Nienke Hoogvliet, straddling the field of furniture and new textile experiments, who designed 'Sea Me' carpet (Fig. 6.3), woven using yarn made from sea-harvested algae. The designer hopes that algae could become a viable alternative to viscose, a well-known synthetic material that is not environmentally friendly (Howarth, 2014; Kuitert, 2014).

Fascinating experiments are also – and above all – in the field of bioplas-

2 Kelp is a large brown alga that grows in underwater forests. Kelp is commonly used in food, especially in Asian countries. A popular name for it is also Kombu.

Figure 6.2. Oki Naganode by Julia Lohmann (2013) exhibited at Victoria and Albert Museum, London. Adapted from *Broken Nature. XXII Triennale di Milano* (p. 152), by P. Antonelli & A. Tannir (Eds.), 2019, Milan, Italy: Mondadori Electa. Copyright 2013 by Julia Lohmann.

Figure 6.3. Sea Me rug by Dutch designer Nienke Hoogvliet. Adapted from *Nienke Hoogvliet* website, 2020, retrieved from https://www.nienkehoogvliet.nl/portfolio/seame/ Copyright 2014 by Femke Poort.

Figure 6.4. The Agari Project by Ari Jónsson, 2016. Adapted from *Broken Nature. XXII Triennale di Milano* (p. 154), by P. Antonelli & A. Tannir (Eds.), 2019, Milan, Italy: Mondadori Electa. Copyright 2016 by Ari Jónsson.

Figure 6.5. Vivobarefoot Ultra III Bloom. Reprinted from *Vivobarefoot* website, 2020, retrieved from https://www.vivobarefoot.com/eu/blog/lookbooks/the-ultra-iii-bloom Copyright 2020 by Vivobarefoot.

Figure 6.6. H.O.R.T.U.S. XL by ecoLogicStudio. Adapted from *ecoLogicStudio* website, 2019, retrieved from http://www.ecologicstudio.com/v2/project.bcat=59&idproj=177 Copyright 2019 by ecoLogicStudio.

tics. Bioplastics are materials produced from renewable sources, rather than petroleum. Algae and microalgae can be a source of bioplastics because it is possible to extract lipids and polysaccharides from them. Bioplastics from algae are used, for instance, for innovative packagings like the one in Fig. 6.4. The Agari Project by Ari Jónsson, a former student in product design at the Iceland Academy of the Arts, consists of a water container made of a compound of agar-agar powder, wholly biodegradable and edible.[3] The bottle also keeps the water fresh, even with high external temperatures (Morby, 2016). A similar experiment was also conducted by Imperial College London alumni Pierre Paslier and Rodrigo Garcia, who invented 'Ooho', an edible and tasteless liquid capsule made from seaweed that can be used as a replacement for small water bottles – for example in sports events such as marathons (Wilson, 2019). Bioplastics have also been used in the world of fashion: recently, Vivobarefoot launched the 'Ultra III Bloom' shoes (Fig. 6.5), the world's first shoe made with algae. The shoes are entirely made of an innovative bioplastic material that guarantees flexibility, resistance, and water permeability. The algae used to create this foam are collected from lakes and ponds, where when in excess, can choke marine life (Pardes, 2017).[4]

The design projects that involve the use of microalgae – products and installations – are also growing in number. For years, some studios have been specializing in environmental design, urban self-sufficiency, and building integrated nature, offering services that include the design of novel architectures and prototypes integrating living matter and producing energy and food on-site. The recent H.O.R.T.U.S. XL at Center Pompidou in Paris, France (Fig. 6.6) is, for instance, only one of the most recent projects by London-based Claudia Pasquero and Marco Poletto, founders of the well-known studio ecoLogicStudio. The next chapter describes and analyzes more than 50 design case studies, including products, installations, and concepts that use microalgae. Finally, it is important to note that in the discipline of design, projects with algae are mainly linked to practice and that scientific research and publications are somewhat limited. There is also often confusion about the properties and characteristics of algae, and less prepared designers are dealing with this topic superficially.

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3 Agar-agar is a natural jelly-like substance that is extracted from red algae. It has a semi-translucent white color and is sold in dried strips or powders. It is a primary ingredient for the preparation of puddings, custards, and jelly.

4 An algal bloom is the result of runoff of nitrogen and phosphorus from fertilizers, entering aquatic systems and, thus, causing abnormal growth of algae. Algal blooms are harmful to marine water systems and can also be toxic to human and animal health. Several projects address this problem, including those for the collection of excess biomass. In the field of design, it is noteworthy the working prototype 'Algae Harvester' by Fredrik Ausinsch, a boat with a particular innovative structure, which was presented at Dubai Design Week in October 2016 (Smith, 2016).

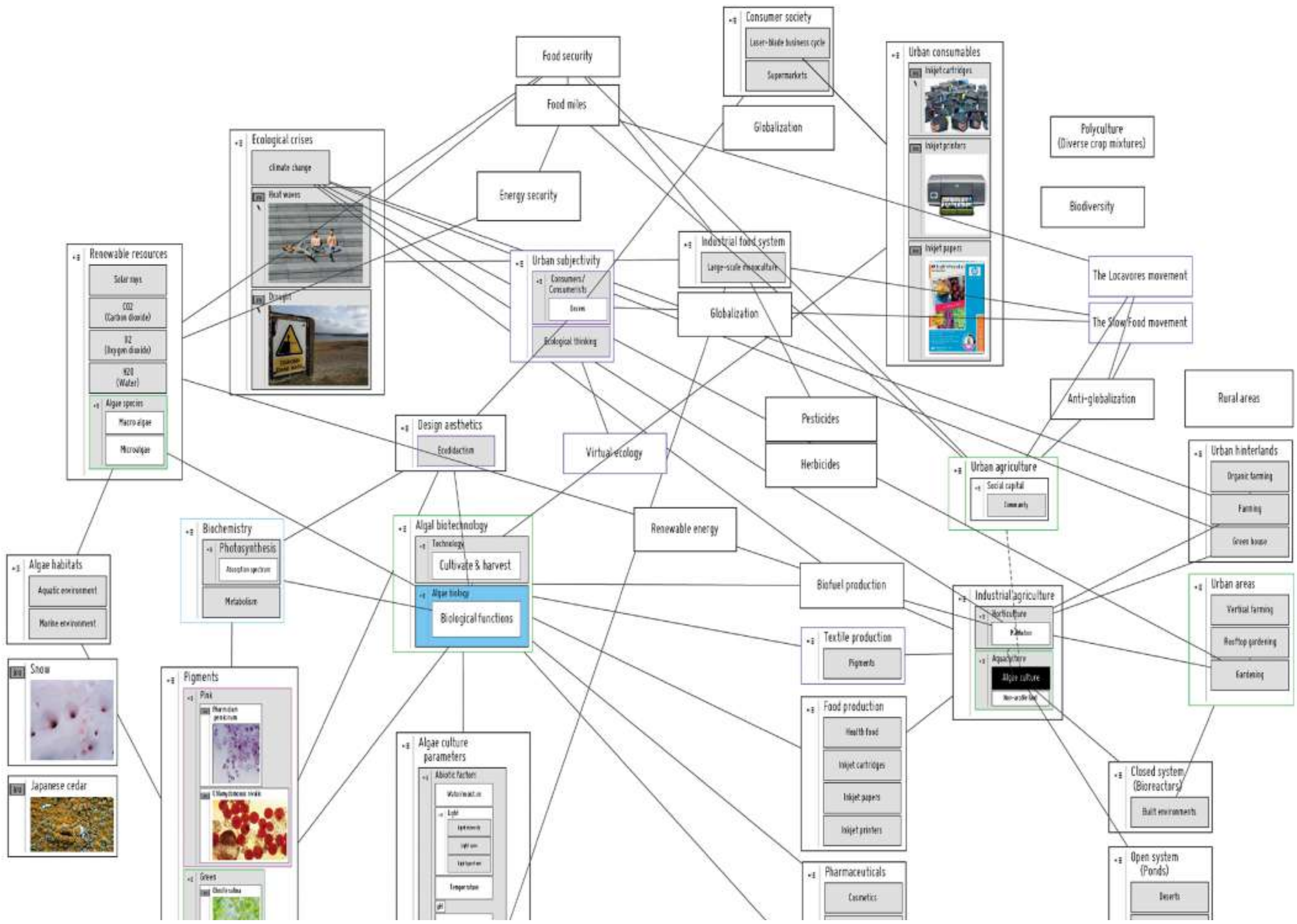

Figure 6.7. Ecosophical perspective on algal biotechnology. Reprinted from *An ecosophical intersection of algal biotechnology and design. Algaerium Bioprinter & algae printing* (p. 7) by Sawa, M., 2017. Copyright 2017 by M. Sawa.

6.2 Why design and microalgae?

By starting from algae, it is potentially possible to connect to a long list of associated topics, also very different from each other and semantically distant from the original study. This commences a multidisciplinary and branched debate that goes far beyond pure biology, technical solutions, and design, opening up to ecological and philosophical perspectives. The studies of Sawa (2016; 2017) clarify this concept pretty well: the researcher theorized an ecosophical perspective on algal biotechnology (Fig. 6.7), to justify the relationships between design and biology. The exploitation of the biological functions of algae and the technology for their cultivation and collection is directly related to the production of food, pharmaceuticals, environmental purification, and renewable resources, to name a few. It is also indirectly connected to broader issues such as ecological crises and climate change, globalization, and the consumer society, as well as agricultural production in urban areas. If in the past, the production of algae implied only the use of rudimental techniques to harvest biomass for food use (such as the African tribes or the indigenous Mexicans), the prospects have now changed, and new and exciting scenarios open up, with virtually infinite secondary and tertiary connections. Therefore

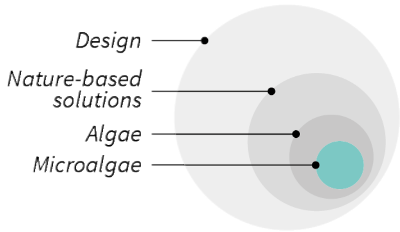

Figure 6.8. Microalgae in design is a practice and research niche that deserves to be explored.

talking about design and algae makes sense, even if it is not an ordinary and fully investigated topic, at least for the moment. Although aware that the field of research and experimentation between design and seaweed (macroalgae) – as described in the previous paragraph – is fascinating and offers innovative solutions especially in the field of biomaterials, it is also appropriate to narrow down and limit the research, which otherwise would be ineffective and dispersive. It is no coincidence that designers who approach algae for the first time find this field challenging to understand because it is too extensive and partly confusing.[5]

This research, therefore, focuses on microalgae and their connection with design. This is a particular topic that is contextualized within a much broader context, as illustrated graphically in Fig. 6.8. Microalgae are not only the subject of study but the pretext for extrapolating design theory from practical projects, with significant implications for the real world. It was decided to work with microalgae for several reasons: first of all, their versatility, and the full range of commercial and industrial applications. As already carefully described in chapter 5.4, microalgae can be used as biofertilizers, pharmaceuticals, and biofuels, as well as cattle and aquaculture feed, and in the cosmetic field. Researchers, scientists, and entrepreneurs also believe that microalgae – due to their ease of cultivation, high yields, and the limited amount of water and land need to grow – could play an important role in pioneering solutions in different contexts, especially to cope with the necessity of producing human food in the upcoming decades. Designers and chefs are already collaborating to create innovative and futuristic microalgae-production devices. They are also experimenting with tasty new recipes based on microalgae, to make them more palatable and slowly change the eating habits of customers (SPACE10, 2019).

Microalgae could be useful not only on Earth but also in space. A new era of space exploration is upon us, and the colonization of new planets –such as Mars – requires new approaches to design and food production. NASA is already collaborating on this topic with designers and scientists (Twilley, 2020). Moreover, the recent exhibition 'Moving to Mars' at the Design Museum in London included, among many other installations, also innovative photobioreactors for microalgal production.[6] In conclusion, talking about design and

5 At the beginning of this research, I was also confused by the multiple varieties of algal properties and uses. It was necessary to get much information and consult experts who could suggest scientific peer-reviewed publications and case studies. On design websites and blogs, where content is not peer-reviewed, information is often jagged and amplifies the confusion. Unfortunately, the latter are the places where most design practitioners begin (and eventually conclude) their research, often not having access to scientific databases.

6 The exhibition 'Moving to Mars' took place from 18 October 2019 to 23 February

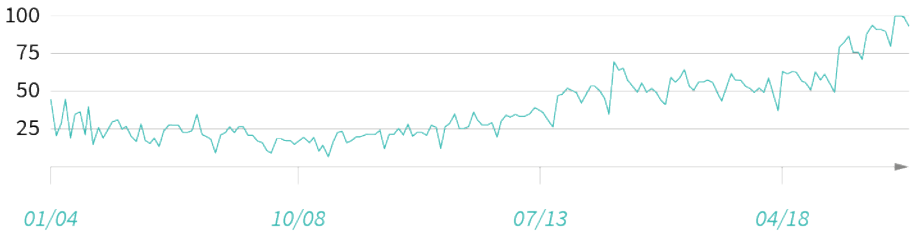

Figure 6.9. Google research trend for the term 'spirulina' (worldwide and for all Google research categories), since January 2004. The interest over time spiked in the last years. Data as at April 2020.

microalgae today may seem an unusual combination. Advances in practice and research, however, demonstrate the opposite. In the near future, design will take on an increasingly important role in projects involving the use of microalgae. These solutions will require the intervention of designers not only for technical but also behavioral and social issues, to facilitate the adoption of new sustainable practices. The research between design and phycology is, therefore, fresh and innovative.

6.2.1 Growing interest, limited research

The interest in microalgae is continuously increasing in several research fields. As already seen in paragraph 4.3 – with particular reference to Figure 4.3 – in recent decades, scientific studies discussing microalgae have increased exponentially. This growth trend, albeit less pronounced, is also found in online searches. Fig. 6.9 shows the interest over time – starting in 2004, all over the world, and for all categories – for the search term 'Spirulina', which is mainly related to healthy food and cosmetics.[7]

However, as regards research in the field of design, scientific publications dealing with design and microalgae are minimal. From research on Scopus, Elsevier's largest abstract and citation database of peer-reviewed literature, it emerges that 24,362 documents are mentioning the word 'microalgae' in the title, abstract, or keywords (data as at December 2019) (Fig. 6.10). Of these, approximately 20% are in the subject area of Agricultural and Biological Sciences, 17% Environmental Science, 11% Chemical Engineering, and 11% Biochemistry, Genetics and Molecular Biology. About 9% of the documents fall into the category 'Other', which also includes the area of Arts and Humanities

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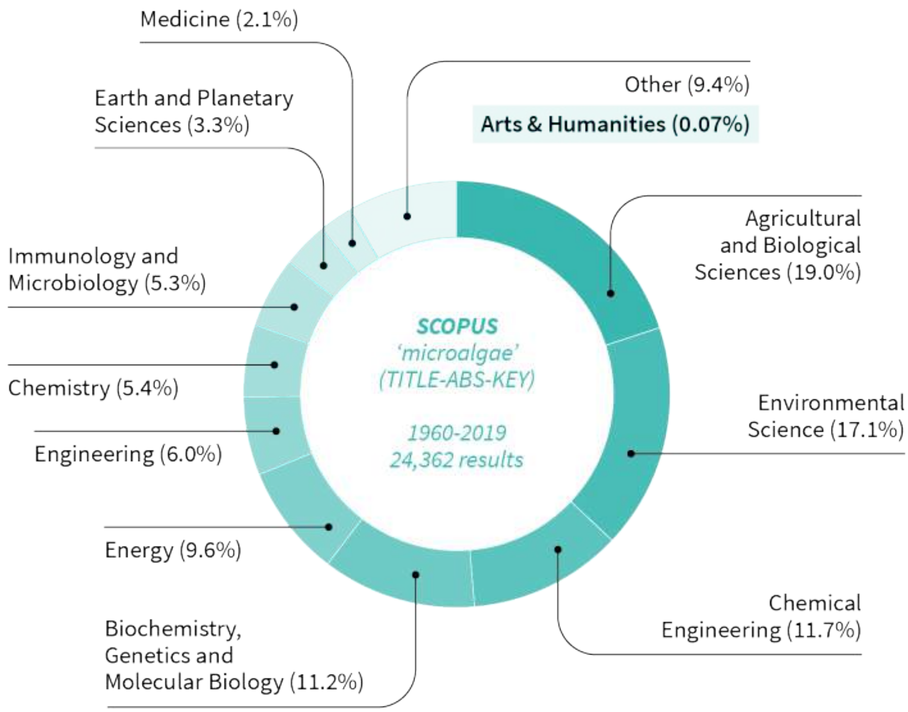
2020 and was curated by Justin McGuirk (Chief Curator at the Design Museum). The exhibition explores how sending humans to Mars is not only a challenge for science but also designers, and it was divided into more sections. The section 'Survival' also envisioned ways of farming through hydroponic farming kits and Spirulina-growing systems. More information at https://designmuseum.org/exhibitions/moving-to-mars

7 For the research of online trends through the tool 'Google Trends', the term 'Spirulina' was used, rather than microalgae, because it is most representative. An incorrectly-informed public probably only knows the commercial name of the most publicized, sold, and adopted microalga – without knowing it is a microalga.

Figure 6.10. Scopus database. Documents by area, including the word 'microalgae' in the title, abstract, or keywords. Percentage of the total (24,362 results from 1960). Only 18 publications fall in the area of Arts and Humanities. Data as at December 2019.



(this encompasses the vast majority of design papers). Within Arts and Humanities, there are only 18 publications (0.07% of the total). Of these, only four also include the word 'design' within the title, abstract, or keyword. Finally, a qualitative analysis shows that only one paper refers to the discipline of design, in its broader definition, and as explained in chapter 2.3 of this thesis.[8] An analysis of EBSCOhost Art & Architecture Source – a well-known and robust database for artists, scholars, and designers that covers many aspects of design and architecture – shows similar results. The database includes indexing and abstracts for 790 academic journals and magazines, 360 full-text periodicals, and 220 full-text books. From 1995 to 2019, only 34 documents mention the word 'microalgae'. Of these, 14 are articles on Academic Journals, mainly of an architectural nature, while the remaining are mainly articles on periodical magazines, principally with reviews of practice-based case studies.

In an attempt to further investigate how the disciplines of Systemic Design and Product-Service System Design (two approaches to sustainable design that have also been adopted in the design phase of this thesis) have recently dealt with the topic of microalgae, the proceedings of two of the most recent and important international scientific conferences on these issues were

8 The paper is Sawa, M. (2016). The laboratory life of a designer at the intersection with algal biotechnology. *Architectural Research Quarterly*, 20, 65–72. doi: 10.1017 / S1359135516000191 The paper explores the relationship between design and the emerging practice of biodesign with microalgae, also reflecting on collaborative processes between teams of scientists and designers.

analyzed. These are: Barbero, S. (Ed.). (2019). *Proceedings of Relating Systems Thinking and Design (RSD7) 2018 Symposium*. Oslo: Systemic Design Association, and Ambrosio, M., & Vezzoli, C. (Eds.). (2019). *Designing sustainability for all*. Proceedings of the 3rd LeNS World Distributed Conference. Milan: Poli. Design editions. The results of the analysis were unexpected: out of a total of more than 300 papers, there is not even one relevant for the study of design and microalgae (or algae in general) (Table 6.1). The term 'algae' is mentioned in only three articles, connected to experiments with materials, and strategies for sustainable fashion. Although this little sample of papers cannot stand for the whole research, the data is quite significant.

However, the book Myers, W. (2018). *Biodesign: Nature+Science+Creativity*. New York, NY: MoMA – a must-read book for biodesign studies and a collection of selected cutting-edge nature-based projects – includes a substantial amount of case studies with microalgae. Out of 74 total cases, nine are using microalgae in different contexts.[9] These case studies are mainly made by design practitioners. It is therefore clear that there is a large gap in research that needs to be bridged, and the difficulty in finding scientific literature to support this thesis is evident. However, this represents a unique opportunity in the advancement of knowledge and theory in this study niche.

Theoretical research must keep pace with practice, which shows new and unexpected solutions every day. For example, microalgae will be the protagonists of EXPO Dubai 2020, where they will be used in the Italian pavilion to subtract CO_2 exhaled by visitors and produce oxygen (Madeddu, 2019). Therefore, the time has come to have a broader approach to the world of microalgae, so that algae will not only be used for technical/stylistic solutions, but as a vector of innovation, sustainability, and well-being, and included in more comprehensive projects.

9 Myers divided the case studies into four macro categories. For each category, the name and the number of microalgae-related case studies are indicated below. Some of these will be explored in the next chapter. The architectural hybrid (2); Ecological object engineering (5); Experimental functions (1); Dynamic beauty (1).

Table 6.1. The number of papers relevant to the study of design and microalgae is limited. Practical case studies are instead slightly more common.

Publication	**Type**	**Total Papers/Cases**	**Relevant**	**Percentage**
Biodesign: Nature+Science+Creativity	Book	74	9	12.1%
Designing sustainability for all. Proceedings of the 3rd LeNS World Distributed Conference	Conference Proceedings	264	0	0%
Proceedings of Relating Systems Thinking and Design (RSD7) 2018 Symposium	Conference Proceedings	42	0	0%

Figure 6.11. To date, there are no methodologies for designers to use algae and microalgae in their projects. Decisions are often taken without careful analysis and comprehensive knowledge.

6.2.2 Need for structured research and methodology

The scarce scientific literature on this topic in the design discipline certainly does not support the multitude of practitioners who want to experiment with microalgae. Their approaches are highly diverse and uneven, and – to date – the literature does not provide any relevant comparative studies and classification of similar projects (Peruccio & Vrenna, 2019). Designers are called to action mainly when it comes to giving shape and aesthetics to products, and often they are involved only in the terminal stages of the design process. The term 'design', especially in the fields of Biotechnology and Bioengineering, has a purely technical meaning for the realization and development of photobioreactors or other similar systems. Its meaning is very far from the wider and more complete one of Industrial Design from the World Design Organization (2015), and that is commonly shared by the design research community.

In the field of design, it is necessary to have clear guidelines to support researchers and designers who approach this area for the first time. These guidelines, structured research, and a theoretical reference framework do not currently exist. In several case studies, the use of microalgae seems to be only a fashionable top-down solution, without careful analysis and comprehensive knowledge (Fig. 6.11). Introducing microalgae into a project means having an adequate response to the circumstances, and should not be an imposed option. Guidelines must necessarily be all-inclusive for product and service designs that can be adapted to different contexts, situations, and geographic locations, such as in cities.

6.3 Design contribution to microalgal studies

Biology, chemistry, and engineering – among others – are sciences that have a lot to offer to the design discipline and that are significantly influential. Conventional thinking sees traditional design and science as separate fields of study and creation. According to Farrell and Hooker (2013), design and science are instead not so different in kind – and provided explicit arguments in this direction. This concept is widely accepted, although the debate is still open, and other researchers consider design and science distinct, albeit related, concepts (Galle & Kroes, 2014). However, based on the evolution of the role of designers in recent decades, it is clear that "*craft skills no longer suffice. We need to discover, define and solve problems based upon evidence. We need to*

Figure 6.12. The mutual exchange of knowledge, methods, and methodologies among two very different disciplines. Shared goals are essential for the advancement of both design and phycology.

demonstrate the validity of our claims" (Norman, 2016). Design is, therefore, imposing itself as a scientific discipline based on well-defined methodologies, methods, and processes. Design could also contribute considerably to the advancement of other subjects. It has already been demonstrated that industrial designers can contribute to scientific research and *"when involved earlier in the scientific research process, designers can challenge the research direction and support scientists in demonstrating, communicating and exploring potential future applications"* (Driver, Peralta, & Moultrie, 2011, p. 17). Multidisciplinary working groups can complete ambitious projects with better results than those of less mixed teams, by breaking down potential communication barriers and activating bidirectional collaborations.

In an attempt to answer the preliminary research question of this doctoral research, that is: '*How can design researchers contribute to microalgal studies?*', Marin Sawa's fruitful and exemplary research is taken as a reference. Sawa is a Research Associate at Imperial College London, and she has been working closely with scientists to produce a sustainable algal bio-ink. Sawa (2016, p. 71), regarding the work of the designer in an algal biotechnology laboratory, suggests that *"a designer is [...] important not just for exploiting the technology but also shaping it. Design thinking and scientific experimentation, together, can be effective in producing new models and new approaches by introducing flexibility into the rigidity of scientific research and industry. Co-invention is possible for design researchers through long-term collaboration. Scientific experiments demonstrate new functionality and uniquely open up both realistic and speculative potential for applications. Taking an analogy from the evolution of algae from cyanobacteria, the role of a designer in scientific research should be more endosymbiotic with the designer physically located within the laboratory"*.

Designers can, therefore, contribute to microalgal studies through active participation in working groups and direct involvement in research. At the same time, through these collaborations, the mutual exchange of knowledge and methodologies between two disciplines is encouraged, toward common goals (Fig. 6.12). The work of biologists is generally very specialized and specific: their education is vertical, and they are remarkably competent in one (or more) distinct aspects of their discipline. The knowledge of a designer, instead, is – usually – more transversal and general. Ongoing research recognize that designers take in information from many sources, rather than attempting to develop deep expertise in a particular field. Far from being a weakness, this represents the real strength of a generalist (Rodgers, 2007). *"In a world of specialists, there is real need for those who can reach across disciplines to communicate and who can bring diverse experts together in coordinated effort"* (Owen, 2007, p. 24). As illustrated by Celaschi (2008), design has the tremendous contemporary potential to bridge the gaps between theory and praxis, possible and realizable. Design as a discipline assumes a central position from where it stretches out mutual connections and influences with other domains. The fluidification of disciplinary boundaries is manifestly a necessity of keeping up with the times and conferring designers the role of mediators and integrators of knowledge. Collaborations between designers and other specialists should be at three levels of interaction: multidisciplinarity, interdisciplinarity, and transdisciplinarity (Piaget, 1972) – defined in order of their efficacy. Multidisciplinarity is the use of solutions borrowed from another discipline. Interdisciplinarity, instead, is an interactional exchange of knowledge among two disciplines, aimed at the enrichment of both. Transdisciplinarity is not only the interaction of separate branches of knowledge but the integration of them as a whole (Celaschi, Formia & Lupo, 2013).

The results that can be obtained from multi-, inter-, and transdisciplinary collaborations are unpredictable and positive. These results not only concern the design of technical-productive solutions, but also of new ways of integrating microalgae into our lives through products, services, systems, and innovative experiences. The role of designers would be focal in the communicative, stylistic, operational, applicative, and managerial parts, while that of the scientists in the technical-biological ones. With a higher number of contributions on this subject from the design community (papers, conferences, collections and analysis of case studies, etc.), research in the field of phycology could also be further influenced. At the moment, however, as there is no rel-

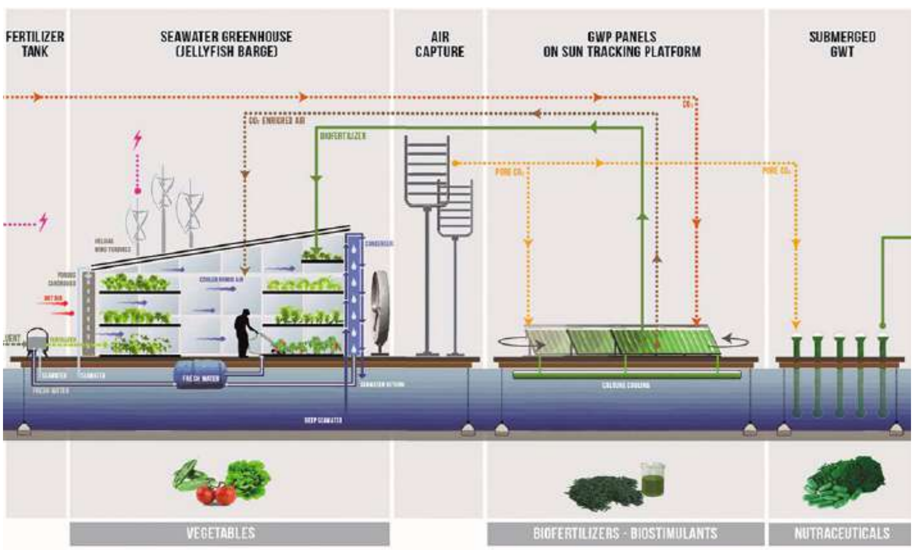


Figure 6.13. Food Islands – a concept by microbiologist Prof. Mario Tredici – produce algae and other foods in offshore waters. Designers could bring added value to such a visionary project. Adapted from *Colture di alghe: possono entrare a far parte della realtà agricola toscana?*, by M. R. Tredici, 2016, retrieved from https://www.eurosportello.eu/sites/default/files/areageotermica_30_03_2016/20160330tredici.pdf Copyright 2016 by Mario Tredici.

evant and sufficient design literature, few biologists are taking design studies seriously. Moreover, most of the research teams have a monodisciplinary outlook, and most scientific journals operate by sectors: this certainly does not foster knowledge sharing. Getting information from design journals would open up exciting new perspectives for scientists to test, adapt, and implement their groundbreaking discoveries in the real world.[10]

In conclusion, it has to be underlined that something is already moving in the field of multidisciplinary research. The Algae Geographies project by Algae Platform and Atelier Luma, for instance, is a transnational platform with key partners in the Mediterranean area. It aims at building an extensive network of designers, engineers, farmers, artists, and makers, to collectively research the potentials of algae and microalgae, "*working alongside indigenous communities to reactivate local economies, [...] to map a network of resources, skills, and cultural documents*" (Antonelli & Tannir, 2019, p 150).[11] Furthermore, virtuous and already detailed projects such as the Food Islands – integrated systems for the sustainable production of food (mollusks, vegetables, seaweed, microalgae, and fishes) – envisioned by microbiologist Prof. Mario Tredici (Fig. 6.13) could benefit from the contribution of designers. Perhaps systemic designers or product-service system designers could help not only with the visual communication but could take on an important role in the design of structures, associated services, usability, and user experience as well.

10 Using the right keywords to promote studies for a particular target audience is mattering. The recently published paper Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi: 10.19229/2464-9309/6212019 is gaining interest. From the statistics of Academia, ResearchGate, and IRIS – the online portal of Politecnico di Torino – it is noted that the researchers who read and suggested this paper are designers and architects, as well as energy systems engineers, botanists, and biotechnologists. Besides, the algorithm is recommending this paper to other potential readers with similar backgrounds.

11 More information at https://atelier-luma.org/en/projects/algae-platform

PART II

State of the art

CHAPTER 7

Case study analysis

In design research, case studies analysis is undoubtedly an important element of qualitative research because it *"is an approach to research that facilitates exploration of a phenomenon within its context using a variety of data"* (Baxter & Jack, 2008, p. 544).[1] All the information collected was supportive of the research question. Moreover, the understanding of real-world cases is likely to involve important contextual conditions pertinent to future design outcomes (Yin & Davis, 2007). The study of these cases was an iterative process characterized both by desk research on relevant documents including scientific publications, newspaper articles, and blog posts, but also interviews and personal communications. It was, therefore, a moment to get to know – personally and telematically – academics, professionals, companies, and institutions from all over the world, who share similar passions and skills.

The case studies presented were selected as they were particularly relevant to the research. Clear parameters in terms of time, context and activity have been identified. Given the specificity of the topic, design projects that did not meet these parameters were not taken into consideration. For example, projects that included the use of seaweed were not analyzed nor mentioned, even

1 Part of the work described in this chapter was also previously published in: Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019

if noteworthy.[2] This chapter illustrates and analyzes a total of 53 case studies (Table 7.1). These were divided into three major macro-areas, namely:

1. Design experimentations (20): Innovative small-scale solutions coming mainly from the world of design practice that use microalgae in many ways.
2. Microalgae in urban contexts (18): City-scale architectural installations, buildings, and pavilions showcasing the properties of microalgae, but also social design projects.
3. Concepts for future cities (15): Futuristic concepts, even with a high degree of unfeasibility, that outline future directions for this type of project.

As far as design experimentations are concerned, these developments range from products to small-scale architectural installations and, in multiple cases, were the result of collaboration with biologists and engineers. They were subsequently divided into sub-categories (product design, printing mediums, etc.). The case studies that involve the use of microalgae in urban contexts have been analyzed through an assessment tool used for the evaluation of urban gardens.[3] The analysis was useful to understand the limits of the projects and to identify new design possibilities. This classification work and the methodology adopted have already been published at the end of 2019 in a scientific journal, as mentioned at the beginning of this paragraph. Finally, a few considerations were extrapolated from the concepts: these were useful for tracing design trends and identifying possible domains of action.

In the sphere of design and architecture, experimentations with microalgae are still rather limited and to date, the literature does not provide any other relevant comparative studies of the existing projects. To ensure the high quality of the research and its updatedness, some of the most significant projects of the last decade were reviewed. The data are updated at September 2019. After this time, the design part of the research took place. This case study selection is rather exhaustive. However, this investigation must be considered as a temporal snapshot. Given the high topicality of these experimentations and the relatively new subject, especially in design research, well-established and emerging designers are starting to work on similar projects. This study is therefore intended to be constantly updated and periodically enriched with new content and case studies.

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2 As mentioned in the previous chapter, and although there are many characteristics in common between seaweed and microalgae, their material properties are completely different, as well as the methods of growth and collection, commercial applications and possible uses in design. Therefore, the research did not take into consideration the case studies that entailed the use of seaweed for the realization, for example, of bioplastics, furnishings, and artistic installations, but only those that included microalgae.

3 Microalgal production in the city has many similarities with urban farming practices, that are becoming increasingly popular and well-known worldwide.


Flood©


Symbiosis


Latro Lamp


Algae-graphies


Moss Table


Living Things


Farma


Timelapse Ink


CMYKA


Exhale Bionic Chandelier


Algaegarden


Skyline Spirulina


BIQ House


Algaevator


Urban Algae Canopy


Floating Fields


BIOtechHUT


The Carbon Sink


Algae Dome

Living Solar Modules

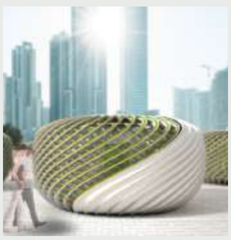

Polder Inversion


Filene's Eco Pods


Bioluminescent Devices


Biolamp


Process Zero


Chlorella Oxygen Pavilion


Algae Farm


French Dream Towers


LIQUID3


Ctrl+N


Algae Curtain


Eco-friendly Lamp


Algaerium Bioprinter


Dino Pet


Algaemy


3D Bakery


Spirugrow


Carbon Eaters


Symbiont


The Coral


Urban Algae Façade


Culture Urbaine


The Third Paradise


Urban Algae Folly


Façade System


WaterLilly 3.17


BioUrban 2.0

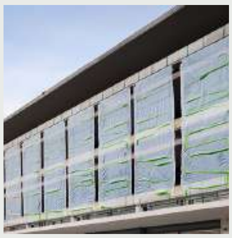


Photo.Synth.Etica


Regional Algae Farm


Algae Green Loop


Algae Mushroom Farm


RiverBox

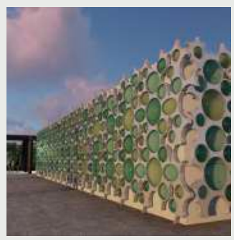

AL.F.I.E.

Table 7.1. An overview of the 53 case studies analyzed in this chapter: Design experimentations (Top), Microalgae in urban contexts (Middle), and Concepts for future cities (Bottom).

7.1 Design experimentations

The following pages present the most representative design experimentations and projects involving microalgae, from 2008 until today. The projects are diverse and range from the realm of product design to fashion design. These are mainly contributions from professionals. However, some projects are the result of academic research, multidisciplinary design programs, and academic spin-offs.

Each case study is presented with a summary sheet, including time and location data, the status of the project at the time of writing and three identifying keywords. The table below shows the summary of all the 20 cases taken into consideration (Table 7.2).

Table 7.2. The most representative design experimentations involving microalgae, from 2008 until today.

	Project name	Designer(s)	Place	Period
1.	Flood©	Mathieu Lehanneur	Paris, France	2008, May
2.	Symbiosis	Jelte van Abbema	Wageningen, Netherlands	2009, October
3.	Latro Lamp	Mike Thompson	Eindhoven, Netherlands	2010, June
4.	Algae-graphies	Lia Giraud	Paris, France	2011, March
5.	Moss Table	Peralta, Driver, & Bombelli	Cambridge, United Kingdom	2011, October
6.	Algae Curtain	Loop.pH	Lille, France	2012, October
7.	Eco-friendly Lamp	Pierre Calleja	Libourne, France	2013, April
8.	Algaerium Bioprinter	Marin Sawa	London, United Kingdom	2013, July
9.	Dino Pet	Yonder Biology	San Diego, California	2013, August
10.	Algaemy	Blond & Bieber	Berlin, Germany	2014
11.	Living Things	Douenias & Frier	Pittsburgh, Pennsylvania	2015, May
12.	Farma	William Patrick	Cambridge, Massachusetts	2015, December
13.	Timelapse Ink	Living Ink	Fort Collins, Colorado	2016, April
14.	CMYKA	Leon Brown	Edinburgh, United Kingdom	2016, December
15.	Exhale Bionic Chandelier	Julian Melchiorri	London, United Kingdom	2017, September
16.	3D Bakery	Klarenbeek & Dros	Zaandam, Netherlands	2017, November
17.	Spirugrow	Bentur	Pordenone, Italy	2018, January
18.	Carbon Eaters	PUMA & MIT Design Lab	Milan, Italy	2018, April
19.	Symbiont	Andriana Nassou	London, United Kingdom	2018, July
20.	The Coral	Hyunseok An	Providence, Rhode Island	2019, June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Flood©

1

Designer(s): *Mathieu Lehanneur*
Place: *Paris, France*
Period: *2008, May*
Status: *Completed*
Keywords: *Furniture, Interior design, Spirulina platensis*

Flood© is an interior design project made by the multidisciplinary, Paris-based designer Mathieu Lehanneur. It is a concept bar in which at its center is placed an aquarium, containing approximately l 100 of *Spirulina platensis*. Oxygen is produced through photosynthesis and re-balances the level of carbon dioxide in the environment, which is often higher in cities. The name of this design derives from the concept of 'flooding' the hollow furniture made out of PVC, i.e., the aquarium-like table. Blown-glass lighting fixtures on the ceiling symbolize the presence of higher quantities of oxygen in the air.[1]

1 For more information about the project and the designer, visit Lehanneur's portfolio website: http://www.mathieulehanneur.fr/works

Figure 7.1. A 100-liters *Spirulina* aquarium is placed at the center of the restaurant. Adapted from *Mathieu Lehanneur* website, 2008, retrieved from http://www.mathieulehanneur.fr/project/flood--129 Copyright 2008 by Cyril Afsa.

Symbiosis

2

Designer(s): *Jelte van Abbema*
Place: *Wageningen, Netherlands*
Period: *2009, October*
Status: *Completed*
Keywords: *Printing, Bacteria, Billboard*

Symbiosis is the project of Jelte van Abbema, a Dutch designer who collaborated with the Department of Microbiology at Wageningen Univesity and Research, Netherlands. *"This experimental project responds to the vast resource consumption and pollution generated by printed media. Going beyond the adoption of alternatives such as soy ink or natural pigments to alleviate the impact of media waste, Symbiosis takes a radical approach, utilizing bacteria to grow letters in Petri dishes"* (Myers, 2018, p. 152).[1] The project won the Rado Prize at the Dutch Design Awards in October 2009 because of its innovation and easiness of adaptation to different contexts (Fairs, 2009).

1 Even if this specific design experimentation does not involve the direct use or cultivation of microalgae like *Spirulina* or *Chlorella*, some bacteria are considered microalgae too. For this reason, and for its innovativeness, it has been selected among the other case studies.

Figure 7.2. Printing with bacteria on a billboard in the Dutch town of Wageningen. Adapted from *Dezeen* website, 2009, retrieved from https://www.dezeen.com/2009/10/27/symbiosis-by-jelte-van-abbema/ Copyright 2009 by Jelte van Abbema.

Latro Lamp

3

Designer(s): *Mike Thompson*
Place: *Eindhoven, Netherlands*
Period: *2010, June*
Status: *Early-stage development*
Keywords: *Lamp, Electrical current, Photosynthesis*

Latro Lamp is a speculative concept lamp by Mike Thompson that utilizes living microalgae as its power source. The idea drew inspiration from a scientific breakthrough by a group of researchers from the Department of Material Science and Engineering at Stanford University and the School of Mechanical Engineering at Yonsei University. The research evaluated the feasibility of generating a small electrical current to be drawn from a living algal cell (*Chlamydomonas reinhardtii*) during photosynthesis (Ryu et al., 2010). Thompson's project responds to a potential future market: the lamp is placed outside in the daylight to synthesize food from CO_2 and water, and the energy produced is stored in a battery, ready to be called upon at night. Latro Lamp's users are required to feed microalgae by blowing in a hole placed at the top of the device. A light sensor monitors the light intensity.[1]

1 For more information, visit https://inhabitat.com/algae-powered-latro-lamp-transforms-co2-into-light/

Figure 7.3. Latro Lamp by Mike Thompson. Adapted from *Designboom* website, 2010, retrieved from https://www.designboom.com/design/mike-thompson-latro-algae-lamp/ Copyright 2010 by Susana Camara Leretthe.

Algae-graphies

4

Designer(s): *Lia Giraud*
Place: *Paris, France*
Period: *2011, March*
Status: *Possibly filing for a patent*
Keywords: *Photography, Petri dishes, Living images*

Lia Giraud is a French artist who got a Ph.D. in 'Sciences, Art, Creation, Recherche' at Université PSL, Paris. In her video and photographic work, she proposes the experience of images as a material, showing the relationships between humans and visual representations. Algae-graphies is a series of 'living images' obtained by inoculating Petri dishes with cyanobacteria and exposing them in a special chemical environment. Later, conjure images with a contact-based negative while adapting them to light and focus. Darker areas are characterized by higher cell density. The fixation process is considerably difficult, resulting in images with a limited life span and continuously changing. Giraud is considering patenting the process she used.[1]

1 Full interview: Hallauer, E., & Côme, T. (2012, June 29). Lia Giraud: Algae-graphies [Blog post]. Retrieved from http://strabic.fr/Lia-Giraud-Algae-graphies

Figure 7.4. Microalgae exposed and fixated on a Petri dish to develop algae-based photographies. Adapted from *Lia Giraud* website, 2011, retrieved from http://www.liagiraud.com/videos/cultures/ Copyright 2011 by Lia Giraud.

Moss Table

5

Designer(s): *Carlos Peralta, Alex Driver and Paolo Bombelli*
Place: *Cambridge, United Kingdom*
Period: *2011, October*
Status: *Early-stage development*
Keywords: *Furniture, Energy production, Biophotovoltaic*

Moss Table is a conceptual design artifact developed by a group of researchers from Cambridge University and Bath University. The product showcases the potential of biophotovoltaic (BPV) technology – a process that generates renewable energy from the photosynthesis of living organisms (in this case moss, but also microalgae can be used) – suggesting possible future domestic uses of hybrid natural/artificial objects. The table is at an early-stage development and can provide BPV energy for small electronic devices (e.g., digital alarm clock). Nevertheless, it is not able to power the integrated lamp yet. Future research in this field may lower the prices of these kinds of devices, and BPV energy may become a competitive alternative to conventional technologies. The product was exhibited at 'En Vie – Alive'[1] in Paris, 2013.

1 The exhibition, curated by Carole Collet, took place at Espace Fondation EDF 6 (Paris) from 26 April to 1 September 2013. Visit: http://thisisalive.com

Figure 7.5. The BPV table generates clean energy from the photosynthesis of moss or microalgae. Adapted from *En Vie – Alive* website, 2013, retrieved from http://thisisalive.com/biophotovoltaic-moss-table/ Copyright 2011 by Carole Collet.

Algae Curtain

6

Designer(s): *Loop.pH*
Place: *Lille, France*
Period: *2012, October*
Status: *Completed*
Keywords: *Curtain, Architectural drapes, Installation*

Algae Curtain is an installation developed by London-based spatial laboratory Loop.pH. The studio, founded in 2003 by Mathias Gmachl and Rachel Wingfield, is conducting a long-term experiment in growing microalgae indoor. Algae Curtain was designed as part of the Energy Futures Project, and commissioned by EDF and Lille3000 for the Festival Fantastic in October 2012. It consists of an architectural drape made up of transparent tubes and silicon casts, filled up with a *Nannochloropsis* inoculum. Considering the tenfold growth of microalgae compared to trees, this algae-based photobioreactor is allegedly supposed to produce the 'Future Fruits', which can provide biofuel to be used locally.[1]

1 For more information visit Loop.pH portfolio website (http://loop.ph/portfolio/) and https://inhabitat.com/the-algae-curtain-a-is-a-living-photosynthesizing-textile-installation-that-provides-bio-fuel/

Figure 7.6. Transparent plastic tubes are knotted together to create a suggestive pattern. Adapted from *Loop.pH* website, 2012, retrieved from http://loop.ph/portfolio/algae-curtain/ Copyright 2012 by Loop.pH.

Eco-friendly Lamp

7

Designer(s): *Pierre Calleja*
Place: *Libourne, France*
Period: *2013, April*
Status: *Ongoing*
Keywords: *Lamp, Furniture, CO_2 capture*

Pierre Calleja is a biochemist that in the early Nineties started researching aquaculture: later, he begun exploring the field of phycology. In 2013, together with his team at FermentAlg – a chemical company based in France – designed an eco-friendly lamp powered by microalgae. The lamp uses the energy created from photosynthesis to emit light, while the algae live thanks to the carbon dioxide absorption (TEDx Talks, 2013). The energy is stored in a built-in battery, utilizing BPV technology similarly to 'Latro Lamp' (paragraph 7.1.3) and 'Moss Table' (paragraph 7.1.5).

A prototype has been set up in FermentAlg's parking space in Libourne (Bordeaux), to test and assess its performances in CO_2 capture. Suez Group showed interest in this solution (Taojo, 2018) and later decided to produce and install 'The Carbon Sink' (paragraph 7.2.14).

Figure 7.7. French biochemist Pierre Calleja working on the Eco-friendly Lamp. Adapted from *Inhabitat* website, 2016, retrieved from https://inhabitat.com/living-microalgae-lamp-absorbs-co2-from-the-air/ Copyright 2016 by FermentAlg.

Algaerium Bioprinter

8

Designer(s): *Marin Sawa*
Place: *London, United Kingdom*
Period: *2013, July*
Status: *Completed*
Keywords: *Printing, Domestic technology, Health food production*

As regards experimentation with pigments, the prototype of 'Algaerium Bioprinter' is an innovative device that allows digital printing utilizing a sustainable algal bio-ink (Sawa, 2016). It adapts industrial-scale algal production to a home environment and provides digitally printed healthy food. Functioning as an ink reservoir, it may contain different microalgal streams (e.g., *Spirulina*, *Chlorella*, *Haematococcus*).[1] The device was developed by Dr. Marin Sawa, Research Associate at Imperial College London, during her Ph.D.

As a biodesigner investigating the ecological intersection between design and biotechnology and having no previous experience in chemistry, she collaborated with a group of expert biologists and phycologists. She later was involved in a study about electricity generation from digitally printed cyanobacteria (Sawa et al., 2017).

1 Like the 'Moss Table' also this prototype was exhibited at 'En Vie – Alive' in Paris, 2013.

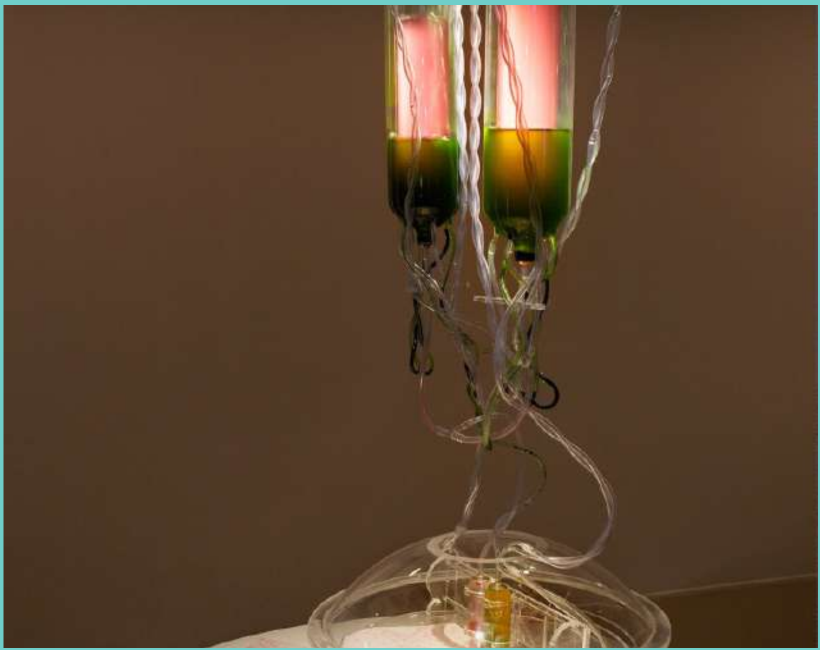

Figure 7.8. The 'Algaerium Bioprinter' prototype is displayed at En Vie – Alive, an art, design and architecture exhibit that took place in Paris from April to September 2013. Adapted from *En Vie – Alive* website, 2013, retrieved from http://thisisalive.com/algaerium-bioprinter/ Copyright 2013 by Carole Collet.

Dino Pet

9

Designer(s): *Yonder Biology*
Place: *San Diego, California*
Period: *2013, August*
Status: *Pledged on Kickstarter*
Keywords: *Lamp, Bioluminescence, Dinoflagellates*

Dino Pet is a lamp that glows in the dark. It is designed to stimulate children's imagination while teaching them about nature. A polyethylene dinosaur-shaped tank is filled with Dinoflagellates, unicellular algae that convert the light they are exposed to during the day into chemical energy at night. Dinoflagellates follow a circadian rhythm, and bioluminescence is visible only during dark cycles. This bioluminescent lamp was developed by Yonder Biology, a California-based company that commercializes new biologically-inspired products. It does not require electricity to work: the life of the microorganisms depends on their exposure to sunshine, temperature, and nutrients. To maintain intense bioluminescence, the Dino Pet needs to be periodically shaken. The average life of the microalgae is 1-3 months. It is possible to extend this period by adding a growth medium.[1]

1 Further information on the product: https://inhabitat.com/dino-pet-is-a-living-toy-that-glows-in-the-dark-with-bioluminescence/

Figure 7.9. Dino Pet, a night lamp that exploits the bioluminescence of dinoflagellates. Adapted from *Kickstarter* website, 2013, retrieved from https://www.kickstarter.com/projects/yonder/dino-pet-a-living-bioluminescent-night-light-pet/description Copyright 2013 by Yonder Biology.

Algaemy

10

Designer(s): *Blond & Bieber*
Place: *Berlin, Germany*
Period: *2014*
Status: *Completed*
Keywords: *Textile, Fashion, Natural pigments*

The Berlin-based design studio Blond & Bieber by Essi Johanna Glomb (textile designer) and Rasa Weber (product designer) invented Algaemy, an analog device that can print textiles with microalgal ink. Abstract shapes are imprinted on fabric to create unique patterns with mottled colors. The project was just the beginning of a longer investigation on the potential of microalgae in sustainable fashion. The designers collaborated with the German research institution Fraunhofer for microalgae. Later the same year with Trippen, a German shoe brand, for producing a prototype of microalgae-printed shoes. The inks are produced on-site: each color is made by using different microalgae and cyanobacteria, including *Anabaena*, *Haematococcus pluvialis*, *Monodus*, *Nannochloropsis limnetica*, *Nannochloropsis oculata*, *Rhaphoneis*, *Scotiellopsis*, *Spirulina platensis*.[1] The project was a nominee for the German Design Award 2015.

1 Blond & Bieber's website: http://blondandbieber.com/algaemy

Figure 7.10. Algaemy textiles are characterized by abstract coloured shapes over a plain white fabric. Reprinted from *Motherboard* website, 2014, retrieved from https://motherboard.vice.com/en_us/article/ypw3aw/microalgae-dyes-make-for-clothes-that-change-colors-as-theyre-worn Copyright 2014 by Blond & Bieber.

Living Things

11

Designer(s): *Jacob Douenias and Ethan Frier*
Place: *Pittsburgh, Pennsylvania*
Period: *2015, May*
Status: *Completed*
Keywords: *Installation, Symbiotic living, Home environment*

Living Things is an installation by Jacob Douenias and Ethan Frier that took place at the Mattress Factory Museum in Pittsburgh, Pennsylvania, from May 2015 to April 2016. The installation showcased futuristic furnishings celebrating a symbiotic relationship between human beings and microorganisms. In this case, *Spirulina* is cultivated through glass bioreactors incorporated within the furniture of the kitchen, the dining room, and the living room. The idea of the designers was to use these living structures to convert light, heat, and CO_2 into high-quality biomass, which can be eaten, used as biofertilizer, or converted into biofuels. For the project, both aesthetics and technical functions were taken into consideration. Vessels were hand-made by the Pittsburgh Glass Center. The design process is well documented on Douenias and Frier's portfolio websites.[1]

1 Links: http://www.douenias.design/ and http://www.ethanfrier.com

Figure 7.11. Living Things, an installation by Jacob Douenias and Ethan Frier at Mattress Factory Museum in Pittsburgh, Pennsylvania. Adapted from *Ethan Frier* website, 2016, retrieved from http://www.ethanfrier.com/living-things Copyright 2015 by Ethan Frier.

Farma

12

Designer(s): *William Patrick*
Place: *Cambridge, Massachusetts*
Period: *2015, December*
Status: *Completed*
Keywords: *Desk PBR, Pharmaceutical drugs, Home production*

Different devices have been designed for the domestic production of *Spirulina*. Farma is the work of William Patrick from MIT Media Lab, which is a table photobioreactor capable of producing and filtering microalgae, creating a powder to be inserted in capsules (Patrick, 2015). The aim is to let people brew their pills in a decentralized way, rather than buying them in a pharmacy. Part of Patrick's work was to demonstrate the easiness of building an at-home system. The project was also meant to *"make people think about how we want synthetic biology to fit into our lives"* (Peters, 2015). The device itself is composed of a few elements, most of them ad-hoc designed and engineered. To replicate it, product design and mechanical engineering skills may be required. Nevertheless, the instructions for the construction of the device have been made available online for independent users.[1]

1 Available on Instructables website: https://www.instructables.com/id/Farma-an-at-home-bioreactor-for-pharmaceutical-dru/

Figure 7.12. Farma is a home PBR for the self-production of pharmaceutical drugs made with *Spirulina*. Adapted from *William Patrick* website, 2015, retrieved from https://www.iamwillpatrick.com/FARMA Copyright 2015 by William Patrick.

Timelapse Ink

13

Designer(s): *Living Ink*
Place: *Fort Collins, Colorado*
Period: *2016, April*
Status: *Pledged on Kickstarter*
Keywords: *Living ink, Magic Pen, Green algae*

Similarly to 'Algaerium Bioprinter' (paragraph 6.1.8), the research group of Living Ink Technologies is working on the marketing of a time-lapse ink, with which dynamic illustrations can be created. The company managed to pledge $ 60,961 from 977 backers on Kickstarter, and now the product is on the market.[1] The founders, Scott Fulbright, and Steve Albers came to this outcome during their Ph.D. studies at Colorado State University. Given the fact that the majority of pigments used within the industry derive from petroleum, they believe that algae-based bio pigments may be disruptive in packaging applications. Living Ink Technologies is partnering with leading eco-brands in the attempt to reduce carbon footprint.[2]

1 See Kickstarter campaign: https://www.kickstarter.com/projects/livingink/living-ink-time-lapse-ink

2 More information on their website: https://livingink.co

Figure 7.13. The safe and sustainable 'Timelapse Ink' by Living Ink. Reprinted from *Inhabitat* website, 2015, retrieved from https://inhabitat.com/fascinating-timelapse-pen-uses-living-algae-for-ink/living-ink-technologies-algae-pen/ Copyright 2015 by Living Ink.

CMYKA

14

Designer(s): *Leon Brown*
Place: *Edinburgh, United Kingdom*
Period: *2016, December*
Status: *Completed*
Keywords: *Algae-die, Ink-jet printer, Consumer interest*

CMYKA is the work of Leon Brown, a British product designer and former student at The University of Edinburgh, Edinburgh College of Art. Brown has been researching possible connections between design and synthetic biology: he studied several projects that included the use of seaweed and microalgae, like 'Algaemy' by Blonde & Bieber (paragraph 6.1.10), and 'Farma' by William Patrick (paragraph 6.1.12).

CMYKA is a regular printer in the form *"but functionally [...] attempts to bridge gaps between current synthetic biology practices within major industry and the consumer realities [...] within the home everyday"* (Brown, 2016). The concept behind this product is similar to the one of a fish aquarium or a terrarium. Different algal streams can grow in a small tank, and a bio-ink is extracted to make a unique printed media. Thousands of natural inks, with different textures, can be created. Brown hopes that with CMYKA, ordinary consumers may gain interest in the interaction with the living organisms while revealing future influences between design and biology.

Figure 7.14. CMYKA is an algae dying system using an ink-jet printer. Adapted from *Edinburgh College of Art - Product Design* website, 2016, retrieved from https://sites.eca.ed.ac.uk/designnarratives/algae-the-shape-of-things-to-come/ Copyright 2016 by Leon Brown.

Exhale Bionic Chandelier

15

Designer(s): *Julian Melchiorri*
Place: *London, United Kingdom*
Period: *2017, September*
Status: *Completed*
Keywords: *Ceiling lamp, Indoor air purifier, Leaf modules*

Julian Melchiorri is an innovation design engineer, entrepreneur, and CEO of Arborea, a start-up operating in the food-tech sector.[1] Exhale Bionic Chandelier is an indoor air purifying system: the light of the chandelier illuminates the 70 artificial leaves, arranged symmetrically in a circular array. These are hollowed and filled with living microalgae, which make photosynthesis. A feeding pump provides the necessary nutrients to algae for their growth. The product is entirely hand-made and is a great example of biomimicry. The shapes drew inspiration from both Art Nouveau and Islamic Art: for this reason, it is now part of a permanent collection at the Victoria and Albert Museum in London (Narea, 2017).

1 More information about Melchiorri's work: https://www.julianmelchiorri.com/

Figure 7.15. The Bionic Chandelier is composed by leaf modules, filled with microalgae. Reprinted from *Julian Melchiorri* website, 2017, retrieved from https://www.julianmelchiorri.com/Bionic-Chandelier Copyright 2017 by Julian Melchiorri.

3D Bakery

16

Designer(s): *Eric Klarenbeek & Maartje Dros*
Place: *Zaandam, Netherlands*
Period: *2017, November*
Status: *Ongoing*
Keywords: *3D printing, Algae polymer, Local biofabrication*

3D Bakery is a series of 3D-printed objects made by a bioplastic derived from algae. Klarenbeek and Dros believe that such a material could be used to eventually replacing traditional plastics. The designers also worked with other raw materials such as cocoa bean shells and mycelium. After a few years of joint research with Wageningen University and Research – Netherlands, they were invited to open an algae lab at the Atelier Luma in Arles, France. They later established a European network, called 'Algae Geographies' that proposes new models for circular production of algae, functions as an aggregator of knowledge, and promote the use of renewable resources in wetlands around the Mediterranean.[1] Some of these products were also exhibited at 'Broken Nature' in Milan, 2019. Many designers, even from Turkey, are part of this network (M. Çıracı, personal communication, July 12, 2019).

1 More information at: https://atelier-luma.org/en/stories/algae-geographies-by-algae-platform-broken-nature-triennal-01-03-01-09

Figure 7.16. 3D printed objects made by algae polymer. Adapted from *Dezeen* website, 2017, retrieved from https://www.dezeen.com/2017/12/04/dutch-designers-eric-klarenbeek-maartje-dros-convert-algae-biopolymer-3d-printing-good-design-bad-world/ Copyright 2017 by Studio Klarenbeek & Dros.

Spirugrow

17

Designer(s): *Bentur*
Place: *Pordenone, Italy*
Period: *2018, January*
Status: *Canceled*
Keywords: *Home appliance, Automation, Fresh Spirulina*

Spirugrow is a promising automated supplement-growing home appliance that lets users prepare and consume fresh *Spirulina* daily. It is engineered and designed for intuitive and user-friendly operation. The product was invented by Bentur, an Italian start-up company, and Fotosintetica & Microbiologica, a university spin-off. A team of biologists, engineers, and entrepreneurs worked on the design and the commercialization strategies. Spirugrow was backed on Kickstarter and reached a considerable success, but the funding was ultimately canceled by the creators apparently to improve the performance and safety of the device.[1] The company's revenue was based on the devices sold to the end-users. Users could also purchase a subscription plan for a monthly supply of nutrients, salts, and CO_2 cartridges. The device was supposedly able to produce up to g 20 of fresh *Spirulina* per day.

1 The blog section of Bentur's Kickstarter page: https://www.kickstarter.com/projects/2010590116/spirugrow/posts/2223980

Figure 7.17. Spirugrow is the first home-device that grows *Spirulina* to consume fresh. Adapted from *Kickstarter* website, 2018, retrieved from https://www.kickstarter.com/projects/2010590116/spirugrow/ Copyright 2018 by Bentur.

Carbon Eaters

18

Designer(s): *PUMA and MIT Design Lab*
Place: *Milan, Italy*
Period: *2018, April*
Status: *Completed*
Keywords: *Wearable, Air pollution monitoring, Oscillatoria*

This cutting-edge biodesign experimentation debuted during Milan Design Week 2018, and is part of a broader research project entitled 'Biodesign: Living and Breathing the Future of Performance'. It is the result of a collaboration with the sports company PUMA and the MIT Design Lab.[1] These T-shirts respond to environmental factors by informing their wearers about air pollution levels. Microbially-activated buttons are mounted on the fabric of the clothes. They contain a particular microalga called *Oscillatoria* (a cyanobacterium like *Spirulina*). *Oscillatoria* reacts to the levels of CO_2 in the atmosphere within one hour: if the levels are low, it has a brownish color. When the levels of CO_2 increase, the color changes into purple, indicating bad air quality. Such a 'biologically-smart' T-shirt can be worn by athletes to be informed in real-time about their surroundings.

1 More information at: https://design.mit.edu/projects/puma-biodesign

Figure 7.18. Carbon Eaters, a T-shirt able to respond to the quality of air. Adapted from *MIT Design Lab* website, 2018, retrieved from https://design.mit.edu/projects/puma-biodesign

Symbiont

19

Designer(s): *Andriana Nassou*
Place: *London, United Kingdom*
Period: *2018, July*
Status: *Concluded*
Keywords: *Home PBR, Indoor air purifier, Biophilic design*

Andriana Nassou attended a double Master's program called 'Global Innovation Design' run jointly between the Royal College of Art and the Dyson School of Design Engineering – Imperial College London. Her work 'Symbiont' is an indoor air purifier which harnesses microalgae (supposedly *Chlorella* or *Spirulina*). According to the designer, the product can purify the air of a 20 m^2 space, producing an amount of oxygen that equals to 36 house plants.[1] It is based on the principles of 'biophilic design' with forms that enhance the functions of natural systems.[2] Her work was exhibited in July 2018 at Imperial, together with more than fifty innovative products designed by the School's postgraduate students.

1 See: https://www.andriananassou.com/symbiont

2 For more information on biophilic design, it is suggested to read: Kellert, S. R., & Calabrese, E. F. (2015). *The practice of biophilic design*. Retrieved from www.biophilic-design.com

Figure 7.19. Symbiont structure close-up. Adapted from *Andriana Nassou* website, 2018, retrieved from https://www.andriananassou.com/symbiont Copyright 2018 by Andriana Nassou.

The Coral

20

Designer(s): *Hyunseok An*
Place: *Providence, Rhode Island*
Period: *2019, June*
Status: *Completed*
Keywords: *Home production, Wall-mounted BR, Coral bleaching*

The Coral is an indoor, wall-mounted bioreactor that produces *Spirulina* for domestic use. It is composed of 16 cells that fit into a wooden four-by-four grid, each of them seeded with an algae inoculum, purified water, salts, and nutrients. Electric pumps allow carbon dioxide to flow in the culture in a mesmerizing way. Each container is ready to be harvested after around two weeks (Solondz, 2019): this allows users to have a daily dose of fresh *Spirulina* (around g 3 serving).

The boxes are designed to resemble the pattern of corals, to symbolize the importance of algae in their revitalization. Coral bleaching is, in fact, a worldwide phenomenon caused by global warming that causes corals to expel the symbiotic algae living in their tissues. The project also aims at changing the current preconception of algae, suggesting new ways of integrating them into our daily lives.[1]

1 More information at: https://www.dezeen.com/2019/07/04/hyunseok-an-algae-the-coral-micro-farm/

Figure 7.20. The Coral microalgae farm. Adapted from *Hyunseok An* website, 2019, retrieved from http://ulr.im/pages/thecoral.html
Copyright 2019 by Hyunseok An.

7.21 Considerations

The above-described projects have been labeled as 'experimentations' due to their high innovativeness, freshness, and uniqueness. Experimentations that involve the use of microalgae in design practice are, in fact, still rather limited and not mainstream. The aims of these projects are quite different. They are made to produce food, to create drugs, to purify the air, to assess the air pollution levels, as biomaterials or bio-inks, etc. They range from low-tech and low-budget products to quality and highly engineered gadgets. In multiple cases, they were also the result of collaboration with biologists and engineers. Out of the 20 experimentations taken into account, 10 of them can be included in the field of product and furniture design; 4 are printing mediums and inks; 4 are lamps; 2 are in the field of fashion design (see Fig. 7.21). It is thus recognizable higher interest in the last years for the design of products that embedded microalgal production. Microalgae are particularly appealing also for lighting designers, most probably due to their primary necessity of being illuminated for growing: photobioreactors can be considered a particular kind of lamps too. Furthermore, special interest is raising on the extraction of pigments from microalgae. Bio-inks have already been used as sustainable solutions in several applications. These include printing on paper and fabrics, but also to refill felt-tips. Up to this time, microalgae are gaining popularity also in the world of sustainable fashion. In the next future, there will be a higher request for eco-friendly and smart clothes, and the use of microalgae can be a viable alternative to polluting petroleum-based inks and to electronic sensors for measuring air quality.

Figure 7.21. Out of the 20 experimentations taken into account, 10 of them are in the field of product and furniture design; 4 are printing mediums and inks; 4 are lamps; 2 are in the field of fashion design.

Several of the mentioned realizations have been developed within an academic environment: as a result of Ph.D. or Master's theses (like Algae-graphies, Moss Table, and Algaerium Bioprinter, to name a few), or of broader research projects. Experimentations are also coming from top universities like MIT in Cambridge (Boston), and Imperial College London. Without disregarding the importance of the research from other universities and given the excellence of these institutions, the direction of current and future studies seems to be the right one. As regards the projects that were born out of academia (or with weaker connections with it), some of them are already on the market or will soon be all set to be commercialized. This is an important point because it underlines the readiness of entrepreneurs in entering into this business, which is still partly unexplored. Investments in time, human resources, and money are still required for some, to scale up the projects that are promising but still at early-stage development. Others instead already received capitals for previous and future implementations. Some of the artifacts analyzed in the case studies cards were marked with status 'completed'. They will probably never been further modified, nor improved. These are mostly the cases of projects developed by single designers or duos, which, for many reasons, do not have the resources for continuing them. For this reason, most of the design experimentations are not prolonged over time, following a trend similar to other larger-scale projects, as will be analyzed in the next paragraphs.

Many of the projects included the use of *Spirulina*, not necessarily due to its particular nutritional properties but due to its notoriety compared to other microalgae streams. As a matter of fact, "*Chlorella and Spirulina are widely commercialized in health food stores gaining worldwide popularity*" (García, de Vicente, & Galán, 2017, p. 1018). Finally, some of the projects claim to be used as indoor air purifiers, but they do not provide information on the effective improvement of the air quality to the final user. Assessing their efficiency requires deep technical analysis. To conclude, the public, which is poorly informed about the characteristics and benefits of microalgae (see Appendix: Food for the future – Online survey) needs to be educated: the methods of designers are effective in this. At the same time, however, many of the projects – which in some cases are inspired by nature while in others have a more modern and appealing look – continue to represent 'alien' elements to the daily life of many, thus hindering the efforts of making the production and the use of microalgae something available for everyone.

7.2 Microalgae in urban contexts

Cultivating microalgae in cities may seem an unusual practice, yet a "*future of scalable microfarms for home, school and community gardens, urban and rooftop farms and even living buildings that are local, sustainable and profitable*" (Henrikson, 2013, p. 14) is upon us. Professionals from all over the world have been using microalgae not only for the creation of small design objects. Instead, they have also designed larger installations, in some cases even on the urban scale. To be completed, these projects required collaboration from multiple parties and joint efforts. Among the stakeholders involved, municipalities played an important role in providing eventual licenses and promoting the projects with citizens.

In the following pages, 18 projects of different types and from all over the world are presented (Table 7.3). Among these designs, there are artistic-cultural installations, gardens, and devices for indoor use, but also social projects and successfully-launched business activities, among others. Each project is presented and summarized through a common template.

Such different projects also have very distinctive characteristics: among these, for example, the budgets for their implementation and the overall life spans, that considerably vary. Their only common constant is the capability of producing microalgae. The projects were analyzed according to the methodology described in the following paragraph. The analysis identified the pros and cons of each project, their limits and the design opportunities that emerged. Similar solutions could be some of the viable means to imagine a sustainable future for cities and to plan resilient prospects characterized by new equilibria.

7.2.1 Analysis methodology

The literature does not provide any other relevant comparative studies on projects that involve the production of microalgae in urban scenarios. The analysis of the case studies illustrated below highlights the potential and criticality of the different developments, the design trends, and the relative periods of operation. To have a more comprehensive view, this study took into consideration exemplary cases of diverse types, including installations, architectural and infrastructural integrations, as well as social projects. 18 cases from 2011 to the present are examined.

The production of microalgae in cities has multiple points in common with the better-known urban and peri-urban farming practices. Even if they may seem inanimate and not very empathic, microalgae are living organisms in all respects, which react to external factors resulting in more or less healthy yields. Growing microalgae, therefore, requires competent people (at least with basic notions) and available to devote part of their time. The same is valid for those who engage in traditional gardening activities. Extensive literature has shown that urban gardens play an important role in urban regeneration,

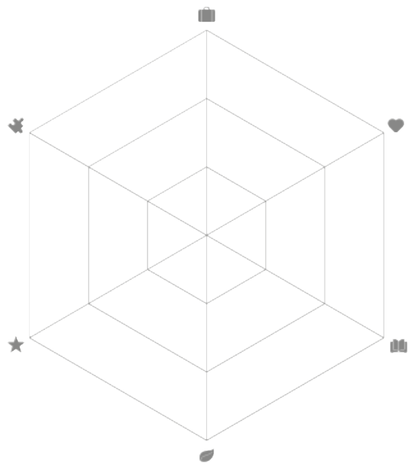

Figure 7.22. The radar chart used for assessing and comparing the case studies.

- Job creation
- Social inclusion
- Education/divulgation support
- Environmental impact
- Value creation
- Generation of synergies on the territory

combining social and environmental benefits. Although the types of cultivation and seasonal cycles change, the community values that are transmitted remain firm. Urban microalgae cultivations are, therefore, similar to urban vegetable gardens. Because of these similarities, the case studies were analyzed, adopting a methodology similar to the one used by MADRE (2018) for the assessment of selected urban farming activities. This involved the determination of several parameters, later compared through a composite radar chart (Fig. 7.22). The analysis identified the contribution of each project to six different challenges. The parameters have a qualitative connotation and are displayed on a scale of 1-3, in which 1 expresses a minimum contribution and 3 a significant contribution. The description of the challenges and the evaluation details follow.

1. **Job creation:** new activities related to maintenance, production, harvesting, processing, marketing, promotion, and distribution of products (primary and processed). This also includes the training of specialized personnel and is useful for fighting poverty in the most degraded areas.
2. **Social inclusion:** initiatives that directly involve local communities without distinction of sex, age or ethnicity and are aimed at empowering people from disadvantaged neighborhoods.
3. **Education/divulgation support:** transmission to a wider public of principles linked to environmental sustainability, healthy diet, and food security. This encompasses the education of children, adults, and the elderly through traditional or alternative pedagogical methods. The divulgation takes into account the media coverage of the project or the number of visitors in the case of exhibitions and fairs.
4. **Environmental impact:** to evaluate the contribution to this challenge, the quantity of biomass produced, the sustainability of the techniques applied for the production and collection, and the measures adopted for the eventual distribution have been taken into account.

5. **Value creation:** retailing and brand building are ways to consolidate the quality of the products, permitting consumers to recognize the added value.
6. **Generation of synergies on the territory:** collaboration with third parties encourages the development and maintenance of the projects. This generates fruitful interactions with citizens and consumer associations, public authorities at local and/or regional level, small and medium private companies, professionals, schools, Universities, and Research centers.

Following the complete description of each case study and its radar chart. Limits of the projects, design opportunities, and remarkable considerations can be found at the end of the chapter.

Table 7.3. The most representative projects involving microalgae in urban contexts, from 2011 until today.

	Project name	Designer(s)	Place	Period
1.	Algaegarden	Ring, Parker, & Fredericks	Grand-Métis, Canada	2011, June
2.	Skyline Spirulina	EnerGaia	Bangkok, Thailand	2013, January
3.	BIQ House	ARUP	Hamburg, Germany	2013, April
4.	Algaevator	Stevermer & Zhang	Cambridge, Massachusetts	2013, December
5.	Urban Algae Canopy	ecoLogicStudio	Milan, Italy	2014, April
6.	Urban Algae Façade	Cesare Griffa	Milan, Italy	2014, April
7.	Culture Urbaine	Cloud Collective	Geneva, Switzerland	2014, June
8.	The Third Paradise	Michelangelo Pistoletto	Copenhagen, Denmark	2014, October
9.	Urban Algae Folly	ecoLogicStudio	Milan, Italy	2015, May
10.	Façade System	MINT Engineering GmbH	Berlin, Germany	2015, November
11.	Floating Fields	Thomas Chung	Shenzhen, China	2016, March
12.	BIOtechHUT	ecoLogicStudio	Astana, Kazakhstan	2017, June
13.	The Carbon Sink	Fermentalg & SUEZ	Paris, France	2017, July
14.	Algae Dome	SPACE10	Copenhagen, Denmark	2017, September
15.	Living Solar Modules	Solaga	Berlin, Germany	2017, October
16.	WaterLilly 3.17	Cesare Griffa	Turin, Italy	2018, February
17.	BioUrban 2.0	BiomiTech	Puebla, Mexico	2018, June
18.	Photo.Synth.Etica	ecoLogicStudio	Dublin, Ireland	2018, November


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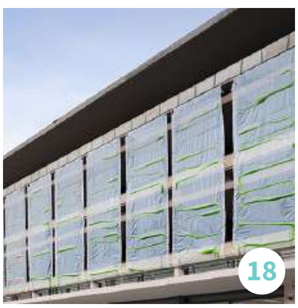
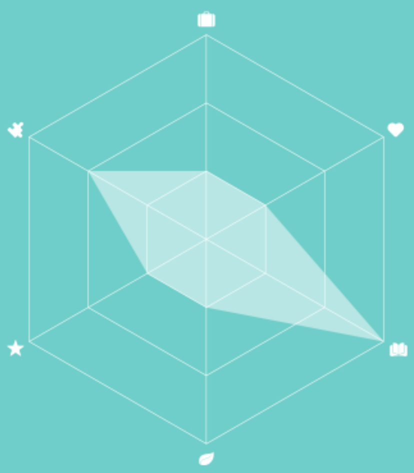

18

Algaegarden

Designer(s): *Heather Ring, Brenda Parker, and Synnøve Fredericks*
Place: *Grand-Métis, Canada*
Period: *2011, June*
Duration: *15 months*
Status: *Concluded*
Keywords: *Garden, Interactive installation, Landscape design*



Algaegarden is the project of a multidisciplinary team composed by Heather Ring, Brenda Parker, and Synnøve Fredericks, whose competencies are ranging from architecture to art and biology. They also collaborated with a few suppliers and consultants like the Canadian Phycological Culture Centre, ESMER, and Varicon Aqua Solutions. Algaegarden was open to the public from June to October 2011 during the 'Festival international de jardins' in Grand-Métis, Quebec, Canada.[1] The garden lasted for 5 months, and, given the public appreciation, it was also exhibited in 2012 and 2013.

The garden celebrates the potential and the beauty of microalgae through an artistic and interactive installation. Wooden and steel frames are supporting curtains of hanging plastic tubes, filled with different species of microalgae (e.g., *Spirulina*, *Chlorella*, and *Haematococcus*, among others), to show a full spectrum of mutating colors though the seasons. Manually-activated pumps, easy to use by everyone, can aerate the cultures. This activity is also a funny and curious game for adults, and even more for children. Algaegarden looks at new and out-of-the-box ways of producing energy and food, demonstrating that microalgae can become part of our daily lives.[2]

Given the characteristics of this project, its educational value is high. Also, the project was possible thanks to the involvement of diverse parties: individuals, private, and public institutions. The other parameters do not have relevant connotations.

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1 See: http://www.festivalinternationaldejardins.com/ALGAEGARDEN/

2 More information on Synnøve's website: https://www.synnove.net/the-algaegarden/

1

Figure 7.23. Overview of the Algaegarden. Steel frames are supporting the 'curtains of tubes'. All the pictures in this page are adapted from *Pruned Blog* website, 2011, retrieved from https://pruned.blogspot.com/2011/08/algaegarden.html Copyright 2011 by Martin Bond.

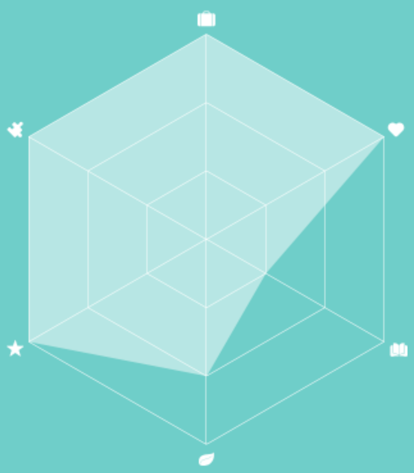
Figure 7.24 (Left). A child is blowing air into the tubes through a hand pump.

Figure 7.25 (Below/Left). The microalgae inocula are poured into the pipes.

Figure 7.26 (Below/Right). Different microalgae coltures. Purportedly *Spirulina*, *Chlorella* and *Haematococcus*. Copyright 2011 by Heather Ring, Brenda Parker and Synnøve Fredericks.

Skyline Spirulina

Designer(s): *EnerGaia*
Place: *Bangkok, Thailand*
Period: *2013, January*
Duration: *6 years and 8 months*
Status: *Ongoing*
Keywords: *Rooftop farming, Socially-oriented start-up, Branding*



EnerGaia is a Thai company that started its activity in 2009 with the intent of capturing industrial CO_2 flue gas. In late 2012 their mission evolved and started to produce microalgae for food use. Their produces are sustainable and with high nutritional values. Moreover, they do not compete with traditional foods, since they do not utilize arable land.[1] They come up with an innovative idea that fits well with the climate of tropical regions and urban contexts: they grow *Spirulina* on rooftops in cylindrical PBRs (Kumar & Abdul, 2019). One of their production facility is situated on the rooftop of a luxury hotel in Siam Square, in the city center of Bangkok. The company distributes fresh and dry biomass to both high-spending customers and people in need (Ortolani, 2016) while providing jobs, directly cooperating with local disadvantaged communities.

Products are sold in selected shops in the city to guarantee the freshness and quality of *Spirulina*. They are also selling online, through a spin-off brand called 'Skyline Spirulina'[2], and partly to European B2B customers. The company recently also moved to Indonesia, India, and Bangladesh and is currently working with the Bill & Melinda Gates Foundation to promote the production of *Spirulina* in rural areas. EnerGaia won "*various awards from development organizations (Blue Ocean, USAID) that loved its mission [...]. Now the firm may appear to be 'going corporate', deviating from its roots*" (Merrill & Schillebeeckx, 2019).

Nevertheless, and for all the above-mentioned reasons, Skyline *Spirulina* is a virtuous case study that greatly contributes to many of the identified challenges. The interview with Ehsanul Karim, former General Manager of EnerGaia Bangladesh, can help to clarify how (see Appendix).

1 More information on EnerGaia's website: https://energaia.com

2 See: https://skylinespirulina.com

2

Figure 7.27 (Above). Barrels of *Spirulina* on the rooftop of the Hotel Novotel Bangkok on Siam Square. All the pictures in this page are adapted from *The Guardian* website, 2016, retrieved from https://www.theguardian.com/sustainable-business/2016/apr/07/spirulina-kale-thailand-urban-farming-environment-food Copyright 2016 by Paola Di Bella/Redux.

Figure 7.28 (Left). The *Spirulina* farm extends on a space of 80 m^2, with around 40 barrels that contain up to 250 liters of water each.

Figure 7.29. A bartender makes a shake with *Spirulina*, apple juice and cucumber.

BIQ House

Designer(s): *ARUP*
Place: *Hamburg, Germany*
Period: *2013, April*
Duration: *6 years and 5 months*
Status: *Ongoing*
Keywords: *Integrated architecture, Closed-loop system, Bio-façade*

The BIQ House in Hamburg is the first building in the world that used microalgae to produce the biomass and thermal energy necessary for its needs. It was started to be built in September 2012 and inaugurated in April 2013. It is still in operation today. The south-west and the south-east sides of the building are covered in flat panels PBRs, that produce biomass and heat. Underground, in an energy management center, the biomass is harvested and the heat redistributed in the building, to be used for supplying hot water or for heating 15 residential units. The bio-responsive facade has multiple benefits:

- The biomass can be used to produce power and generate heat, according to the needs;
- During sunny days, microalgae grow faster. Their higher cell density helps to provide shading;
- The CO_2 required for the algae growth can be taken – for example – from boilers. This will avoid further carbon emissions to enter the atmosphere.

The project has been tested by an interdisciplinary team of architects, designers, engineers, and biologists, and has a good efficiency conversion of light to biomass and light to heat.[1] It is, thus, strongly technology-driven and it is still necessary to understand the real daily benefits for the inhabitants. Considering the quantity of biomass produced, its environmental impact is positive. Nevertheless, other intangible, yet perceivable aspects could be investigated further. This may activate long-lasting local cooperations and providing also more jobs if the implementation would be on a wider scale.

1 The full-scale bio reactive façade called SolarLeaf, was installed for the first time on the BIQ House at the International Building Exhibition (IBA) in 2013. The system can operate all year round. More info on ARUP official website: https://www.arup.com/projects/solar-leaf

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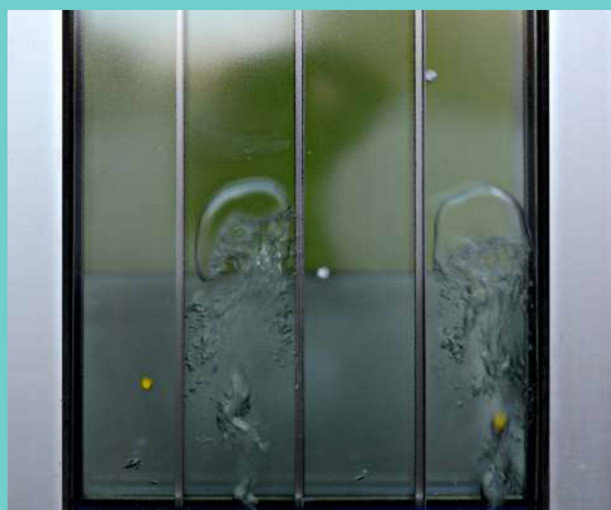
Figure 7.30. The south-west and the south-east sides of the building are characterized by a second layer of photobioreactors (129 in total), that are set into the façade. All the pictures in this page are adapted from *Archello* website, 2013, retrieved from https://archello.com/project/biq-house/ Copyright 2013 by ARUP.

Figure 7.31 (Below/Left). Detail of the façade.

Figure 7.32 (Below/Right). A flat panel photobioreactor in action.



Algaevator

Designer(s): *Tyler Stevermer & Jie Zhang*
Place: *Cambridge, Massachusetts*
Period: *2013, December*
Duration: *3 months*
Status: *Concluded*
Keywords: *Lightweight architecture, Gravity PBR, Spatial experience*

Algaevator, by Tyler Stevermer in collaboration with Jie Zhang (MIT alumni) was designed as part of the Burglars of Transnatural Transparency (BoTT) Lab pavilion in Cambridge, Massachusetts. It was inaugurated in December 2013, and the installation lasted for three months. The pavilion also hosted the Pleura Pod, a plastic wall system with automated temperature controls to grow contained algae.[1]

Algaevator investigates the connections between architecture and biotechnology in the attempt to produce algae for consumer products and alternative fuels. Moreover, lightweight architectural surfaces create extra-ordinary spatial experiences (Stevermen, 2014). "*The system [...] can be used in neglected buildings to help regenerate urban environments and with that unique structure, the Algaevator can be considered as gravity-based photobioreactor [...]. This funnel-shaped structure also optimizes sun exposure for microalgae production and can also harvest rainwater for additional sustainability*" (Deniz & Keskin-Gundogdu, 2018, p. 64).

Algavator's innovativeness is high. This case study is a remarkable architectural experimentation that required multidisciplinary approaches, resulting in a particularly high educational impact for the visitors. Considering the materials used for the structure (PVC and PETG) and the short lifespan of the project, its overall sustainability is questionable. The quantity of biomass produced, moreover, does not seem to be enough to subtract a fair amount of CO_2.

1 The designers collaborated with Jinyeong Moon, Ph.D. student in Electrical Engineering. More information at: https://architecture.mit.edu/architecture-and-urbanism/project/pleura-pod-bott-lab-pavilion-project

4

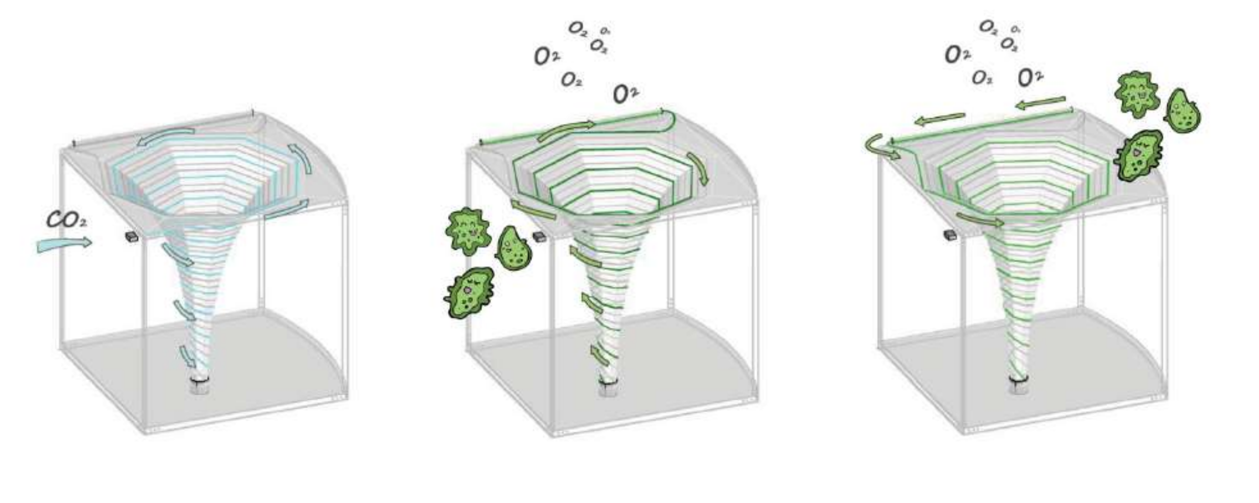


Figure 7.33 (Above). The three separate spirals. 1. Carbon dioxide; 2. Microalgae ascension; 3. Microalgae descension. All the pictures in this page are adapted from *inhabitat* website, 2016, retrieved from https://inhabitat.com/algaevator-transforms-algae-production-into-a-beautiful-work-of-art-and-architecture/ Copyright 2016 by Iwan Baan.

Figure 7.34 (Left). Detail of the transparent membrane and of the central spirals.

Figure 7.35. Aerial view of the pavilion.

Urban Algae Canopy

Designer(s): *ecoLogicStudio and Carlo Ratti Associati*
Place: *Milan, Italy*
Period: *2014, April*
Duration: *12 days*
Status: *Concluded*
Keywords: *Urban installation, Bio-digital canopy, Man-made ecology*

Urban Algae Canopy is a well-known experimental urban installation and a clear example of the so-called 'algaetecture'. The scale 1:1 prototype has been exhibited at the Milan Design Week 2014, from 7 to 18 April, and well before the World Exposition Milan 2015. The canopy is digitally controlled: it reacts in real-time to weather conditions and the movements of the people passing by. Energy, water flow, and CO_2 intake can also be regulated. The structure is rather simple: a four-layered ETFE system is held by an aluminum triangular-shaped frame. Frames are then connected to create a welcoming, canopy-like structure. A small tank placed at the bottom collects the biomass.

According to Ratti (2014), "*the Algaetecture project aims to develop a natural man-made ecology and explore the use of algae as an integrated architectural cladding and urban agriculture system*". If properly engineered, the device is supposed to produce up to kg 150 of biomass daily, the same as around 40,000 m^2 of woodland. Similar projects hold great potential. Urban agriculture is a promising way to cultivating future foods. At present, roofs and facades in cities are inanimate, but they could become productive man-made photosynthetic surfaces.[1]

Given the importance of the event at the national and international levels, this project had significant media coverage. Many people got to discover more about microalgae, design, and urban possibilities. However, the installation was not intended to last long, and its sustainability over time was eventually not taken into consideration.

1 See: http://www.arch2o.com/urban-algae-canopy-carlo-ratti-associati-with-cesare-griffa-ecologicstudio/

Figure 7.36 (Left). Urban Algae Canopy unveiled at Università Statale, Milan. All the pictures in this page are adapted from *ecoLogicStudio* website, 2014, retrieved from http://www.ecologicstudio.com/v2/project.php?idcat=7&idsubcat=59&idproj=129 Copyright 2014 by ecoLogicStudio.

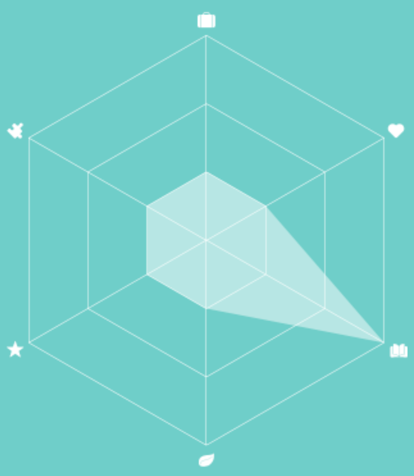
Figure 7.37 (Below/Left). Detail of the point of junction and of the pipes.

Figure 7.38 (Above/Right). Detail of the cladding system.

Figure 6.39. The biomass produced is collected into a glass basin.

Urban Algae Façade

Designer(s): *Cesare Griffa*
Place: *Milan, Italy*
Period: *2014, April*
Duration: *12 days*
Status: *Concluded*
Keywords: *Bioskin, Vertical farm, Temporary installation*



Cesare Griffa is an architect based in Turin, Italy, who has been working on the design of diverse solutions that involve microalgal production. The Urban Algae Façade is a prototype. The façade can be used as a *"vertical farm to be implemented as an architectural skin"* (Descroll, 2014). The structure was presented at the Milan Design Week 2014, together with ecoLogicStudio's Urban Algae Canopy (paragraph 7.2.6). Its design is based on 'WaterLilly 2.0', a vertical surface made by modular plastic containers, in which microalgae can grow. The façade has a positive symbiosis with the building and the surrounding environment, resulting in several benefits. These include, but are not limited to, the reduction of the CO_2 emissions of the building and its increased thermal storage.[1]

The vertical farm has been active for 12 days. After the event, it has been placed in Griffa's studio for further refinements. The plastic used has gone yellow with age, hence unappealing and with a reduced capacity of capturing light for photosynthesis. Thus, this solution is not recommended for long-term implementations (C. Griffa, personal communication, April 18, 2019).

Online media success has been high. Many visitors have had the opportunity to learn about new issues that have not been previously known to them. Also in this case, therefore, the popular value of the project is excellent. The business models hypothesized by Griffa for 'Bioskin' could increase the other evaluation parameters.

1 The operational requirements of Urban Algae Façade are rather similar to the ones of 'Bioskin' a permanent microalgae façade designed by Cesare Griffa Design Lab. See the brochure and the full-service proposition: https://drive.google.com/file/d/0BxapDU9Ar04sREdCRlY1bjZkSW8/view

Figure 7.40. Cesare Griffa in front of the vertical algae wall. All the pictures in this page are adapted from *Cesare Griffa* website, 2014, retrieved from https://cesaregriffa.com/waterlilly/waterlilly-2-0/ Copyright 2014 by Cesare Griffa.

Figure 7.41. Detail of the modules. Water flows from one module to the other through simple spouts.

Figure 7.42. Detail of the conjunctions. Six locking nuts connect five modules together.

Culture Urbaine

Designer(s): *Cloud Collective*
Place: *Geneva, Switzerland*
Period: *2014, June*
Duration: *5 months*
Status: *Concluded*
Keywords: *CO_2 capture, Highway, Viaduct*

Culture Urbaine is the project of The Cloud Collective, a joint force of creative minds from different fields.[1] The project was one of the 13 gardens created for festival Genève: Villes et Champs, an event that focuses on the relationship between human and nature, within the context of the expanding area of Geneva. Culture Urbaine operated from 13 June to 4 October 2014: it was dismantled right after the event (J. Lipsch[2], personal communication, April 30, 2019). The project, which included the installation of a closed transparent pipe system on a viaduct, was carried out near a busy road to use sunlight and CO_2 – both abundantly present on-site. The pipes are supported by a steel structure that also accommodates pumps, filters, and solar panels. Didactic panels provide information on the project for pedestrians and cyclists. *"The site [...] is particularly violent and quite out-of-tune with the idea of the garden as a peaceful natural haven. Instead, the project focusses on the character of the site and tries to prove that even these locations [...] – despite their anonymous and generic character – can play an important role in the production of food and biomass"* (The Cloud Collective, 2014).

Culture Urbaine is of particular interest as it has succeeded in combining food production in an urban environment, in reinterpreting the existing infrastructures, and in the maintenance of green spaces. Given the amount of biomass produced and the efficiency of the PBR system (the designers partnered with Lgem, a dutch company specialized in high-output turnkey solutions), this project is characterized by a good level of sustainability. Also, this project was possible because of the many synergies between different public and private stakeholders.

1 More information about the Cloud Collective at: https://www.thecloudcollective.org/

2 Joris Lipsch is an Architect and Co-founder of Studio matters, a member of The Cloud Collective.

Figure 7.43 (Above). View of the pipes. All the pictures in this page are adapted from *inhabitat* website, 2014, retrieved from https://inhabitat.com/overpass-algae-garden-turns-co2-emissions-into-combustible-biomass-in-switzerland/ Copyright 2014 by Cloud Collective.

Figure 7.44. The photobioreactor makes use of the site's abundance of carbon dioxide and sunlight.

Figure 7.45. Didactic panels provide information on the project for pedestrians and cyclists.

The Third Paradise

Designer(s): *Michelangelo Pistoletto*
Place: *Copenhagen, Denmark*
Period: *2014, October*
Duration: *2 months*
Status: *Concluded*
Keywords: *Conceptual art, Nature and artifice, Synthetic biology*

The Third Paradise is a conceptual art installation by Italian action and object artist and art theorist Michelangelo Pistoletto. He is working on this idea since 2003, and his works have been exhibited all over the world.[1] From 14 October to 13 December 2014, Pistoletto showcased the New Sign of Infinity in the courtyard of Charlottenborg Palace, Andersen's Contemporary, Copenhagen.

The installation consisted of a 50-meters long plastic tube filled with approximately 200 liters of microalgae *Synechococcus sp.* Visitors could walk through it, and children were rather curious about such out-of-the-ordinary installation. *"Pistoletto was very satisfied with the new dimension added to his symbol; the way it was becoming alive by having living organisms floating through"* (Center for Synthetic Biology, 2014). The University of Copenhagen was involved in shaping this sign, and a small forum about the nature of synthetic biology took place on October 15.

This case study has been hard to categorize and define due to the intrinsic invaluable artistic features. Art is a medium to spread messages, and it is impossible to quantify its effects on society. Moreover, in some cases, it not as immediate to understand for a large audience. However, it was not possible to exclude this project from the list and based on the evaluation parameters identified, this project achieved a limited score.

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1 The Third Paradise symbolically represents a mathematical infinity sign. The opposites circles represent the artificial and the natural world. The middle one is their conjunction, in the attempt to overcome conflicts toward new humanity. It is suggested to read Oliva, A. B. (Ed.). (2013). *Michelangelo Pistoletto. Il terzo paradiso.* Milano: Electa.

Figure 7.46. People interacting with the installation. All the pictures in this page are adapted from *University of Copenhagen* website, 2014, retrieved from https://synbio.ku.dk/news/pistoletto/

Figure 7.47. Algae floating through the New Sign of Infinity in the courtyard of Charlottenborg Palace, Copenhagen.

Figure 7.48. Italian painter, action and object artist and art theorist Michelangelo Pistoletto drawing his symbol.

Urban Algae Folly

Designer(s): *ecoLogicStudio*
Place: *Milan, Italy*
Period: *2015, May*
Duration: 6 months
Status: *Concluded*
Keywords: *Interactive pavilion, Bio-digital future, Innovative agriculture*

Urban Algae Folly (UAF) is an installation by the well-known, London-based, ecoLogicStudio (Marco Poletto and Claudia Pasquero). UAF was designed for the World Exposition Milan 2015, Italy, and was active from 1 May to 31 October 2015. It was located at the entrance of the Future Food District, curated by Carlo Ratti Associati, to showcase the most cutting-edge projects of building-integrated urban agriculture. Its composition is based on the one experimented earlier with the Urban Algae Canopy (paragraph 7.2.6). Triangular plastic curtains are connected through a modular tree-like steel structure. Inside, *Spirulina* grows vigorously thanks to the high amount of sunlight that receives. Even if the overall look may appear alien, its canopy-like structure is familiar and welcoming for visitors, that can also chill out under the shadow during hot sunny days. The basement has a compartment for hosting tanks, pumps, and many other technical parts.

The installation is a perfect example of what a bio-digital future may look like: *Spirulina* subtracts CO_2, releases oxygen, and provide high-quality nutrients. At the same time, visitors can interact with the UAF through their smartphones, regulating the oxygen and insolation levels of the culture, or participate in periodical harvesting events (ecoLogicStudio, 2015).

The project had an outstanding exposure with millions of visitors from all over the world: for this reason, its educational value is extremely high. Also, the installation required the join efforts of biologists, architects, and engineers, and this is a good example of fruitful collaboration.

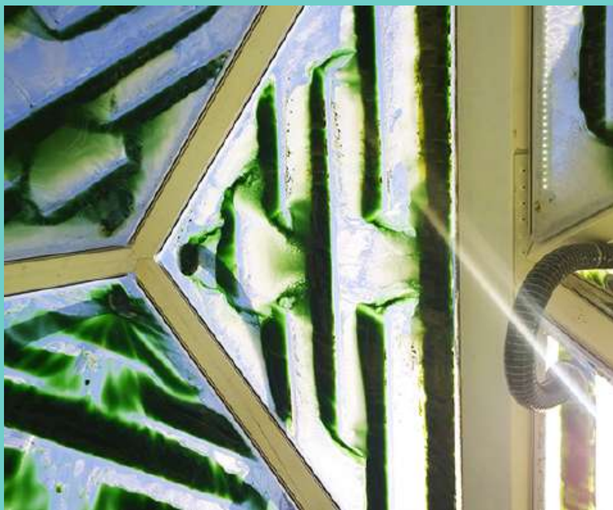


Figure 7.49 (Above/Left). *Spirulina* growing under optimal light conditions. All the pictures in this page are adapted from *ecoLogicStudio* website, 2015, retrieved from http://www.ecologicstudio.com/v2/project.php?idcat=3&idsubcat=71&idproj=147 Copyright 2015 by ecoLogicStudio.

Figure 7.50 (Above/Right). A complex network of tubes channels the biomass to a collection tank.

Figure 7.51 (Left). UAF in the 'Future Food District' - Milan EXPO2015.

Figure 7.52. Visitors can interact with the pavilion through their smartphones and attending the periodical harvest events.

Façade System

Designer(s): *MINT Engineering GmbH*
Place: *Berlin, Germany*
Period: *2015, November*
Duration: *3 years and 10 months*
Status: *In operation*
Keywords: *Microalgae façade, Partner cooperation, Patented solution*

Façade System is the project of MINT Engineering[1], a German company that designs and distributes systems for cultivating microalgae. The structure has been installed on the façade of an office building in the EUREF Campus in Berlin Schöneberg, since November 2015. The campus hosts several innovative companies and start-ups. The pilot project was finalized and tested by CEO Gunnar Mühlstädt, together with specialized engineers and piping system suppliers. *"The system also withstood the winter undamaged, as expected. [...] Thus, proof is furnished that the cultivation of microalgae is also possible in the metropolitan area without having to consider using agricultural land"* (GF Piping Systems, 2016).

The system is running for more than 3 years and is fully certified to produce food after German food regulations. The produced biomass is not sold since they use it for analytics and to optimize the process of production. MINT Engineering is working to launch a B2C product to be distributed to end customers in the near future (G. Mühlstädt, personal communication, May 7, 2019).

Façade System seems to be a simple project but is rather complex. The system is patented and engineered to maximize production and guarantee yields. Also, the project required the participation of several partners, including researchers and engineers, but also the authorizations from EUREF management and the food certifications from the regulators. For these reasons, it achieves a higher level of sustainability, ensure jobs for a small team of experts, and strengthen relations between the parts. Hopefully scalable, it is a good example of an urban algae garden that should be taken as reference.

1 More information about MINT Engineering at: https://www.mint-engineering.de/en/home/

Figure 7.53. Due to its exposition, the photobioreactor can be regulated adaptively with a controller. Retrieved from https://www.gfps.com/content/dam/gfps/master%20Content/Pictures/Company/References/MINT_02.jpg

Figure 7.54 (Below). The system is installed on the façade of a building in EUREF Campus in Berlin Schöneberg. The campus hosts several innovative companies and startups. Retrieved from https://www.gfps.com/content/dam/gfps/master%20Content/Pictures/Company/References/MINT_01.jpg

Floating Fields

Designer(s): *Thomas Chung*
Place: *Shenzhen, China*
Period: *2016, March*
Duration: *10 months*
Status: *Concluded*
Keywords: *Productive pond-scape, Regenerative design, Community*

Floating Fields in Shenzhen, China is an innovative award-winning architectural project by Thomas Chung (principal investigator), Associate Professor of Architecture at the Chinese University of Hong Kong. It was concluded in February 2016 on the occasion of the Urbanism/Architecture Bi-City Biennale (UABB) and was open to the public during the course of the event.[1] The project was extended for the rest of 2016 but eventually was stopped due to a change in client management. However, the construction and infrastructure may still be currently in place (T. Chung, personal communication, May 14, 2019).

The project consists in the transformation of an abandoned flour factory into *"a productive and leisure pond-scape, demonstrating how architectural design can integrate concepts of aquaponics, floating plots, algae cultivation, self-cleansing water cycle, and sustainable food production"* (Chung, 2016, p. 36). Microalgae were harvested in ponds and photobioreactors to produce fish feed and to improve the purification of the water.[2] The area was conceived as a research laboratory on regenerative design, as well as a recreational location for the local community. It is, undoubtedly, a great example of how microalgae and other nature-based solutions can be used in cities, in temporary brownfield sites, or even permanently. The project also involved many stakeholders: local government, universities, event organizers, real estate managers, among others.

1 It was awarded the Organizing Committee Grand Prize and it was the winner for the World Architecture Festival 2016 for the category 'Production Energy And Recycling – Completed Buildings'.

2 Collaboration with Prof. Ho Kin Chung from The Open University of Hong Kong.

Figure 7.55. Aerial view of the UABB site at the Dacheng Flour Mills in Shekou, Shenzhen. All the pictures in this page are adapted from *ArchDaily* website, 2016, retrieved from https://www.archdaily.com/783314/floating-fields-wins-shenzhen-uabb-award-and-is-set-to-continue-through-2016 Copyright 2016 by Thomas Chung.

Figure 7.56 (Left). Microalgae are harvested to produce fish feed and to improve the purification of the water.

Figure 7.57 (Below/Left). Children catching fishes at the closing Harvest Festival, to make fish soup.

Figure 7.58 (Below/Right). Floating salad fields and visitors on a small boat.

BIOtechHUT

Designer(s):	*ecoLogicStudio*
Place:	*Astana, Kazakhstan*
Period:	*2017, June*
Duration:	*3 months*
Status:	*Concluded*
Keywords:	*Future city farming, Super-food, Bioenergy*

The BIOtechHUT is a futuristic pavilion designed by ecoLogicStudio for Astana Expo 2017 (10 June to 10 September 2017). The installation explores the relationship between human and biology in the Anthropocene, especially focusing on the urban production of microalgae for food and biofuels. The pavilion is divided into smaller spaces: the Garden Hut is a place where to harvesting and processing microalgae. Central tanks are collecting the produced biomass. H.O.R.T.U.S. (Hydro Organisms Responsive to Urban Stimuli) is characterized by an organic shape. It is a long tubular photobioreactor in which a culture of *Spirulina* grows. Visitors are encouraged to blow into some masks, to feed microalgae with their CO_2. The Algae Photo-Bioreactor Room provides a rather lit space for microalgae to grow. Finally, the Lab is a space for experiments, where periodical live-science shows take place. The overall structure was designed to allow maximum solar penetrations. The project was possible thanks to the cooperation with marine biologists and microalgae experts.[1]

BIOtechHUT is a complex project, probably not easily adaptable and scalable. It lies at the border between successful experimentations and concepts that are difficult to implement in the present world. Nevertheless, it had a high media resonance and allowed many visitors to dream about the cities of the future. Technically, many solutions should also be improved to ensure high yields.

1 More information about then project at: http://www.ecologicstudio.com/v2/project.php?idcat=3&idsubcat=71&idproj=162

Figure 7.59. The 'Garden Hut' and its harvest area. All the pictures in this page are adapted from *ecoLogicStudio* website, 2017, retrieved from http://www.ecologicstudio.com/v2/project.php?idcat=3&idsubcat=71&idproj=162 Copyright 2017 by NAARO.

Figure 7.60. The installation called 'H.O.R.T.U.S.' (Hydro Organisms Responsive to Urban Stimuli). Visitors are encouraged to blow into pipes, to providing carbon dioxide useful for the microalgae to grow.

Figure 7.61 (Below/Left). Detail of the 'Garden Hut'. Tubular PBRs are exposed to light and filled with water and nutrients.

Figure 7.62 (Below/Right). A live science show takes place in 'The Lab'.

The Carbon Sink

Designer(s):	*Fermentalg & SUEZ*
Place:	*Paris, France*
Period:	*2017, July*
Duration:	*2 years and 2 months*
Status:	*Ongoing*
Keywords:	*Urban furniture, Morris column, CO_2 capture*

The Carbon Sink is the work of a team of engineers from Fermentalg, a biotechnology company specializing in the production of oils, proteins and pigments from microalgae and SUEZ, an international group engaged in the sustainable management of resources. The groups decided to pool their expertise to leverage the use of microalgae in capturing CO_2. The urban photobioreactor they came up with after years of researches and continuous improvement can subtract carbon dioxide and transforming it into oxygen and biomass, to be used in cities and/or in neighboring industrial sites. The partners are also exploring ways for assessing the impact of the Carbon Sink, while also figuring out how to potentially subtract other pollutants from the air.

A first device was placed in July 2017 in the 14th district of Paris – Place Victor et Héléne Basch, a touristic area. The PBR was installed inside a typical Parisian urban furniture called 'Colonne Morris' (Morris' column) for a few weeks (Lecompte, 2017). Later in March 2019, a second CO_2 capture plant was installed in Créteil, France.

"These carbon sinks could be set up in highly polluted urban areas, where a single sink would have the same purification capacity as 100 trees, i.e., the removal of one ton of CO_2 from the atmosphere every year" (Fermentalg, 2017). Undoubtedly this is a promising technology that can be beneficial for the environment. A single column will not be enough to reduce emissions, but a network of columns could be a viable solution. The company will hopefully implement a solid business model that can also provide a few more jobs in the city. Also, the visibility in the city center of Paris was important to arouse the interest of citizens, investors, and local government.

Figure 7.63. The Carbon Sink installed in the 14th district of Paris. Adapted from *RFI* website, 2017, retrieved from http://scd.en.rfi.fr/sites/english.filesrfi/imagecache/rfi_large_600_338/sites/images.rfi.fr/files/aef_image/algae_column2.png Copyright 2017 by Fermentalg.

Figure 7.64. The Carbon Sink installed in Créteil (Paris) on March 19, 2019. Adapted from "Créteil: Suez inaugure son puits de carbone révolutionnaire", by S. Bartolomé, 2019, March 20, *Le Parisien*. Retrieved from http://www.leparisien.fr/val-de-marne-94/creteil-suez-inaugure-son-puits-de-carbone-revolutionnaire-20-03-2019-8036457.php Copyright 2019 by Simon Bartolomé.

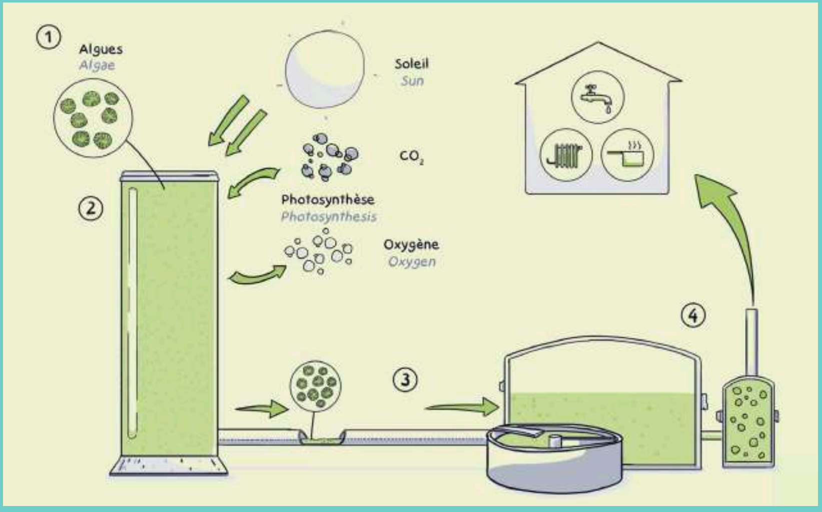
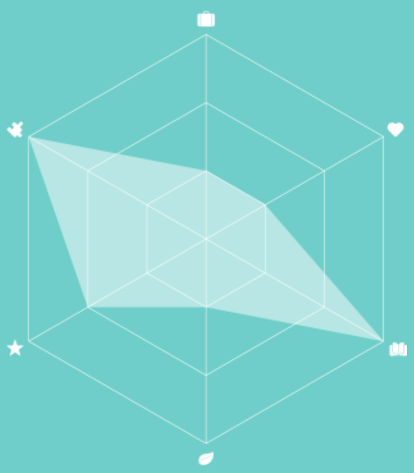


Figure 7.65. Illustration of the process, from the photosynthesis to the production of energy from the biomass. Reprinted from "Puits de carbone," by SUEZ, 2017, *Open_resource Magazine*, *1*(4), p. 104. Copyright 2017 by Adrien Galerneau.

Algae Dome

Designer(s): *SPACE10*
Place: *Copenhagen, Denmark*
Period: *2017, September*
Duration: *3 days*
Status: *Concluded*
Keywords: *Food producing pavilion, Urban gathering, Experimental recipes*



The Algae Dome is a project by SPACE10, a Copenhagen-based external innovation hub for IKEA. The studio has a multidisciplinary approach to projects. The team includes architects, designers, engineers, and even an in-house chef.[1] Characterized by a four-meter high hemispherical-shaped structure that allows the housing of a flexible tube in which *Spirulina* grows, the Algae Dome was presented in Copenhagen during the 2017 CHART Art Fair[2] (31 August to 2 September 2017). The installation was aimed at stimulating reflection on the potential of microalgae for preventing malnutrition and mitigating climate change, in the attempt to create a productive space available to citizens for chatting and gathering. With the cultivated biomass, visionary recipes were created, including *Spirulina* chips and the Dogless Hotdog. After the event, the installation was dismantled and not reused for other occasions (E. Dagný Ásgeirsdóttir, personal communication, May 21, 2019).

Despite the rather short duration of the installation, the project has many exemplary features. The educational component is strong because it directly involves citizens, allowing them to see, touch, and taste Spirulina-based products. Many parties have collaborated: these include private companies and single professionals in different fields. The project is not only a mere installation, because it creates an all-round, immersive experience for visitors. Also, the packaging of the food was branded with appealing graphics. If provided with a grounded social business model, this project can be scaled up and represent an even more impactful solution for urban settlements.

1 For more information about SPACE10 and its innovative research projects, visit https://space10.io

2 https://chartartfair.com/chart-social-programme-chart-art-fair-2017-details-announced/

Figure 7.66. The Algae Dome in the evening. Adapted from *SPACE10* website, 2017, retrieved from https://space10.io/project/algae-dome/ Copyright 2017 by Niklas Adrian Vindelev.

Figure 7.67. People gathering and chatting under the Dome. Adapted from *ArchDaily* website, 2017, retrieved from https://www.archdaily.com/879269/algae-dome-by-space10-could-combat-chronic-malnutrition/59b6fbf7b22e38e2030001fb-algae-dome-by-space10-could-combat-chronic-malnutrition-photo/ Copyright 2017 by Niklas Adrian Vindelev.

Figure 7.68. A sample of *Spirulina* chips by SPACE10's chef-in-residence Simon Perez. Reprinted from *SPACE10* website, 2017, retrieved from https://space10.io/project/algae-dome/ Copyright 2017 by Niklas Adrian Vindelev.

Living Solar Modules

Designer(s): *Solaga*
Place: *Berlin, Germany*
Period: *2017, October*
Duration: *1 year and 11 months*
Status: *Ongoing*
Keywords: *Roof-mounted system, Scalable solution, Biogas production*

Solaga is both the name of the startup and the product line designed by Johann Bauerfeind and Benjamin Herzog, two young German engineers graduated from Humboldt University, Berlin.[1] Solaga offers a variety of products addressed both to private clients and enterprises. The co-founders started to work on this solution in November 2015, and the first functioning prototype was presented publicly in October 2017. Currently, the startup is active in promoting the products in fairs (J. Bauerfeind, personal communication, May 22, 2019).

The product consists of a small-scale roof-mounted system to produce microalgae for biogas production. Organic acids produced by the cyanobacteria are fed into a biogas column, where microbes are fermenting, producing methane. The system is efficient and can be theoretically installed anywhere. Microalgae just need water, sunlight, and carbon dioxide to thrive. According to the calculations of the engineers 50 m^2 of panels over a rooftop are supposed to be able to provide enough energy for an entire family of four people. Also, the biogas can be safely stored on-site for up to one year (Mitha, 2019).

Solaga's project is pragmatical, technical, and easily scalable. Their business model is profit-oriented and does not embed particular social or educational values yet. Nevertheless, it seems to be working well and, given the high efficiency, also has a rather positive environmental impact. The founders are envisioning an urban system in which Solaga's panel may play a central role in decentralized energy production. For that reason, they are working to present a more efficient panel with lower maintenance costs.

1 More information at Solaga website: https://www.solaga.de

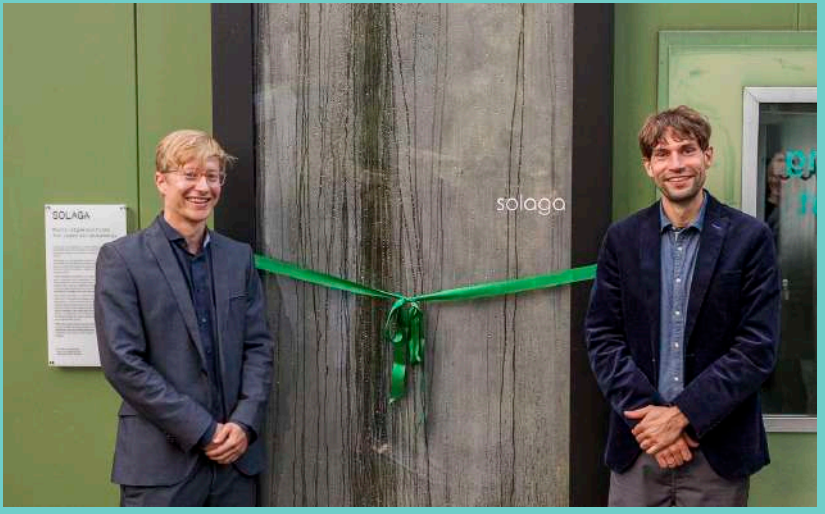


Figure 7.69. Johann Bauerfeind (left) and Benjamin Herzog (right), co-founders of Solaga, in front of the first prototype of the Solar Module. Adapted from *Wunderding* website, 2017, retrieved from http://www.wunderding.co/micro-algae-for-energy-and-clean-air/ Copyright 2017 by Solaga.

Figure 7.70. Phothosynthesis in process inside the glass panels.

Figure 7.71. A flat panel PBR for the production of solar biogas is tested in Solaga facilities.

WaterLilly 3.17

Designer(s): *Cesare Griffa*
Place: *Turin, Italy*
Period: *2018, February*
Duration: *5 months*
Status: *Concluded*
Keywords: *Community PBR, Indoor/Outdoor, Economic scenario*

WaterLilly 3.17 is the project of Cesare Griffa, together with a small team of designers and makers from Turin, Italy.[1] It is one of the latest developments of the 'WaterLilly' series and consists of a full-scale prototype of a photobioreactor, to be used in commercial indoor or outdoor spaces. The structure is quite simple. Vertical glass pipes are placed in an artificially-lit wooden box. The pipes can contain up to 100 l of *Spirulina* culture. A service module is placed at the bottom of the device and can accommodate a bigger tank, a photovoltaic system, a CO_2 pump, and electric controls. The fabrication of the device started in October 2017; in January 2018, the hydraulic tests took place. The inoculum was then provided,[2] and the PBR activated in February. It has been tested and remained fully operative until June 2018. Currently, it is not used, since some of the glass pipes are broken and need to be replaced (C. Griffa, personal communication, April 18, 2019).

The device is intended for a communitarian use. Griffa built WaterLilly 3.17 to engage the community, and an economic scenario was also hypothesized, including a corollary of activities to ensure the sustainability of the project (Griffa and Vissio, 2018). The study noted that the system would be economically viable if the labor is considered as part of the family/community activities, or if it is shared with other activities (e.g., building management). Griffa's project should be taken as a reference. It is educational for communities, and given the business model suggested, people can become 'algaepreneurs' and thus guarantee an extra (or a primary) source of income.

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1 The team includes C. Griffa, G. Cannucciari, D. Olivero, P. Perlino, M. Salomone, and A. Vissio.

2 Inoculum from Fotosintetica & Microbiologica, a Florence-based company that strictly cooperates with the Department of Chemistry and the Department of Environmental Sciences of the University of Florence, Italy.

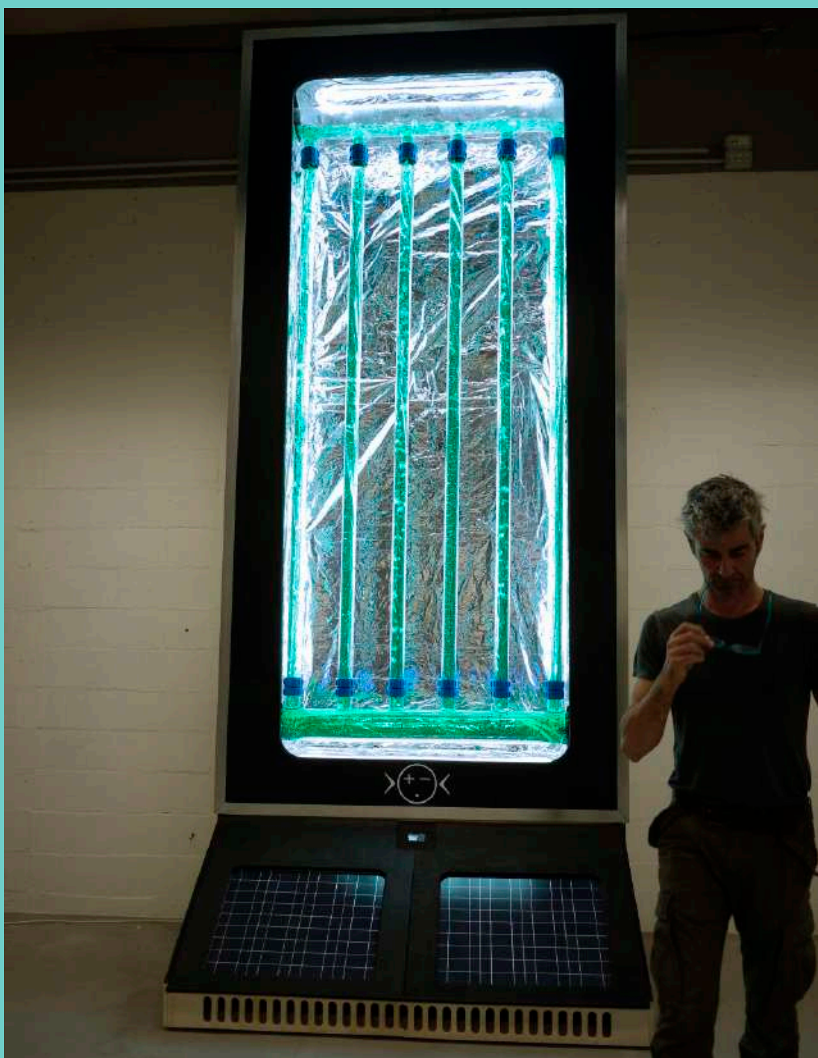

Figure 7.72 (Above/Left). Detail of the service module, that can be equipped with a photovoltaic system. All the pictures in this page are adapted from *Cesare Griffa* website, 2019, retrieved from https://cesaregriffa.com/waterlilly/waterlilly-3-17/ Copyright 2017 by Cesare Griffa.

Figure 7.73 (Above/Right). Detail of the horizontal and vertical glass pipes and of the manifolds. Small plastic balls highlight the flows generated by the bubbling system.

Figure 7.74 (Left). WaterLilly 3.17 is now showcased in Cesare Griffa's architecture and design studio in Turin, Italy.

BioUrban 2.0

Designer(s): *BiomiTech*
Place: *Puebla, Mexico*
Period: *2018, June*
Duration: *15 months*
Status: *Ongoing*
Keywords: *Air purification, Indoor/Outdoor, Artificial tree*

BioUrban 2.0 is an all-Mexican solution to fight air pollution in cities. The patented device can absorb carbon dioxide and other pollutant compounds such as nitrogen oxides, PM10, and PM2.5. The tree-like structure is more than 4 meters high. It is supposed to be placed in outdoor urban spaces, but also in malls, hotels, residential complexes, corporate buildings, or shared workspaces. It has outstanding properties: it can clean the air equivalent to the daily breath of 2,890 people. Also, it releases an amount of oxygen equivalent to that of 368 young trees annually.[1]

The first devices were installed by BiomiTech in Puebla – Mexico, Colombia, and Panama. The others will soon be placed in Turkey, Mexico City, and Monterrey. *"The major doubts about the BioUrban are linked to the high cost of the device, around 50 thousand dollars"* (Vincenti, 2019).

BioUrban has a positive impact on air quality, which is also directly related to the quality of life of citizens. Its structure, similar to a tree, is highly evocative. The installation of multiple devices would require the creation of an expert maintenance service. This case study is proven to be commercially viable and deserves to be taken as a reference.

1 See BiomiTech. (n.d.). BioUrban 2.0 [Brochure]. Retrieved 2019, January 7, from http://biomitech.com/wp-content/uploads/2018/06/BioUrban-2-En.pdf

Figure 7.75 (Above). BioUrban 2.0 installed in front of 'Complejo Cultural Universitario BUAP' in Puebla, Mexico. Adapted from *Más México* website, 2019, retrieved from https://mas-mexico.com.mx/biomitech-tecnologia-mexicana-que-mejora-la-calidad-del-aire/ Copyright 2019 by BiomiTech.

Figure 7.76. BioUrban 2.0 in an indoor environment. Retrieved 2019, January 7, from http://biomitech.com/wp-content/uploads/2018/06/BioUrban-2-En.pdf Copyright 2018 by BiomiTech.

Photo.Synth.Etica

Designer(s): *ecoLogicStudio*
Place: *Dublin, Ireland*
Period: *2018, November*
Duration: *3 days*
Status: *Concluded*
Keywords: *Bio-digital curtain, Vertical Plastic PBR, Real-time CO_2 capture*

Photo.Synth.Etica is one of the most recent projects by ecoLogicStudio. This large-scale modular bio-digital curtain was installed on the main façade of the Printworks building at Dublin Castle, during the week of the Climate Innovation Summit 2018. It lasted 3 days, from 6 to 8 November. Microalgae are growing between two plastic layers and are fed with nutrients and carbon dioxide from the air. Oxygen is released from the top of the curtains, and the biomass harvested can be used for the production of bioplastic raw material (the same plastic material of which the curtain is made). The curtain is estimated to capture 1 kg CO_2 per day. This equals to around 20 tall trees. *"Thanks to their serpentine design, the modules optimize the carbon sequestration process and the full curtain pattern is reminiscent of a large trading data chart that embodies Climate-KIC's commitment to promoting new models to solve the global climate crisis"* (urdesignmag, 2018).

The project is an innovative and low-cost solution compared to other non-temporary architectural installations. It was of great impact during the event and potentially adaptable to many other contexts. The amount of algal biomass produced could be optimized. This installation is not easy to evaluate since it lies at the border between the domains of art and design.

Figure 7.77. The cladding system installed during during the week of Climate Innovation Summit 2018. All the pictures in this page are adapted from *ecoLogicStudio* website, 2019, retrieved from http://www.ecologicstudio.com/v2/project.php?idcat=3&idsubcat=71&idproj=174 Copyright 2019 by ecoLogicStudio.

Figure 7.78. The curtain is composed of several bioplastic modules, each of them digitally designed.

Figure 6.79. Marco Poletto and Claudia Pasquero, co-founders of ecoLogicStudio.

7.2.20 Limits and possibilities of the projects

The analysis of the case studies also examined their spatial and temporal locations (Fig. 7.82). Interestingly, the average duration of most projects is a few months (in certain cases only some days), therefore relatively limited. Those that stand out for a longer operational time – even years – are mainly architectural integrations or activities with a solid business model, where the multidisciplinary contribution of several experts has been crucial. A longer duration is a factor that allows a series of fruitful collaborations to be planned and put into practice. The radar chart (Fig. 7.81), resulting from the overlapping of the diagrams obtained from the analysis of each case study (Fig. 7.80), shows the global contribution of the projects to each challenge. The darker areas indicate greater contribution. Such new experimentations, unfettered by the established canons, need to be explained and narrated as much as the properties of microalgae: the educational value of the projects is therefore generally high. Environmental sustainability is another very important element. However, technical performances often appear unsuitable, resulting in aesthetically attractive but inefficient projects. In some cases, moreover, the biomass produced is not even utilized as it is not certified for food use.

Regardless of duration, there is a tendency to include projects within far more extended contexts, such as city events or multi-purpose areas, as if to emphasize the need to connect them to the surroundings. Apart from some exemplary cases, most do not ponder the possibility of using microalgae as a vector of economic growth and social integration. These are two undoubtedly critical areas of practice and research that deserve to be explored. Finally, the communication and promotion of the values of these projects are particularly compelling but poorly investigated. The case studies analyzed have significant limitations but, at the same time, present new possibilities. To design for the benefit of the community, dealing with the problems of cities with resilient thinking, projects like these should operate with a larger range of action, and in the long term, with the intent of favoring their scalability. This approach would promote new visions not only linked to the creation of a product but also the economic and social infrastructures in their entirety (Peruccio, Vrenna, Menzardi, & Savina, 2018).

Figure 7.80 (Facing page). Visual depiction of overall contribution of the case studies to the various challenges.

- Job creation
- Social inclusion
- Education/divulgation support
- Environmental impact
- Value creation
- Generation of synergies on the territory

7.2.21 Considerations

The architectural dimension and that of the product, as well as the self-production and the urban farming, operate on different scales and therefore need distinct approaches. Although the implementation of projects which envisage microalgal production is not immediate due to technical, operational, and management complexities, various projects are in the start-up phase also in Italy, such as the one in Mirafiori (the former Fiat plant) by TNE – Torino Nuova Economia (Luise, 2019). Worthy examples, such as the Algae Dome and

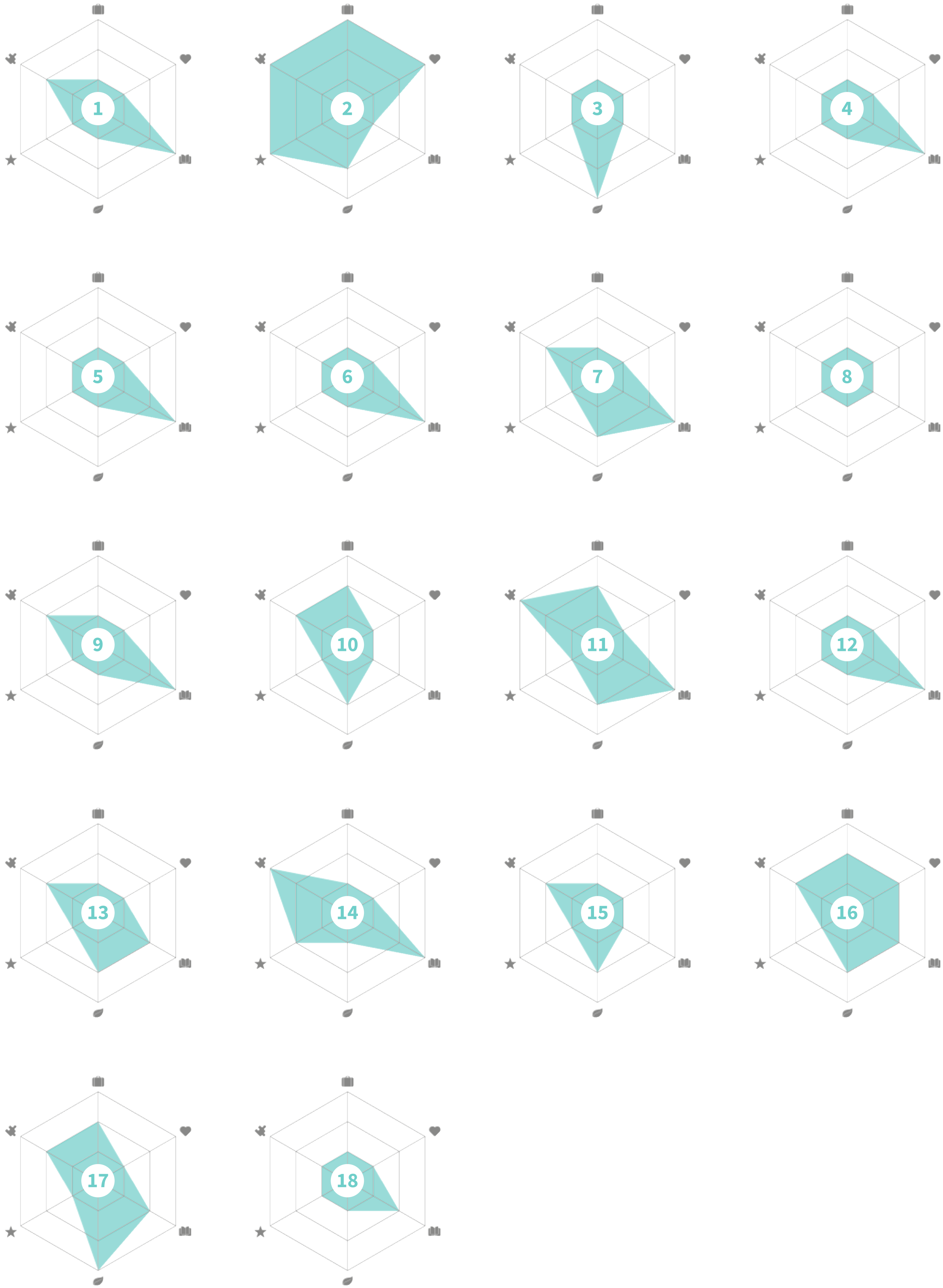
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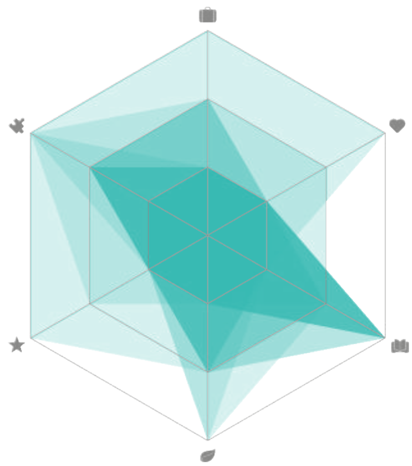
Figure 7.81. Overview of the main contributions of all the case studies taken into account.

- Job creation
- Social inclusion
- Education/divulgation support
- Environmental impact
- Value creation
- Generation of synergies on the territory



Skyline Spirulina, should be taken as reference. These two projects, considerably different from each other, are indeed effective because they involve several stakeholders (private companies, institutions, research centers, etc.). As far as business models are concerned, those of the French Spiruliniers and the rural villages in developing countries could also be adapted to the urban environment. In the face of low investments and rudimentary technologies, these models enable the generation of employment and the production of healthy and sustainable food in abundance.

Urban microalgae farms on flat roofs, in brownfield sites, in common spaces, but also indoor, would make the air cleaner and create new food supply areas without competing with those dedicated to traditional agriculture. The biomass could also be used as fertilizer for vegetable gardens and parks. Like any other urban farming practice, the relative products, services, and systems would allow the population to be involved *"enhancing the common social and cultural identity for city residents"* (Ackerman, Conard, Culligan, Plunz, Sutto, & Whittinghill, 2014, p. 190). Shortly, microalgae production could experience a rapid rise. If *"some envision huge centralized algae farms producing food and energy on a vast scale [...] others see networks of smaller farms"* (Henrikson, 2013, p. 11). Realizations can be, for example, devices for community use, that can also serve as places for social aggregation. These could be located in neighborhoods, schools, or shopping centers and show the real-time quantities of biomass produced and of CO_2 removed. The distribution could be made by volunteers, who would get credits to be spent within a network of business partners.

Similar solutions could be some of the viable means to imagine a sustainable future for cities and to plan resilient prospects characterized by new equilibria. The major obstacle for the moment seems to be cultural, as microalgae do not have a familiar taste and appearance. However, local cultivation in the city could change this perception and therefore provide extra motivation for the adoption, also imagining new uses for the fresh biomass.

The case studies analysis was particularly important in this research, as it

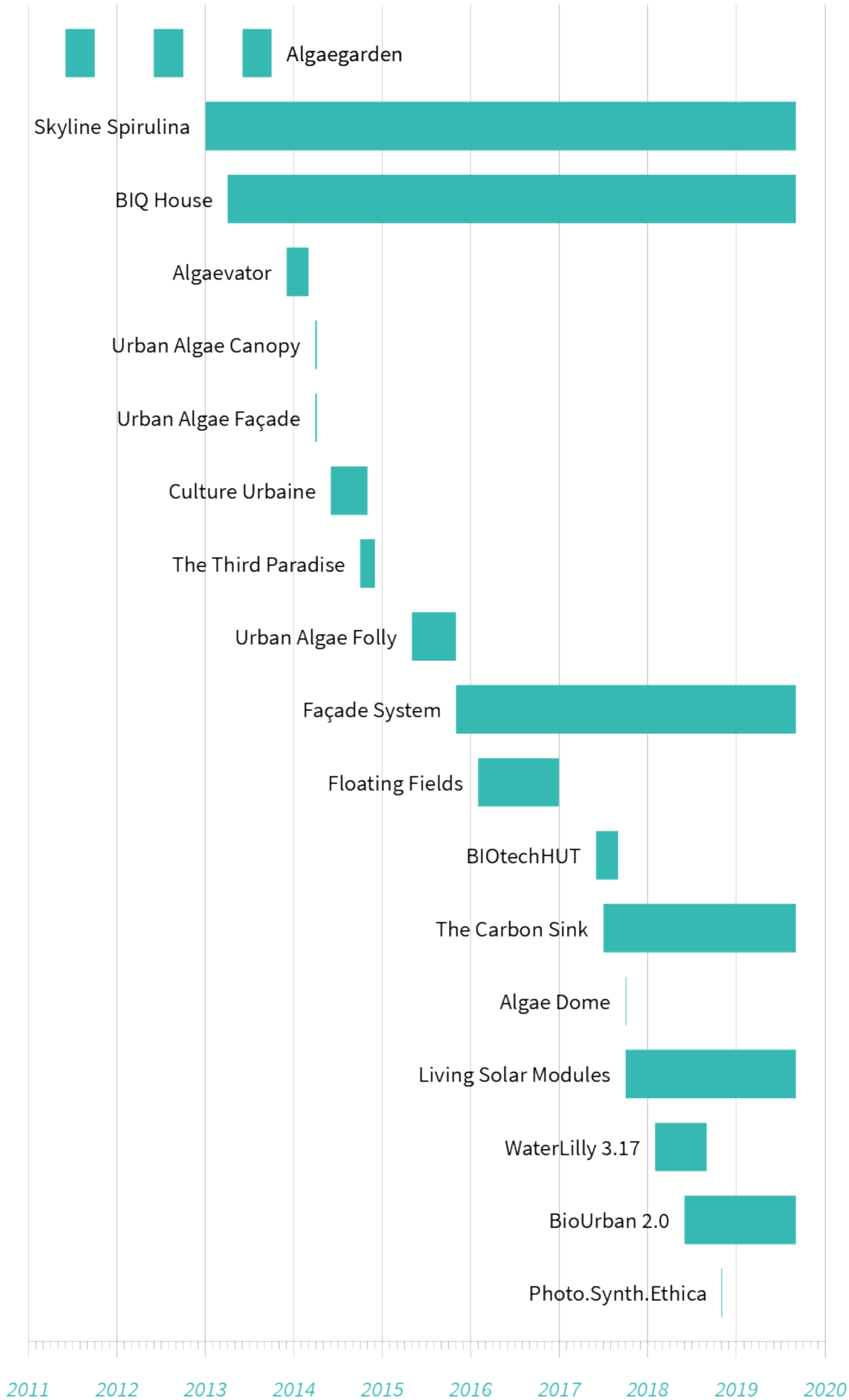


Figure 7.82. Period of activity of the projects analyzed. The average duration is a few months (in some cases even days). Those that stand out for a longer operational time – even years – are mainly architectural integrations or activities with a solid business model Data as at 1 September 2019.

has allowed identifying the prevailing gaps, especially in design practice. Also, it helped in defining the fields of action in which to operate during the consequent design phase. It additionally highlighted the fact that the designers who introduced microalgae into their projects have never had an overall, comprehensive vision of the project, but have focused deeply on one or more aspects, without considering others.

7.3 Concepts for future cities

The design experimentations and the urban installations that have been analyzed are real-world projects that have already been completed and/or are still active. However, due to the difficulties in the implementation and the innovativeness of this type of project, many others are still at the preliminary stages of their development or conceptual phase. This chapter reviews fifteen concept projects requiring the use of microalgae in city contexts. These projects are the result of academic research, degree theses, project proposals that have never been implemented, and the work of mono/multidisciplinary teams that have participated in national or internationally-relevant competitions. Some of these conceptual projects have already won awards, published in design magazines, or are being developed by startup companies. A case study analysis would not be completed without an overview of these concepts. Concepts allow readers to draw more relevant considerations and have a privileged vision about the present-day practices and what may happen in the future. Some of these concepts are incredibly radical and futuristic, therefore difficult to put into practice at the moment. At the technological level, they present interesting innovations that need to be refined and engineered.

The concepts do not only represent what the designers imagine, but they incorporate the values that citizens would like to have in future resilient cities. By surfing the internet, it is probably possible to come across many other similar concepts: new concepts are appearing monthly. The selection made here (Table 7.4) is, therefore, not exhaustive but well represents what the future design directions may be.

Table 7.4. The most representative concepts involving microalgae in urban contexts, from 2011 until today.

	Project name	Designer(s)	Place	Period
1.	Polder Inversion	Freddy Curiél	Rotterdam, Netherlands	2009, April
2.	Filene's Eco Pods	Höweler + Yoon	Boston, Massachusetts	2009, October
3.	Bioluminescent Devices	Eduardo Mayoral González	New York, New York	2010, July
4.	Biolamp	Peter Horvath	Budapest, Hungary	2010, October
5.	Process Zero: Retrofit Solution	HOK & Vanderweil	Los Angeles, California	2011, May
6.	Regional Algae Farm	ecoLogicStudio	Simrishamn, Sweden	2011, July
7.	Algae Green Loop	Influx Studio	Chicago, Illinois	2011, December
8.	Algae Powered Mushroom Farm	10 Design	Kinshasa, Congo	2011, December
9.	RiverBox	SabrTech	Herring Cove, Canada	2012, May
10.	AL.F.I.E.	Giordano & Marino	Turin, Italy	2014, October
11.	Chlorella Oxygen Pavilion	Adam Miklosi	Budapest, Hungary	2016, November
12.	Algae Farm	Raquel Pereira Silva	Amsterdam, Netherlands	2017, March
13.	French Dream Towers	XTU Architects	Hangzhou, China	2018, May
14.	LIQUID3	Ivan Spasojevic	Smederevo, Serbia	2018, August
15.	Ctrl+N	Capra et al.	Turin, Italy	2019, June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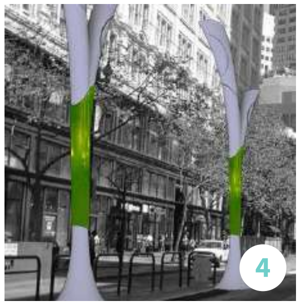
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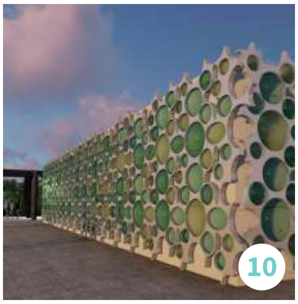
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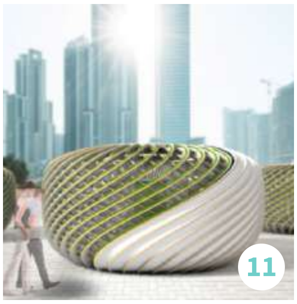
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Polder Inversion

1

Designer(s): *Federico Curiél*
Place: *Rotterdam, Netherlands*
Period: *2009, April*
Status: *Concept*
Keywords: *Polder, Waterscape, Biofuel production*

The project is an architectural attempt to transform a polder into a productive reality, while exploiting its artificiality, preserving its natural environment, and satisfying some of the needs of the expanding city of Rotterdam, Netherlands. Microalgae are mass-produced into artificial water basins connected through an underground piping system to facilitate the harvesting (Curiél, 2009). The biomass yielded can then be used for the extraction of lipids for biofuels. Due to the location of the site, importance has been given to the connections with the existing roads, and the nearby train station: a new axis can become an important link for the whole metropolitan network. The masterplan includes routes for bikes and pedestrians, a diffused hotel, and information points. The result is a productive waterscape that reminds of the typical tulip fields. Curiél is now based in Shenzhen, and among several other projects, he worked on a few concepts for integrating microalgae into the built environment, but none of them has been implemented yet (F. Curiél, personal communication, August 1, 2018).

Figure 7.83. The project involves productive areas but also leisure spaces and routes for bikes and pedestrians. Reprinted courtesy of Federico Curiél, 2009. Copyright 2009 by Federico Curiél.

Filene's Eco Pods

2

Designer(s): *Höweler + Yoon and Squared Design Lab*
Place: *Boston, Massachusetts*
Period: *2009, October*
Status: *Concept*
Keywords: *Prefabricated modules, Brownfields, Experimental research*

As a result of a collaboration between Höweler + Yoon and Squared Design Lab, the project consists of a set of modular pods that serve as biofuel production facilities and incubators for scientific research. They can be arranged by a robotic arm, to ensure maximum productivity. The obtained structures are temporary and can be easily moved, even on rails. The Eco Pods are placed at the stalled Filene's construction site in Boston downtown. *"The proposed location [...] and their highly visible nature are designed to raise awareness of important energy-production processes on which we depend. The architects see this as anticipatory architecture that is capable of generating a new micro-urbanism that is adaptable, inexpensive, and environmentally beneficial"* (Myers, 2018, p. 50). The project is also supposed to act as an information center and catalyst for sustainable awareness.[1]

1 More information at: https://www.dezeen.com/2009/10/02/eco-pods-by-howeler-yoon-architectureand-squared-design-lab/

Figure 7.84. The Eco Pods in operation at Filene's construction site, Boston downtown. Adapted from *Squared Design Lab* website, 2009, retrieved from http://www.squareddesignlab.com/projects/eco-pod
Copyright 2009 by Squared Design Lab.

Bioluminescent Devices

3

Designer(s): *Eduardo Mayoral González*
Place: *New York, New York*
Period: *2010, July*
Status: *Concept*
Keywords: *Bioluminescence, Algae billboards, Sustainable cities*

Bioluminescent devices can be used to organically illuminate parks, streets, highways posts, and city signs without the need to use electricity, nor requiring heavy manufacture to produce electronic components, hard to dismantle, and with several environmental downsides. Eduardo Mayoral González from the University of Seville – Spain, collaborated with One Lab in Brooklin, New York, to test the best microorganisms and containers for these glowing devices to work. It "*utilizes a species of bacterium, Vibrio fischeri, than naturally glows pale green in the dark, and a species of alga, Pyrocystis fusiformis, that emits blue light when excited by movement. Notably, both microorganisms produce luminescence in a circadian rhythm, meaning that they are more active and thus produce more light at night*" (Myers, 2018, p. 127).

Several design applications may be envisioned to reintegrate nature into the built environment, toward more sustainable cities and greener architectural performances.

Figure 7.85. Lighting devices and billboards that are powered by bacteria can be used in cities (this artistic rendering shows Times Square in New York). Adapted from *Biodesign: Nature+Science+Creativity* (p. 126), by W. Myers, 2018, New York, NY: MoMA. Copyright 2010 by Eduardo Mayoral González.

Biolamp

4

Designer(s): *Peter Horvath*
Place: *Budapest, Hungary*
Period: *2010, October*
Status: *Concept*
Keywords: *Street lamp, Air cleaning, Biofuel production*

Biolamp is a concept project by the Hungarian designer Peter Horvath. It was selected as an innovative product by the City of Milan, and a scale non-working model was exhibited at the Well-Tech Award in 2013, during Milan Design Week.[1] The upper part of the street lamp includes a fan that sucks CO_2 from the air and redirects it into an internal spiral piping system, where microalgae grow. A second outlet releases the oxygen generated from the photosynthetic activity of the algae, thus functioning as an air purifier. The amount of oxygen transformed is directly proportional to the effective use of the lamp. As regards the algal biomass, it is collected through underground tubes and used for the extraction of biofuels. The project attracted the interest of some internet users coming from China that nowadays is facing serious air pollution problems in cities (Ella, 2017).

1 More information at: https://www.coroflot.com/peet/biolamp

Figure 7.86. A rendering of Horvath's Biolamp in a urban context. Adapted from *Designboom* website, 2010, retrieved from https://www.designboom.com/project/biolamp/ Copyright 2010 by Peter Horvath.

Process Zero: Retrofit Solution

5

Designer(s): *HOK & Vanderweil*
Place: *Los Angeles, California*
Period: *2011, May*
Status: *Concept*
Keywords: *Retrofit, Modular bioreactors, Graywater recycling*

The concept by HOK and Vanderweil won Metropolis Mag's Next Generation Design Competition in 2011, for the redesign of a Federal government office built in Los Angeles in the '60s.[1] The proposal incorporates a glass piping system on the sunny south facade. *"This network of bioreactors performs various functions: here the algae reproduce; extracting nutrients from the building's graywater, helped by energy from the sun, they photosynthetize, thereby producing lipids for on-site conversion into fuel and oxygen to enhance the office atmosphere"* (Myers, 2018, p. 52). The fatty lipids extracted from the algae can then be burned for heat and electricity generation. The current overall energy demand would, therefore, be dramatically reduced. The functioning of the system is similar to the one of the BIQ House in Hamburg, that was constructed a couple of years later (see paragraph 7.2.4).

1 More information at: https://inhabitat.com/algae-powered-federal-building-retrofit-wins-next-generation-design-competition/

Figure 7.87. The microalgae can synthesize wastewater and absorb carbon dioxide generated by nearby traffic to produce oils, which can be extracted for fuel. Adapted from *Biodesign: Nature+Science+Creativity* (p. 55), by W. Myers, 2018, New York, NY: MoMA. Copyright 2010 by HOK & Vanderweil.

Regional Algae Farm

6

Designer(s): *ecoLogic Studio*
Place: *Simrishamn, Sweden*
Period: *2011, July*
Status: *Concept*
Keywords: *Urban design, Regional development, Integrative strategy*

In July 2011, the first plan for the Simrishamn Regional Algae Farm project was proposed by ecoLogic Studio. Simrishamn is a municipality in Sweden characterized by a decaying fishing industry and an aging population that needed novel solutions for the revitalization of the local economy. A first exhibition was hosted in the regional Marine Center: it was conceived as an interactive public space for cultivation, education, and discussion on algae-related topics. The plan included both a top-down and a bottom-up approach for the design and installation of microalgae production facilities, floating algae farms, touristic attractions, etc.[1] *"ecoLogic's integrative, interactive strategy creates vitalizing educational resources connected in a considered social and environment network. It avoids the hermeticism of a [...] research centre, divorced from the rest of life"* (Bullivant, 2011).

1 More information at: http://www.ecologicstudio.com/v2/project.php?idcat=3&idsubcat=59&idproj=110

Figure 7.88. New symbiotic algae and seafood/fish farms generated in Crane Greenhouses. Adapted from *Domus* website, 2011, retrieved from https://www.domusweb.it/en/architecture/2011/09/16/algae-farm.html Copyright 2011 by ecoLogic Studio.

Algae Green Loop

7

Designer(s): *Influx Studio*
Place: *Chicago, Illinois*
Period: *2011, December*
Status: *Concept*
Keywords: *Retrofit, Iconic buildings, Closed energy loops*

This futuristic concept was realized by Influx Studio, to rethink the greenhouse gas emissions produced by an area of Chicago. The project is an algae retrofit of the Marina City's Towers, some of the most innovative buildings downtown. They were designed in 1964 by architect Bertrand Goldberg and were ranked among the tallest mixed-use buildings in the world. According to the designers, such iconic towers could well showcase the potential of microalgae to produce food, clean the air, create energy on-site, and process wastewaters. The design includes 18 spiral-shaped PBRs at the top of the buildings. Wind turbines produce electricity while capturing CO_2. A modular piping system is adapted to fit the parking structure. The project was a novel architectural approach for the creation of closed energy loops and for involving the people in producing their food.[1]

1 More information at: https://www.archdaily.com/191229/algae-green-loop-influx-studio

Figure 7.89. Fisheye render view of the retrofitted Marina City's Towers. Adapted from *Archdaily* website, 2011, retrieved from https://www.archdaily.com/191229/algae-green-loop-influx-studio/01-fisheye

Algae Powered Mushroom Farm

8

Designer(s): *10 Design*
Place: *Kinshasa, Congo*
Period: *2011, December*
Status: *Concept*
Keywords: *Symbiotic production, Urban homeless, Rural poors*

In 2011 the 'International Algae Competition', organized by R. Henrikson and M. Edwards, took place: it posed the challenge to design visionary algae food and energy systems. More than 140 applicants with different backgrounds submitted futuristic ideas.[1] The Algae Powered Mushroom Farm, designed by 10 Design Group, is a movable structure for the production of microalgae and mushrooms, where algae are used as a food source and fertilizer for the latter. The structure can be easily shipped in containers and *"placed anywhere in the world to support micro-economic development in poverty stricken regions [...]. Two target groups are urban homeless and rural poor. Congo-Kinshasa in Africa was selected for the first farm"* (Henrikson, 2013, p. 78). The project was highly appreciated by the participants and won the Appreciation Prize.

1 More information about the competition at: http://www.spirulinasource.com/algae-network/algae-competition/

Figure 7.90. A render of the Algae Powered Mushroom Farm in a rural area of Congo-Kinshasa. Adapted from *Algae microfarms* (p. 78), by R. Henrikson, 2013, Richmond, VA: Ronore Enterprises. Copyright 2013 by 10 Design Group.

RiverBox

9

Designer(s): *SabrTech*
Place: *Herring Cove, Canada*
Period: *2012, May*
Status: *Research and development*
Keywords: *Modular platform, Shipping containers, Production*

RiverBox by SabrTech is a modular and rapidly deployable platform for the production of microalgae. Algae are harvested in a shipping container, complemented with lighting systems and glass piping tubes. Mather Carscallen, founder and CEO of the company, believes that in the next decade, investors in the fields of microalgae are expected to rise. For this reason, he is now perfecting the project, to be able to launch it on the market as soon as favorable. Since the promising market for microalgal biofuels crashed in the early 2000s (prices of fossil fuels were expected to rise dramatically, but they actually did not), the company's goal is to produce microalgae at lower costs, to use the biomass for animal feed and other low-value products, as high-value products, such as pharmaceuticals, become saturated.[1]

1 More information at: https://news.algaeworld.org/2017/04/sabrtech-to-launch-portable-algae-growing-system-soon/

Figure 7.91. RiverBox, an easy-to-transport and modular algae-growing system. Adapted from *SabrTech* website, 2017, retrieved from http://www.sabrtech.ca. Copyright 2017 by SabrTech.

AL.F.I.E.

10

Designer(s): *Roberto Giordano and Valentina Marino*
Place: *Turin, Italy*
Period: *2014, October*
Status: *Filed for patent*
Keywords: *Green facade, Architectural integration, Business model*

AL.F.I.E. (Algae Facade Integrated Envelope) is the project of a research group from Politecnico di Torino, composed by professors, researchers, and Master's students. It was submitted to the international competition 'World Sustainable Building 2014 – Barcelona' (Maccario & Micheletto, 2015). It is an "*advanced outer skin layer fully integrated with the water system of the building. It contributes to recycling greywater by photobio-purification with the help of microalgae cultivated on the facade*" (Marino & Giordano, 2015, p. 86). The research group filed for a patent that has been recently granted, but they are still looking for partnerships for commercialization (R. Giordano, personal communication, January 15, 2019). A group of Ph.D. and M.B.A. students within the program 'Innovation for Change 2016'[1], proposed a business model for eventually starting a company (D. Pisasale, personal communication, July 20, 2018).

1 Link to the program: http://dottorato.polito.it/it/innovation_for_change

Figure 7.92. A potential application of AL.F.I.E. modular facade. Reprinted courtesy of Valentina Marino, 2014. Copyright 2014 by Valentina Marino.

Chlorella Oxygen Pavilion

11

Designer(s): *Adam Miklosi*
Place: *Budapest, Hungary*
Period: *2016, November*
Status: *Concept*
Keywords: *Oxygen bar, Relaxing hub, Air purifier*

Chlorella Oxygen Pavilion is the Master's thesis project of A. Miklosi and Grand Prize Winner for the 2016 Biodesign competition.[1] It is a concept oxygen bar, where people can breathe fresh and clean air, based on microalgal production (*Chlorella*). An internal central algae fountain distributes the oxygen that circulates inside the space thanks also to the sinuous design. On the outer shell, tubular photobioreactors are mounted in a circulating direction, to maximize photosynthetic activity. The pavilion, which has a diameter of more than 6 m, features a futuristic sliding door system and can accommodate a few people. Inside, the chairs can be arranged to create social or more personal spaces. The project is conceived to be a sort of relaxation hub to be placed in frenetic urban environments, but not limited.[2]

1 This and other projects at: https://news.algaeworld.org/2016/10/biodesign-competition-winners-announced-algae-takes-center-stage/

2 More information at: http://adammiklosi.com/project/chlorella

Figure 7.93. Chlorella Oxygen Pavilion in an urban settlement. Adapted from *Inhabitat* website, 2016, retrieved from https://inhabitat.com/are-algae-powered-oxygen-bars-on-the-horizon/chlorella-pavilion-lead-2/ Copyright 2016 by Adam Miklosi.

Algae Farm

12

Designer(s): *Raquel Pereira Silva*
Place: *Amsterdam, Netherlands*
Period: *2017, March*
Status: *Concept*
Keywords: *Advertising, Bus stops, Lung disease prevention*

Algae Farm is a concept by R. P. Silva developed during her internship at Havas Lemz, an advertising agency in Amsterdam. The project supposedly drew inspiration from ‘Culture Urbaine’, an urban photobioreactor installed on a viaduct close to a highway in Switzerland (see paragraph 7.2.8), and is part of a broader campaign for Longfonds, a Dutch foundation for the prevention of lung diseases.[1] According to the designer, one of the best integration of urban PBRs could be in bus stops. While waiting for the bus, commuters can read information about the foundation and breathe clean air. Once ready, algae can be harvested and used for producing health pills. Silva got in touch with LGem, a local company manufacturing PBR systems: many other solutions, some of them out of the ordinary, were also hypothesized.[2]

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1 https://www.longfonds.nl

2 Silva’s portfolio website: http://www.raquelpereirasilva.com/portfolio__page/algae-farm/

Figure 7.94. A render view of the Algae Farm at a bus station in Amsterdam. Adapted from *Raquel Pereira Silva* website, 2017, retrieved from http://www.raquelpereirasilva.com/portfolio_page/algae-farm/ Copyright 2017 by Raquel Pereira Silva.

French Dream Towers

13

Designer(s): *XTU Architects*
Place: *Hangzhou, China*
Period: *2018, May*
Status: *Patent*
Keywords: *Patent-pending facade, Futuristic building, Aquaponics*

XTU Architects proposed a futuristic high-rise design for a multipurpose complex (exhibition, hotel, office, and residential) to be built in Hangzhou, China. The curved towers incorporate systems for rainwater collection, aquaponics, and a greenhouse. The facades are covered with flat-panel photobioreactors that can produce oxygen while absorbing carbon dioxide. The company has been working with microalgae for years, experimenting also with the design of other products including, curtain-like plastic bag PBRs, algae booths, etc.[1] Currently, their patent is pending, to use biofacades to allow better insulation and utilize the internal temperature of the building to regulate the one of the microalgal cultures (Wang, 2018).

1 More information about XTU Architect's experimentations at: https://www.xtuarchitects.com/lab#/algoscreen/

Figure 7.95. French Dream Towers complex. Adapted from *XTU Architects* website, 2018, retrieved from https://www.xtuarchitects.com/french-dream-towers-hangzhou-china-1/ Copyright 2018 by XTU Architects.

LIQUID3

14

Designer(s): *Ivan Spasojevic*
Place: *Smederevo, Serbia*
Period: *2018, August*
Status: *Concept*
Keywords: *Urban PBR, Compensation for trees, Air purifier*

LIQUID3 is a concept by Dr. Ivan Spasojevic and the biophysics team from the Institute for Multidisciplinary Research in Belgrade, Serbia. The device uses microalgae to capture carbon dioxide and release oxygen in the atmosphere. Its innovation lies in the urban installation, to compensate for the photosynthetic activity of trees in heavily polluted areas. A device with a base of 3 m^2 is claimed to produce as much oxygen as two trees.[1] The price for a single device ranges from € 3,000 to € 4,000, but the costs would be lower if produced on a larger scale. The first device is supposed to be installed in the city of Smederevo in the upcoming months. The biomass produced can be sold to be used as a fertilizer. Given the topical interest, Spasojevic's project attracted the interest of international media (Gordillo, 2018).

1 More information at: http://www.rs.undp.org/content/serbia/en/home/presscenter/articles/2018/vode__i-__panski-mediji-o-inovativnoj-ideji-iz-srbije-za-klimatski.html

Figure 7.96. A render view of LIQUID3 in the streets of Belgrade, Serbia. Adapted from *Platforma inovativnih rešenja* website, 2018, retrieved from http://inovacije.klimatskepromene.rs/wp-content/uploads/2018/08/Liquid3-1.jpg Copyright 2018 by Ivan Spasojevic.

Crtl+N

15

Designer(s): *Capra, M., Barone, E., de Matteo, M. Puppi, M., & Garg, R.*
Place: *Turin, Italy*
Period: *2019, June*
Status: *Concept*
Keywords: *Water purification, Nitrogen recovery, Water bodies*

The research began within a program jointly developed by Politecnico di Torino, Collège des Ingénieurs Italia, and CERN IdeaSquare.[1] Crtl+N is basically used as *"a water treatment module that grows microalgae for water purification and nitrogen recovery"* (Capra et al., 2019, p. 27). It can filter the exceeding levels of nitrogen in freshwater bodies, mainly coming from farming activities. The multidisciplinary team, composed of Ph.D. and M.B.A. students, worked on the validation of their idea and got in touch with an environmental NGO from Brescia, to test the prototype on the shores of the Italian Lake Idro (Fasani, 2019). In June 2019, the project was presented to potential investors at Fondazione Agnelli in Turin. The team is considering to continue with the project, conscious that the product is still at an early-stage development (F. Capra, personal communication, June 27, 2019).

1 More information at: http://dottorato.polito.it/it/innovation__for__change

Figure 7.97. A render view of Crtl + N. Reprinted courtesy of Maurizio Capra, 2019. Copyright 2019 by Maurizio Capra.

6.3.16 Considerations

The concepts illustrated are the most representative of a series of continuously evolving experiments, buildings, and projects worldwide. It is certainly hard to grasp such dynamic transformations, and for this reason, it is likely that new concepts are currently under ideation or proper development. Other ideas even more futuristic than the ones presented previously, can be found online or non-scientific publications. It is the case, for example, of 'Hydrogenase' (Fig. 7.98), a space-age algae farm envisioned by the Paris-based architect Vincent Callebaut.[1] The architect is a unique visionary: operating between the fields of engineering, biomimicry, architecture, and biology, he imagined a future world in which the shortage of fossil fuels and a new green revolution led to the necessity of moving part of the population into floating cargo airships, able to produce energy from microalgae, and to provide food to the inhabitants with vegetable gardens, useful also for water phyto-purification. Another visionary concept is the project called 'Solar Spore' by Alexandre Brassart, Sylve Truyman, and Pierre-Jacques Truyman (Fig. 7.99). Developed in 2017 for the Jacques Rougerie Foundation – an institution with the aim of acting toward a planetary awareness of the major issues of sea and space colonization[2] – Solar Spore is an orbital solar power plant that opens up like a flower and produces microalgae for electrical energy, oxygen, and hydrogen. Despite the impressive work and imaginative effort, concepts like these are captivating but very hard to put into practice, probably at least for several decades.

The selection of concepts presented is, indeed, made by keeping their potential feasibility into consideration. They are related to different fields: some are architectural integrations, some are installations, some others are based on a draft of business models. The concepts were also not classified, but just a few keywords were used to define their main features. As a matter of fact, a classification of these concepts would not have additional relevant information, nor would it have been useful to extract substantial considerations in this study. It can be noted that many projects are coming from the academia, as a result of appreciable Master's theses: these are the cases of 'Polder Inversion' by Federico Curiél (paragraph 7.3.1), and 'Chlorella Oxygen Pavilion' by Adam Miklosi (paragraph 7.3.11). 'Bioluminescent Devices' (paragraph 7.3.3) by Eduardo Mayoral González is also the fruit of multidisciplinary research and international joint efforts between universities. The academia demonstrates, one more time, of being a place in which ideas can bear and thrive ahead of the times. Many architects and designers are looking for pragmatical

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1 Vincent Callebaut is a Belgian-born, Paris-based lead 'archibiotect' and he is referenced as the best eco-prospective and visionary architect by the Time Magazine. More information about his projects at: http://vincent.callebaut.org

2 More info at https://www.fondation-jacques-rougerie.com/

solutions, that can be more easily implemented in the real world, eventually with restricted budgets. For example, the retrofit renovations presented in Los Angeles (paragraph 7.3.5) and Chicago (paragraph 7.3.7), in the United States. Existing buildings, in some cases even iconic, became places in which recently developed technologies can be showcased, and new behaviors can be taught. Some other designers, instead, looked for solutions that could improve living conditions, as the contribution to subsistence farming (paragraph 7.3.8) or the re-imagination of entire regional economies (paragraph 7.3.6). The concepts selected are not only to be intended as hypothetical or speculative projects. Some of them are just at en embryonic stage. Given the willingness of the creators to put their ideas into practice, eventually scaling them up, some of these projects will hopefully be implemented. These are the cases of AL.F.I.E. (paragraph 7.3.10) – a device that is patented but not yet installed – and LIQUID3 in Belgrade (paragraph 7.3.14), an urban PBR that is supposed to be placed in the city shortly. Confidence is also placed in the prospective realization of RiverBox (paragraph 7.3.9) and Ctrl+N (paragraph 7.3.15), since they seem to be based on solid business models, and led by multidisciplinary teams of engineers, designers, and entrepreneurs.

Reading about new microalgae-based conceptual projects is undoubtedly fascinating and acts as a stimulus for doing more. Even if most of these ideas will probably never come to light, it is evident that more and more people are attracted by this topic. A growing interest is rising in the fields of architecture and design, but not limited to a restricted kind of application. At this stage, it is strongly advised to take notes of these recent experimentations, having in mind that eye-catching solutions are not necessarily the most effective ones. Learning more about these ideas also projects ourselves into the future, traveling forward in time. "*Therefore, envisioning a sustainable future is the first necessary step to plan and design resilient, self-sustaining prospects*" (Peruccio, Vrenna, Menzardi, & Savina, 2018, p. 752). The only feasible scenario is the one we aim for, and concepts like these are leading the way.

Figure 7.98. Hydrogenase algae-farm to recycle CO_2 for bio-hydrogen airship. Adapted from *Vincent Callebaut* website, 2010, retrieved from http://vincent.callebaut.org/zoom/projects/100505_hydrogenase/hydrogenase_pl008.jpg Copyright 2010 by Vincent Callebaut.

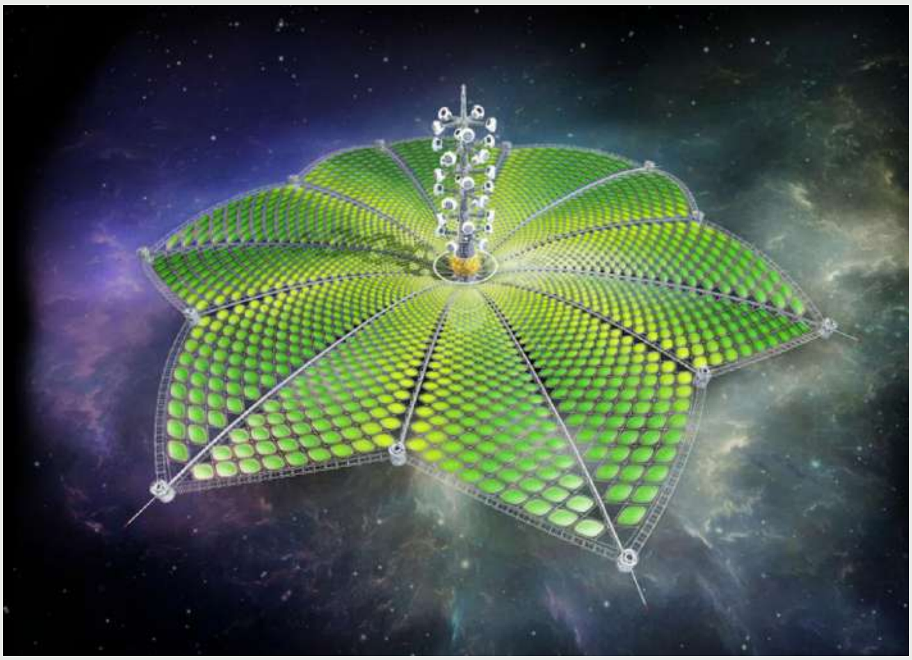


Figure 7.99. Solar Spore, a visionary bio-morphologic architecture that uses algae for producing electrical energy, oxygen, and hydrogen in space exploration. Adapted from *Fondation Jacques Rougerie* website, 2017, retrieved from https://www.fondation-jacques-rougerie.com/projet/17-s-coup-de-coeur-solar-spore Copyright 2017 by Alexandre Brassart, Sylve Truyman, and Pierre-Jacques Truyman.

PART III

Project development

CHAPTER 8

Project

The historical moment we live in is characterized by climate change, exponential population growth, socio-economic imbalances, a global pandemic, and decidedly has uncertain prospects. Thus, it is imperative to work diligently to achieve the UN Sustainable Development Goals and build a better future (see paragraph 2.2.2 – Toward 2050). The role of academia in this call is as crucial as that of governments and supranational bodies. As illustrated in the previous chapters, this thesis aims to satisfy – at least partly – goals No. 2, 3, 8, 11, and 12. The research is remarkably close to goals No. 2 (Zero hunger) and No. 12 (Responsible consumption and production). Given the importance of superfoods as present and future sustainable meal alternatives – especially microalgae due to their high nutritional value and user acceptance – it is legitimate to ask how the design discipline can contribute. But above all, how this research thesis can be useful for both academics and practitioners: through a design project. To answer this question, the following chapter illustrates the development process of a product and a product-service. Therefore, this thesis's practice-based research is the most appropriate approach to extrapolate relevant data and propedeutic considerations.

As you will be reading shortly, the project has been initially conceived to work within a city and on different scales. It can still be easily adapted to other geographical, economic, social, and cultural contexts, just by making a few essential changes and with due considerations. The project is also intended to be replicated, copied, and improved with an open-source and do-it-yourself perspective. The dissemination of the project via the internet – on digital collaboration platforms and industry blogs – and through publications on scientific journals, allowed to reach many people with disparate backgrounds. These include academics, professional designers, makers, amateurs, biologists, entrepreneurs, as well as students and even chefs. Some of these people were particularly interested and decided to dedicate their time to find out more about the project and contribute to this research's advancement. I firmly believe that the decision to make the project 'open' – rather than patenting a solution for commercial use only – has been the key to getting this study out of the walls of academia and contributing to real-world problems through a practical, but still theoretically-valuable, project.

It is indeed clear that doing design research is a challenging task that requires both theoretical abstraction and practical work, to trace and define new potential design applications and guidelines, and deliver a relevant academic product that could be used as a basis for future research and projects. *"Even though the conditions that have initially framed the field of design have changed significantly and designers now work in a post-industrial, rather than industrial society, designers are still perceived as people who 'make' rather than people who 'think'"* (Muratovski, 2016, p. 190). Practice-based research is therefore important in an academic environment, especially for a doctoral dissertation, because it allows contributing to knowledge both through artifacts and with a substantial textual contextualization (Candy, 2006). The practice-based work in this thesis aims to facilitate microalgal learning in design, communicating its principles, and acting as a fundamental part of a knowledge-building process. The main objectives of this practical experimentation are:

- Fill the practice gaps that were highlighted as a result of the analysis of the limits of the case studies;
- Leverage new and innovative design possibilities;
- Demonstrate that designers can work on projects involving microalgae, focusing not only on the creation of an object but also on a set of complementary services;
- Experiment with the design of new technical solutions;
- Implement one or more devices for *Spirulina* production, mainly for human food use;
- Hypothesize innovative Product-Service Systems in urban contexts, which use microalgae as a vector for healthy and sustainable growth;
- Test the obtained results and validate them;
- Extrapolate, from the practice, the necessary elements to define the guidelines for designers who want to design with this innovative 'material'.

The project development was conducted at Tsinghua University (THU) in Beijing – China, Industrial Design Department of the Academy of Arts & Design

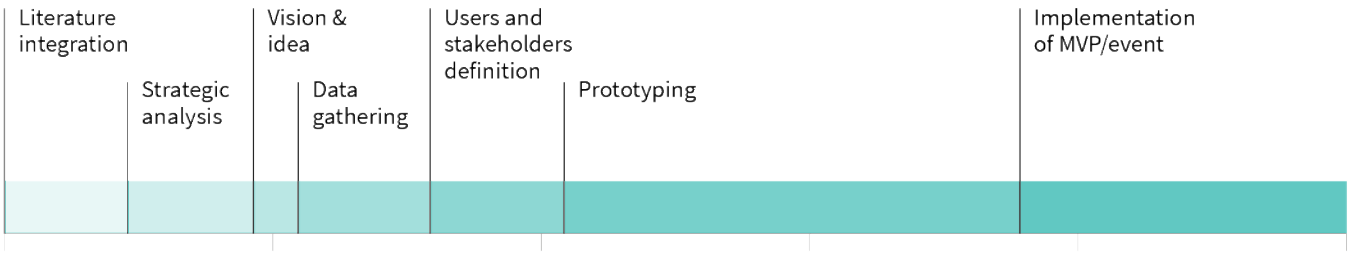


Figure 8.1. Operative plan of the research period at Tsinghua University – Academy of Arts & Design, from 1 September 2019 to 31 January 2020.

(清华大学美术学院). The invitation was received by Prof. Liu Xin, Coordinator of Tsinghua DESIS Lab, initiator of LeNS-China and co-supervisor of this thesis. The visiting research period lasted for 5 months, from 1 September 2019 to 31 January 2020: Prof. Liu provided support for the research project together with his colleague Dr. Zhong Fang, Assistant Professor in Design. Their contribution was significant because they helped in the coordination of some events, involved their students and connected with some Chinese suppliers, overcoming the language barrier. Both also provided periodical useful methodological and design suggestions, that added value to the final project. The choice to collaborate with Tsinghua University was made based on the high quality of the teaching standards and research, and the international relevance of the institution. Tsinghua University is, in fact, perennially ranked as one of the top academic institutions in Asia. The Industrial Design Department ranks among the best design schools in China, along with the College of Design and Innovation of Tongji University in Shanghai. At the same time the possibility of living in Beijing, one of the largest and most modern metropolises in the world, was a way to get deeper into the research, investigating the real needs of citizens and the features of such a big city.[1]

The research work at THU was structured according to the following operational plan. This was originally scheduled over a period of 7 months to conclude the design part and plan the test phase, but it was subsequently shortened to 5 months, due to the COVID-19 outbreak (Fig. 8.1):

- **Literature integration:** Integration of the literature on the topic and methodologies of Product-Service System Design for Sustainability. This phase was also propaedeutic to study PSSD best practices and to explore the Chinese context.
- **Strategic analysis:** Analysis of the reference context/structure and defini-

1 A shorter research period at WUR – Wageningen University & Research in the Netherlands was initially considered. WUR is the only university in the Netherlands to focus specifically on the theme of 'healthy food and living environment', also working with local governments and private companies. Although the research topic was of mutual interest, the joint research proposal was not formalized since it was not aligned with design research, but it was more related to technical solutions in the field of biology/chemistry.

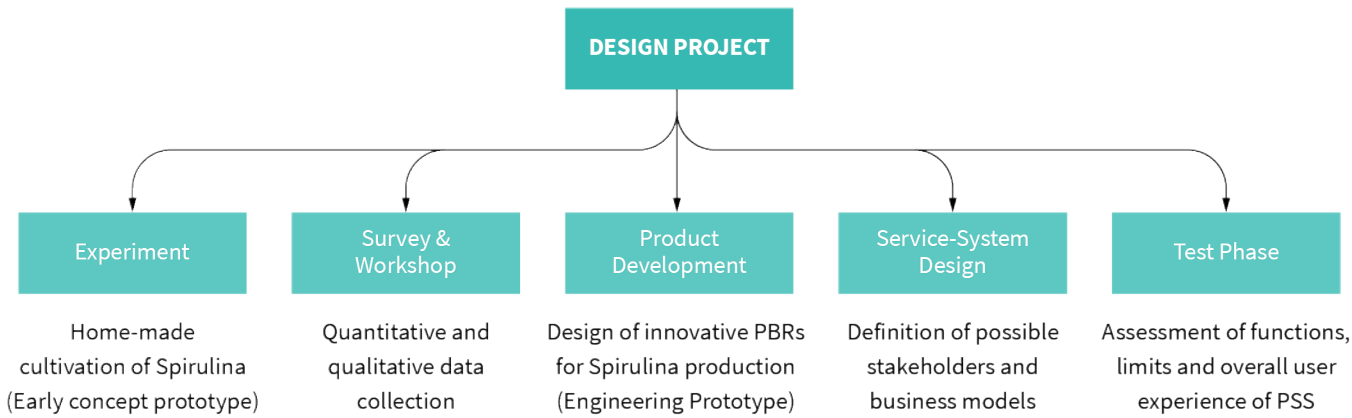
tion of sustainability design priorities.

- **Vision & idea:** Visioning and cluster of ideas for the project, development of a sustainability design orienting scenario in order to explore the opportunities.
- **Data gathering:** Quantitative and qualitative analysis aimed at identifying stakeholders, main problems and opportunities. The research is also aimed at achieving relevant data on consumption habits, palatability, acceptance rates, perception, etc. through online surveys, face-to-face interviews, practical experiments, and a workshop.
- **Users and stakeholders definition:** Definition of primary and secondary stakeholders to involve in the prototyping phase. Definition of the context in which to operate and of the final target users (personas).
- **Prototyping:** Design of a preliminary version of a device and/or of service by taking into consideration its functional rationality, technological appropriateness, operational sustainability, as well as distinctive philosophy (core values).
- **Implementation of MVP/event:** The pilot project could be implemented on a small scale or on the occasion of an upcoming public event.
- **Test phase:** The design projects need to be tested and assessed in all their parts, to guarantee scientific rigor and objectivity.
- **Result collection and analysis:** An in-depth analysis of the results with considerations, limits, guidelines and future research took place after the prototyping and implementation phases.

A design project does not only imply the realization of a product. The following paragraphs document in detail the different parts of a more complex design process (Fig. 8.2). These are, in chronological order:

- **Experiment:** Learning how to grow *Spirulina* at home was an unusual exercise. At the same time, the aquarium that has been set up included a ventilation system, light, and thermal regulation. This can be considered as a first preliminary prototype of a photobioreactor. The practical hands-on with microalgae culture has served to gain insights on the main operation-

Figure 8.2. The design project included an experiment, a survey and worskhop, the product development, the Service-System design, and the test phase.



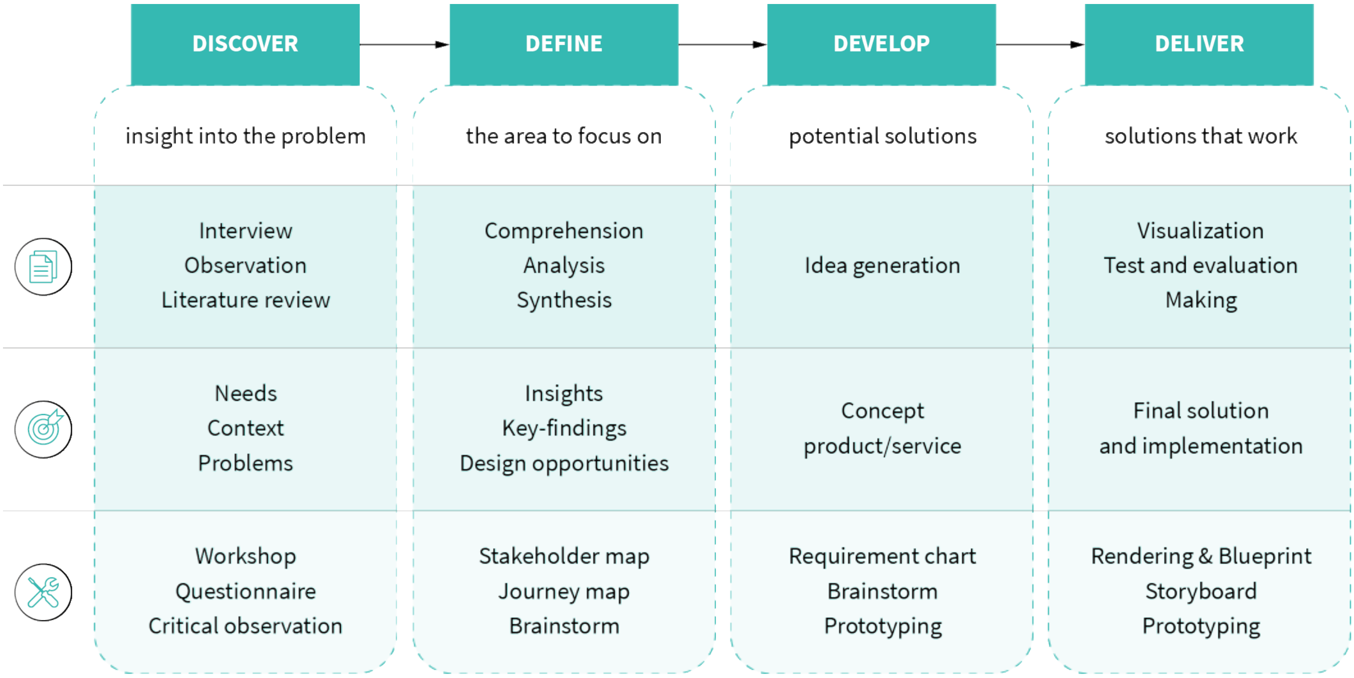


Figure 8.3. The design process followed for the Product-service System (Modified 'Double Diamond' process). For each phase the contents, aims, and tools are presented.

al requirements of a PBR and for the identification of potential troubles for users.

- **Survey and workshop:** A preliminary survey involving more than 500 respondents was necessary to explore the propensity of people in eating and cultivating microalgae. The online survey also identified a specific target of users, who were later invited to attend a workshop. During this event, quantitative data on the palatability of a few Spirulina-based recipes were collected. Participants were also involved in a design session where they had the opportunity to envision hypothetical Product-Service Systems.
- **Product development:** Based on the considerations extrapolated from the case studies analysis and the quantitative/qualitative data collected during the survey and the workshop, the product development phase consisted of the design of two innovative devices for the production, collection, and distribution of *Spirulina* (a home-use device and a public-use device). One of them is a fully-functional engineered prototype. The second remained at a conceptual level. A 1:10 scale model was realized.
- **Service-System Design:** Different services and scenarios in which the devices can operate have been hypothesized. Possible stakeholders and business models were also defined, contextualized to a large metropolis.
- **Test phase:** The products and services have been tested to verify their effectiveness. Different tests were made to assess the functions of the home device, understand its limits, and evaluate the overall user experience.

For the design of the entire Product-Service System, the 'Double Diamond' design process was followed (Bánáthy, 1996).[2] Figure 8.3 shows a re-adapted graphic version, which includes the contents, aims, and tools that have been used for each phase.

8.1 Experiment

Even if harvesting *Spirulina* is a reasonably easy task, difficulties may occur during the process. To gain practical knowledge about its cultivation, a home-made production has been set up. The experiment consisted of running a rudimentary – yet fully-functional – home photobioreactor (Fig. 8.4). The goals of the experimentation are:

- Practical hands-on with microalgae culture;
- Comprehension of the farming process, from the algal inoculum to the final harvesting;
- Identification of potential troubles for non-experts growers;
- Extensions of the first batch for scaling up the production;
- Supply of the necessary components for the construction of a PBR;
- Gaining insights on the operational requirements of a PBR.

The experiment took place in Beijing, China from 18 September to 20 October 2019. The cultivation was located in a home environment. To grow microalgae, it is necessary to have a container in which to place a substrate (water), an energy source (light), a way to mix the culture (an air bubbling device), a supply of nutrients (nitrogen and phosphorus), a temperature control device (digital thermometer), a temperature regulation device (aquarium heater), and an algae cell inoculum. The following components were bought online on Tianmao (天猫), China's leading e-commerce website[3]:

- n. 1 10 l, transparent glass aquarium with dimensions 295x200x215 mm (mod. SUNSUN HRK-300);
- n. 1 LED lamp with easy clip-on support and movable mechanism (mod. AMD-D2/4W);
- n. 1 4W air pump with double air outlet and adjustable gas volume knob, maximum volume 2.8 l/minute per outlet (mod. SUNSUN CT-402);
- n. 1 battery-powered digital thermometer with submersible probe (mod. SUNSUN WDJ-004);
- n. 1 25W submersible aquarium heater, range 18-32 °C (mod. SUNSUN GB-25B);

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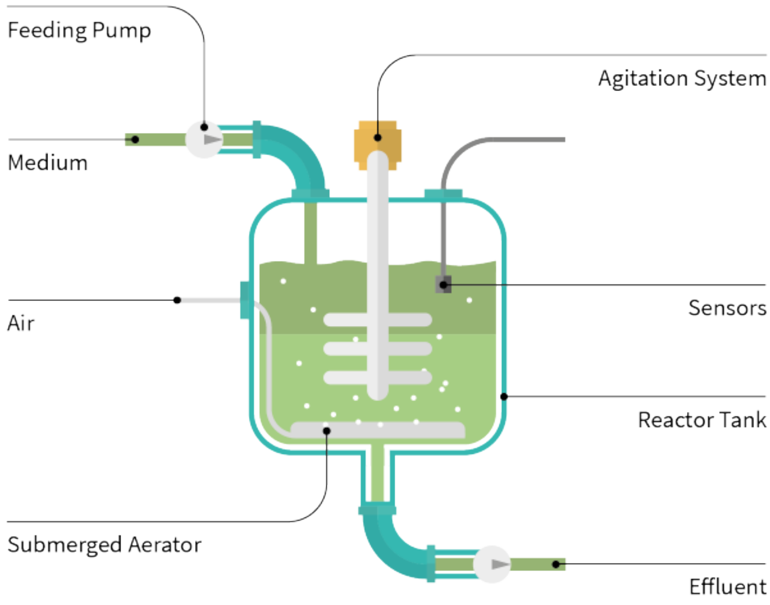
2 The Double Diamond design process was theorized by Prof. Béla Heinrich Bánáthy in a divergence-convergence model proposed in 1996. It was later rearranged and popularized by the British Design Council in 2005.

3 Tianmao is part of Taobao, Alibaba's e-commerce platform. E-commerce is very diffused in China and the purchase of these particular products is easier online than in regular retail stores. Moreover, the sellers usually guarantee a higher quality of the products and better customer service.

Figure 8.4. Main components of a photobioreactor. In the experiment, most of them were included (or simplified).



- Various cabling, return valves, airlines.

The total price for these components was ¥ 223.00 (around € 28.00), so relatively cheap. As regards the *Spirulina* inoculum and the nutrients, they were purchased from the USA for a higher price ($ 137.89, around € 123.00).[4] The supplier, Algae Research and Supply, is a small company located in Carlsbad, California with the mission of promoting the education on aquatic systems through the distribution of knowledge and materials to culture algae. The founder Matthew Huber and his team are providing support on how to harvest microalgae. Their clients are student, teachers, homeschoolers, professors and post-docs, but not limited. They sell products designed to bring the richest possible education and scientific benefits.[5] These materials were bought:

- n. 1 algae culture kit for *Arthrospira platensis* (*Spirulina*): The kit provides information about the strain of algae, an illustrated growing protocol, culture care lessons, and lifecycle background of batch-culture cycles. It comes with a tissue culture flask with breathable cap (50 ml volume), a 1 ml dense culture inoculum in a micro-centrifuge tube, nutrient fertilizer with sodium nitrate and sodium phosphate as sources – this is a modified version of the medium formula called f/2 (Guillard & Ryther, 1962; Guillard, 1975) – and culturing salts that can be added to a 500 ml bottle of drinking

4 This was partly due to the lack of technical/biological Chinese vocabulary, and the resulting difficulty in finding reliable suppliers from China Mainland. The decision of purchasing these materials from abroad was also due to time constraints.

5 For more information on the company and instructional videos on how to grow microalgae at home, visit Algae Research and Supply's website: https://algaeresearchsupply.com

water.

- n. 1 *Spirulina* farming kit: The basic kit includes a biological part (algae culture), a chemical part (nutrients), and a physical part (salts and water mixing). It also comprises a booklet on algal farming and the instruction to set up the culture. In order to start a 19 l culture, the set consists of a *Spirulina* culture (500 ml), a stainless steel bubble tube (around 30 cm length), an air hose (around 15 cm length), a 1 l beaker, culture salts (2 bags for 19 l), culture nutrients (2 bags of 50 ml each), a circular-shaped harvesting sieve (diameter 15 cm), a Secchi stick (a simple analytical device to determine the optical density of the culture), and an instruction manual. The salts and the nutrients provided are supposed to yield from 20 to 40 gr of dry product (or around 500 gr of algal wet paste.
- n. 1 basic pH meter: The device permits to measure the pH range of the growing culture and it is recommended to *Spirulina* growers since algae cultures are sensitive to pH. This meter comes with a protective cap, a screwdriver for the calibration, batteries, instruction for use, and powdered calibration standards.

This experimentation has been a first personal involvement in growing microalgae, and there was not any previous knowledge. The experiment can be considered as an early-stage prototype of a potential product, fairly functional, even if with substantial flaws. The setting up required, in fact, several components that were reused and adapted later on in the design phase of the final device (e.g., control hardware, lighting equipment, air pump, etc.). Once all the materials were delivered at home, the aquarium was placed on a piece of small furniture close to a window, not fully exposed to direct sunlight. The air pump and the bubble tube were then installed, but not put into operation yet. The digital thermometer was also positioned, by placing the probe in the tank. The aquarium was subsequently filled with 2 l of drinking water for the medium (Nongfu Spring – 农夫山泉 – water was chosen due to its alkalinity and the non-presence of chlorine), and the air pump was powered on to aerate and circulate the culture. The tube has been arranged to optimize the air and the water flows. One bag of culture salts was poured in the water, together with the nutrients. The starter formula was stirred with clean hands until completely dissolved. Subsequently, the *Spirulina* culture was added. The LED light was positioned and activated at alternate times, and the algae have been let grow for 48 hours. The total volume of water was increased by 10-20% daily, trying to keep a similar density, until reaching the total volume of 16 l. To have a backup culture, in case of problems with the one in the main tank, a smaller one was set in a 500 ml transparent plastic water bottle.

The algae have been let grow for 2 weeks and the pH levels were controlled periodically. To optimize the temperature of the culture, a heater was placed in the aquarium sometimes. The clumps that were building up, especially on the surface, were easily removed with a colander. The optimal culture density was verified through the use of a Secchi stick. The instrument indicated 10 mm, a rather shallow depth that suggests a very dense culture. The blue-green thick paste was filtered with the sieve, while the water that passed through it was rather clear. A final rinse with fresh water allowed to wash away the alkali salts and the bacteria. Finally, with the help of a spoon and paying attention not to break the sieve, the fresh biomass was collected in a small bottle, resulting in a total of around 10 ml. The remaining water was mainly intracellular. Visual documentation of the steps of the experiment is illustrated in Figure 8.5 (following facing pages).

8.1.1 Considerations

Growing microalgae at home was a stimulating experiment that triggered curiosity. It was also an occasion to get general aquatic science knowledge. Microalgae are living organisms that respond to external stimulations and for this reason, it was important to take care of them responsibly. The culture process itself is not complex: it required minimum maintenance but regular commitment, to control pH values, temperature, and lightning. Even if grown in an indoor environment, to minimize external contamination (especially with dust), a top lid could be useful. It may be effective also to preserve heat.

Table 8.1. Summary of the considerations on the experiment. Pros and cons marked with +/-.

Considerations	**+/-**
Practical hands-on	+
Simple experiment	+
Easiness to find materials	+
Enjoyable activity	+
Needs periodical engagement	−
Partial water evaporation	−
Potential contamination risk	−

Spirulina is a natural edible microorganism. Nevertheless, the produced biomass should be carefully inspected with a microscope to identify potential alien algae streams or bacteria. The supplier does not guarantee that the growth is safe: the safety is a responsibility of the grower. Even if the color, smell, and aspect of the biomass produced in this experiment was unadulterated, it has not been consumed (either fresh or dry) to avoid possible intoxication. Concerning the availability of the components needed, they were rather easy to buy online. Prices were accessible for most of them, except for the nutrients and culture media bought from the USA that were slightly more expensive. This is due to North America's average higher cost of living, and international shipping costs. These costs can be surely lowered manyfold, by identifying local trustworthy suppliers and/or utilizing high-quality inocula coming from fellow farmers.

Supposedly this experiment is, to a certain extent, easy to replicate even for non-experts. Step-by-step instructions, basic education on the topic, and the guidance of specialists are hence essential requirements. Without this support, the culture may die or be contaminated by external agents, hindering growers in their efforts to produce microalgae. Particular complexities during the process have not been identified. Constant engagement is the most important conditio sine qua non for producing a healthy culture that is also safe to eat.

This experimentation achieved the prefixed objectives and guaranteed a fair amount of living culture for the future steps of the project. It was also a necessary and valuable moment for apprehending – not only at a theoretical level but also practically – the basic functioning of a PBR. Most of the components used in the experiment were later utilized for the development of the prototype of the product. This aquarium, with such a particular setup, can be already considered a fully-fledged photobioreactor. Design requirements for a more aesthetically pleasant and intuitive to use device, but not only, were explored later in the research. Summary of these considerations in Table 8.1.

8.2 Survey

Surveys are typical tools for empirical and quantitative research in many fields like statistics, social sciences, marketing, and design.[6] They are used for collecting information from a sample of individuals in a systematic way. The purpose of this survey was to document people's opinions, attitudes, or previous experiences (Leedy & Ormrod, 2010) with food and microalgae. Particularly, the goals were:

- Collect quantitative data through the involvement of a larger pool of people;
- Understand local food purchase behaviors and habits;
- Apprehend responder's eating routines;
- Gaining insights in consumers values;
- Understand the level of satisfaction about their diets;
- Explore the propensity to change food habits and try new foods and recipes;
- Assess their knowledge about microalgae;
- Arouse their curiosity in participating to thematic tasting sessions and workshops;
- Evaluate the interest in cultivating microalgae at home.

Before, online surveys included computer-assisted interviewing and e-mails, but they are increasingly replaced by web surveys. These "*can reach even more people than written questionnaires, there are no associated expenses with mailing, and generally the response rate is somewhat larger because people can submit their responses more easily. An added benefit to this type of questionnaires is that the results are easier to process; or in some cases, the software automatically generates the results*" (Muratovski, 2016, p. 117).

8.2.1 Pre-survey

Some level of pre-testing is important before launching a full-scale survey. Research and marketing companies are recommending such a practice (Kuhn, 2011). This preliminary step was necessary to estimate the length of time nec-

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6 The survey and part of the work described in this paragraph are in some measure based on a previous study: Vrenna, M. (2016). *The system design of Caijia from the consumer's point of view* (Master's thesis, Politecnico di Torino, Italy).


Fig. 8.5.1

Fig. 8.5.2

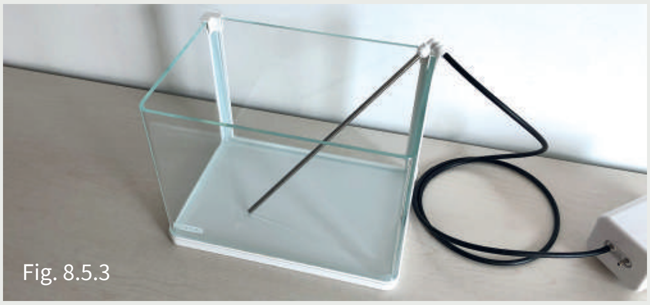
Fig. 8.5.3

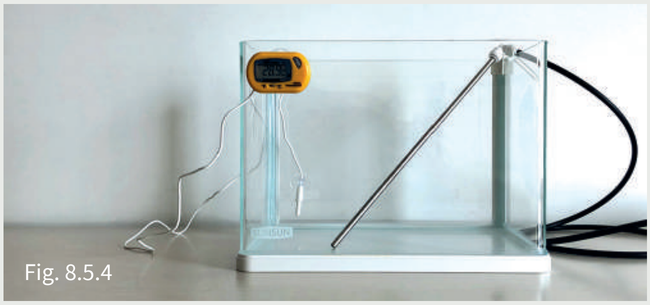
Fig. 8.5.4

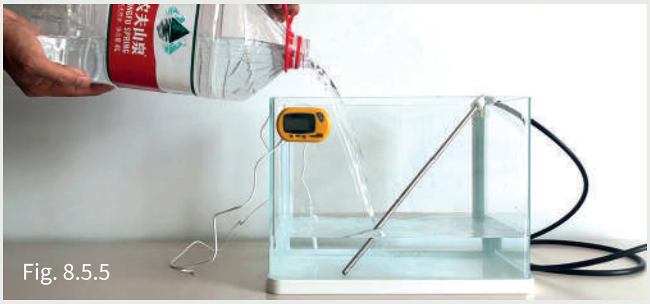
Fig. 8.5.5

Fig. 8.5.6


Fig. 8.5.7


Fig. 8.5.8


Fig. 8.5.9


Fig. 8.5.10

Fig. 8.5.11

Fig. 8.5.12

Fig. 8.5.13

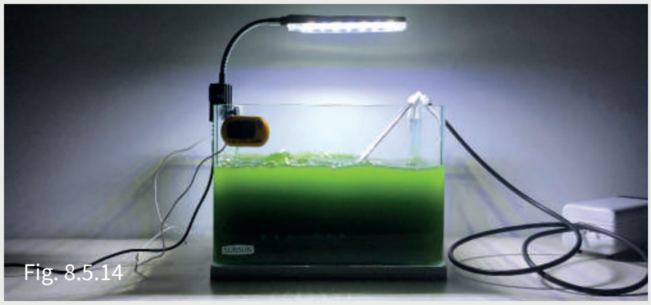

Fig. 8.5.14

Fig. 8.5.15

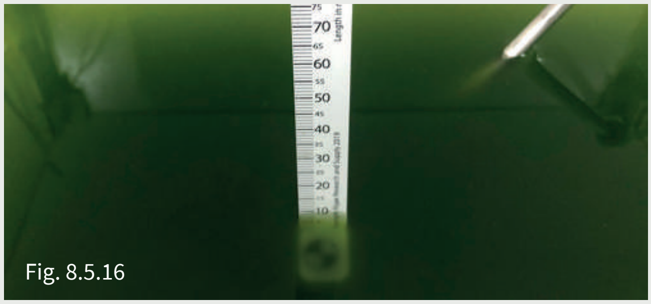

Fig. 8.5.16

Fig. 8.5.17

Fig. 8.5.18

Figure 8.5. Sequences of the home experiment.

1. Positioning of the aquarium;
2. Installation of the air pump;
3. Installation of the bubble tube;
4. Positioning of the digital thermometer;
5. Filling with drinking water;
6. Actioning of the aeration system and optimization of air and water flow;
7. Adding the culture salts;
8. Adding the nutrients;
9. Stirring the starter formula;
10. Adding *Spirulina* culture;
11. Reach of maximum volume;
12. Backup culture in a 500 ml bottle;
13. Periodical control of pH levels;
14. Growth for two weeks;
15. Control of the temperature;
16. Verify of optimal culture density with the Secchi stick;
17. Filtration and final rinse;
18. Collection of the biomass.

essary to complete the survey, improving the questions that may have been misinterpreted, and gaining general suggestions from a selected and a limited number of people. To get these qualitative data, personal face-to-face meetings occurred and a total number of 10 persons (5 Chinese nationals and 5 Westerns) were involved. Separate meetings took place in Beijing from 30 September to 3 October 2019. Responders included university professors, professionals, students, retired people, vegetarians, biologists, pharmacists, and designers. According to some of the interviewees, the first version of the survey was too long, and thus it was later shortened. Further descriptions and detailed answers were inserted, to let people better understand the research context and the properties of microalgae. A few questions related to food habits were also slightly modified. The survey was finally enriched with both static and dynamic pictures, to visually facilitate the comprehension of some parts, and a box for general comments and opinions was added at the end to gain extra qualitative data.

8.2.2 Online survey

The online survey was adapted to the Chinese context: it was written both in Chinese and English languages. For the actual gathering of data, the online instrument Wenjuan (问卷网) was used. Wenjuan is a popular platform in China that lets users create free surveys and carry out professional mathematical data analysis to ensure higher accuracy.[7] The survey included multiple-choice options, questions aimed at identifying the frequency of occurrence, behavioral scales, to identify the likelihood to engage with some particular activities, and Likert scales, to allow responders to express how much they agree or disagree with a particular statement (Likert, 1932). The survey also included a few open-ended questions to gain qualitative data. The questionnaire was entitled 'Food for the future – Survey'. Data were collected from 8 October 2019 until 22 October 2019. The link to the survey[8] was spread digitally, mainly shared on selected WeChat[9] groups with both local people and foreigners of different ages and assorted backgrounds. The topic gained popularity in the groups and started interesting conversations among the users. The full questionnaire can be found in the Appendix: Food for the future – Online survey.

8.2.3 Survey results

The results are quite compelling and in line with the expectations. A total of

7 Mobile apps are available for Android and iOS. Desktop version of the platform at the link: https://www.wenjuan.com.

8 Link: https://www.wjx.cn/jq/46678562.aspx

9 WeChat is a popular Chinese instant messaging mobile application, used also as a social media and mobile payment platform.

504 people answered the survey during a period of 15 days (56% females, 44% males). Most of the interviewed have an age between 18 and 30 years old (18-22: 28%; 23-30: 42%), while around 30% have more than 31 years old (31-40: 17%; 41-50: 8%; 51+: 4%). A great part of the respondents is Chinese (65%) living in first-tier cities like Beijing and Shanghai. Nevertheless, it was also possible to reach an assorted community of foreigners (35%) coming from several countries in Africa, America, Asia, and especially Europe, due to the available instruments and circle of connections. The average interviewee has a good education (Bachelor's or Master's degree level) and is currently a student or employed in a company. A smaller percentage (11%) are freelancers. 54% of the people define themselves as 'food amateurs', people that love to eat any kind of food. Curiously, 36% are 'healthy food lovers' (very attentive to their diets and always looking for organic and healthy food), while 30% are 'meat enthusiasts', a rapidly-rising trend in China that is strictly connected to the higher purchasing power of the consumers, which are embracing Western diets and lifestyles (Moore, 2012). The eating habits are, thus, quite assorted. Even though more than half of the respondents are usually cooking at home, buying groceries from the nearest supermarkets, a similar number eat regularly at the restaurant or uses home delivery services: this suggests that many of them have rather poor cooking skills. When it comes to choosing the right food, it is interesting to note that the most important aspects that are taken into considerations are – in order – the quality, the freshness, and the taste. For these reasons, most of the interviewees are overall satisfied with their diets, but more than 20% believe that their eating habits have to change.

Interviewees were also asked if they knew something about microalgae before. Almost half have never heard of them, and only 26% have eaten *Spirulina* in the past (this includes any form: fresh, dry, pills, transformed, etc.). After having given a brief introduction about the properties of microalgae and assessed their current knowledge, participants were asked if they were willing to eat microalgae in the future. Far beyond expectations, 60% said they were inclined. Among the different options suggested there were other hypothetical 'future foods' such as insects (20%), lab-grown synthetic meat (28%), lab-grown fruits and vegetables (37%), and meal replacements (30%). A selection of representative foods and drinks with added *Spirulina* was later presented. It emerged that most of the people would love to try functional healthy drinks, smoothies, and both salty and sweet foods like pasta, chips, and seasonings, but also Spirulina-based burger buns, chocolate, and croissants. In spite of that, taste (59%), smell (47%), appearance (43%), color (36%) and cultural background (29%), are still considered some of the main barriers to the adoption. Some respondents also pointed out the somewhat expensive prices of the products. The survey aroused the curiosity of the participants and an outstanding 65% of them asserted that would love to participate in a tasting

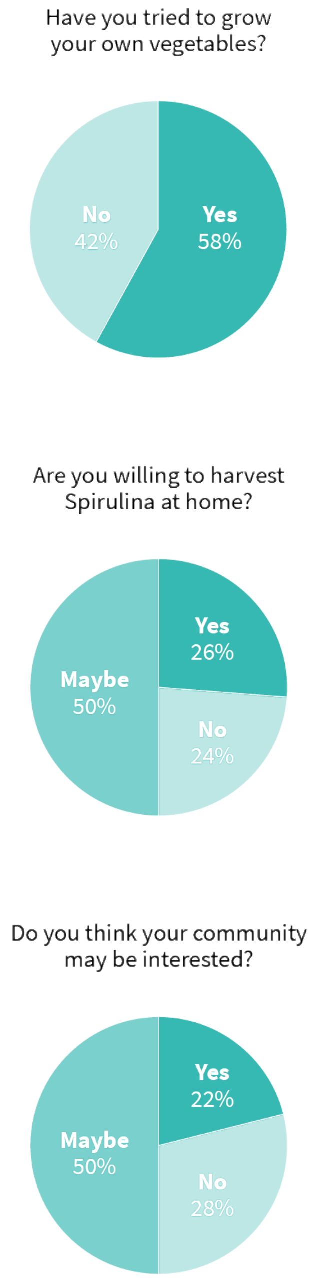

Figure 8.6. Respondents answers for questions 21, 22, and 24 of the online survey.

Table 8.2. Some of the respondent's main concerns for the home production of *Spirulina*.

Respondent	Comment
#4	Depends on price and easiness.
#9	It should be more convenient than buying it on the market.
#34	I will not always want to eat it, and the harvest could be troublesome.
#105	I do not know how to take care of it.
#190	I am scared of eventual pathogen agents.
#200	Too much time devoted to maintain the device will be a minus.
#203	Why not? But I wonder about the price of this equipment...
#445	There may be not much space in my room.

Table 8.3. Some of the respondent's main concerns for the production of *Spirulina* in public or semi-public environments (e.g., residential communities).

Respondent	Comment
#5	Where I live, it is hard to be part of a residential community.
#29	In our community there is not enough space.
#151	It depends on the monetary (or health) benefits of the production.
#180	I am not sure that everybody understands it, especially elderly families.
#201	I wonder who would manage it...
#246	Communities are often not very sustainability-oriented.
#318	They just care about making money and would think it is weird.
#504	Plant costs and retail prices are my main concerns.

event, in which they could try some Spirulina-based foods and drinks.

Finally, the survey aimed at understanding the propensity of people in harvesting microalgae in domestic or semi-public environments. Many people already tried to grow their own vegetables. 26% of them are willing to harvest *Spirulina* at home, and 21% believe that their residential community (compound, school campus, etc.) may be interested in microalgae production solutions that could engage neighbors in common activities, produce income, and purify the air of common spaces. Still, a conspicuous part of the interviewee (50%) is skeptical and not sure that domestic or communitarian solutions may work (Fig. 8.6). Main concerns for the home production resulted in the supposed difficulty in cultivating *Spirulina*, the lack of time for taking care of it, and the scarce knowledge of its real health benefits (Table 8.2). As regards the communitarian device, most of the people thought that time and maintenance costs may be too high and that the device would take considerable space. Moreover, it may be challenging to get all the residents to agree (Table 8.3).[10]

10 Although these concerns may represent an obstacle to the design of new products, services, and systems, they highlight the points on which to focus to produce innovation. Despite the many concerns, there were also many positive and constructive considerations. These served to strengthen the project even more.

8.2.4 Considerations

The online platform used for the survey proved to be stable and performing both in data collection and data extrapolation. The survey was essential in this first design phase to define the future steps of the research. During the two weeks that it was online – but even later – many precious qualitative feedbacks were received from those who responded. On several occasions, even with face-to-face empathic conversations. These provided more personal and articulated information, compared to the ones collected through the questionnaire. It was possible to reach mostly young and educated people, thanks to the available communication channels. At the same time, this suggests that the youngers may be more interested in healthy nutrition, compared to older people, and more likely to collaborate on this topic. Millennials (Generation Y) and Centennials (Generation Z) could, therefore, be the right target for the design of this kind of innovative products and services.[11]

Eating habits are, as expected, rather heterogeneous. Instead, the purchasing methods (home delivery services, supermarkets, online sales channels) are very similar, confirming the propensity to use technology in everyday life and the continuous research for 'convenience' in terms of price, time, and place. The same applies to the values linked to food: quality, freshness, and taste are common among most of the respondents. It is interesting to note that the knowledge about microalgae, their properties, and their uses is unquestionably limited. Only a small percentage of people know about *Spirulina*: they are mostly vegans, vegetarians, and consumers who are particularly attentive to a healthy and balanced diet. A large part of the surveyees seems to have never heard the terms 'microalgae' neither 'Spirulina', and even fewer people have tasted them. Nevertheless, a considerable proportion of respondents believe that microalgae could represent an important source of food in the future and even more people would like to try them (mainly because of their curiosity). As with many other 'exotic foods', there is an initial resistance to change; subsequently, various factors may lead to mass adoption (Moro, 2017).[12]

Microalgae production at home and in local communities were considered

Table 8.4. Summary of the considerations on the online survey. Pros and cons marked with +/-.

Considerations	**+/-**
Quantitative data	+
Qualitative feedbacks	+
Arouse participants curiosity	+
Recognition of the potential of microalgae	+
Interest in future events	+
Limited knowledge on microalgae and *Spirulina*	–
Could not taste products	–

11 According to the Pew Research Center, Millennials are individuals born between 1981 and 1996, while anyone born from 1997 onward is a Centennial (Dimock, 2019). Millennials are the first generation ever to have grown up surrounded by digital technology: this has shaped their cultural, behavioral, and even political attitudes. Centennials are instead digital natives, thus very tech-savvy, spending most of their time online. They are more health-conscious and open-minded compared to previous generations. Both Millennials and Centennials are inclined to adopt new business models. Internet, social media, and technology play a substantial role in their lives (Oxford Royale Academy, 2018).

12 Sushi consumption in western countries has followed the same trend. In the '90s it was a little known food. Cultural factors and a 'fashion' effect have made it – several years later – one of the most consumed foods during short lunch breaks.

Figure 8.7 (Facing page). Some of the pictures taken during the workshop at Tsinghua University, 3 November 2019. These include: the introduction by Prof. Liu Xin (1), the tasting session (2), the 'Microalgae Growing Kit' (3), the design session (4), and the final group presentations (5). Copyright 2019 by Li Tian (李天).

solutions with great potential. At the same time, when designing devices and/or services for this purpose, attention must be paid to a large series of details, to make these solutions possible. These include actual functionality, safety, ease of use and maintenance, with an eye to the aesthetic component as well. Specific details are analyzed later in the design process. The data collected were used solely for academic purpose. Data interpolation was useful for the definition of potential personas and the organization of a thematic workshop. Many people have, in fact, left their contact details to be updated on future initiatives and some interviewees were subsequently invited to attend the event. It is clear that projects which involve the use of microalgae in urban contexts can find fertile ground in the near future and for that reason, novel solutions deserve to be explored. Summary of these considerations in Table 8.4.

8.3 Workshop

Workshops are great opportunities for tangling problems together with a group of people, through a series of activities aimed at getting specific outcomes. In this case, a workshop was organized to achieve specific information, useful for making design decisions with full knowledge of the facts. The goal of the workshop was also educational: participants learned new notions and could explore common concerns with others (Matthes & Dustin, 1980). The workshop took place at Tsinghua University on Sunday, 3 November, to be able to involve a fair number of people.[13] Before that, the results of the online survey were analyzed, to identify the right characteristics of the participants to the session. The event also required the direct and indirect participation of different subjects: attendees, food suppliers, logistic supporters, photographer, and video maker. Because of that, previous meetings occurred with different parts.

The workshop involved 26 people, mainly aged 23-30 years old, and currently studying or working as employees. Most of them have a design background, with previous knowledge on the conceptualization of products and services. Invitees also included design researchers and academics, and professional award-winning design practitioners. The invitees are representative to those respondents who are most accustomed to a change in their habits, and who showed greater interest in the topic during the online survey. They were divided into 9 groups. These people were, for the most part, personally invited to participate in the workshop. A few of them were friends and colleagues, while a few others got to know about the event through printed promotional material or an online invitation sent on WeChat. The workshop was an occasion for "*being with people [...] immersed in the culture that you are investigating. Yet this means a partial immersion, because you need to maintain your objectivity*

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13 The event was held in Tsinghua University, Teaching Building 1, Science and Technology Activity Room (3rd floor) from 14:00 to 16:30.

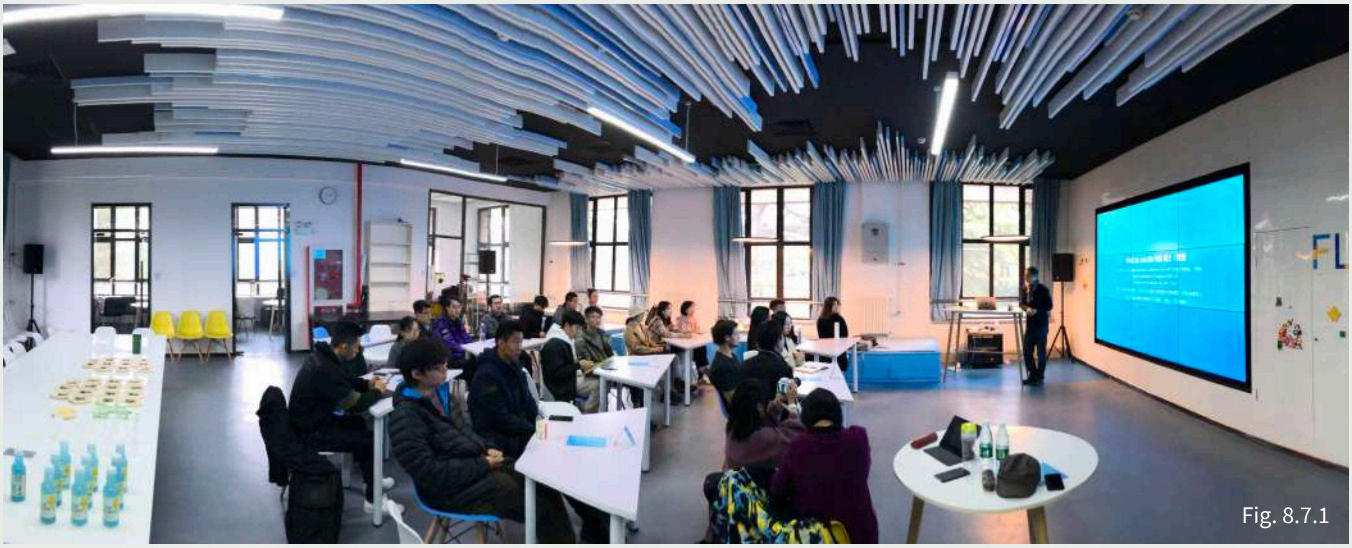
Fig. 8.7.1


Fig. 8.7.2

Fig. 8.7.3


Fig. 8.7.4


Fig. 8.7.5

and impartiality" (Muratovski, 2016, p. 65). The main aims of the event were:

- Assessing participants' general knowledge on algae and microalgae;
- Provide invitees with basic information about the health benefits of microalgae and other potential uses rather than food;
- Get quantitative data on the palatability of the proposed recipes;
- Provide invitees with elementary notions on *Spirulina* cultivation and photobioreactors;
- Getting people to know more about novel foods and persuading them to gain more interest in the topic;
- Understanding their interest in consuming or harvesting microalgae for food use;
- Validate the results of the online survey;
- Engaging the participants in a design session;
- Gaining substantial insights valuable for the design of a Product-Service System involving microalgae.

Through direct observation and informal unstructured interviews, qualitative data were collected from casual conversations. To gain quantitative data instead, participants were invited to answer a set of multiple-choice questions (and a limited number of open-ended ones). Participants were also demanded to work in groups and present their outcomes to the audience. The following paragraphs describe these parts in detail. The full questionnaire can be found in the Appendix: Food for the future – Workshop Survey. After the event, an article was published on LeNS-China official WeChat subscription account.[14]

8.3.1 Event program

The event was entitled 'Food for the future – Workshop'. The naming did not include the words 'microalgae', 'Spirulina' or 'design', so as not to influence potential participants. Instead, it was decided to use more generic terms as for the survey, to attract attention and arouse curiosity. The event was free for people to attend.[15] The gathering lasted for around 2 and a half hours. An ad-hoc, entertaining presentation was made to illustrate the topic and keeping track of the activities that were taking place (the complete presentation can be found in the Appendix: Workshop presentation slides).

In the beginning, Prof. Liu Xin made a brief introduction in which he presented the research domain and connections with sustainable design. Subsequently, the various uses of microalgae were presented in different fields and their beneficial nutritional properties were explained. The event was then

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14 Link to the WeChat article in Chinese: https://mp.weixin.qq.com/s/nwLd82nys19eCoGCXtbZNw

15 Printed material and food was paid with own funds. The space was kindly provided by THU without charge.

structured in three main parts, namely:

- **Part 1 – Tasting time:** the guests tasted and evaluated foods and drinks with *Spirulina* and phycocyanin, prepared for the occasion by a well-known local pastry shop.
- **Part 2 – Growing time:** the participants had the opportunity to learn how to cultivate microalgae through a playful and fun group activity, structured according to simplified steps.
- **Part 3 – Design time:** given the design skills of the participants, this activity was decidedly engaging and required more time than the others. The participants imagined hypothetical urban services and designed innovative products.

In conclusion, the participants had the opportunity to present their ideas and there was a brief Q&A session. Each part of the workshop had a bilingual presentation in English and Chinese and, as a facilitator and together with the help of Sun Yu-Chi, the track of the time was constantly kept during the course of the event (Fig. 8.7).

8.3.2 Tasting session

The tasting session was particularly appreciated by the participants. Many of these had never tasted Spirulina-based products (about 70%) and were rather curious to try new foods, confirming what emerged from the previous online survey. Before the tasting, furthermore, 54% of the workshop participants argued that the smell could be a barrier to adoption, while 46% had prejudices on taste. The snacks presented were the fruit of a collaboration with an Italian pastry shop that was established in Beijing many years ago, but which have never used *Spirulina* powder before.[16] Various recipes were then consulted on the internet to ensure the correct dosage and cooking methods. The chef also experimented with alternative products, which were personally tested before the workshop. Both the owner of the shop and the chef showed enthusiasm and interest in the project: the goods that were baked also reached a rather high quality.

Everyone's tastes were satisfied. A drink, two savory products, and a dessert were tasted: *Spirulina* lemonade, *Spirulina* crackers, and *Spirulina* chocolate cookies (Fig. 8.8). The lemonade can currently be found on the market:

Figure 8.8. The three Spirulina-based recipes that were tasted during the workshop: *Spirulina* lemonade, *Spirulina* crackers, and *Spirulina* chocolate cookies.

16 Initially a Chinese-owned pastry shop located in the logistically-convenient Tsinghua University campus was contacted to bake some pastries. They were provided with *Spirulina* powder, bought from a certified dealer on Taobao but, due to strict sanitary regulations regarding the food that can be bought by third parties, it was not possible to use it. The choice, therefore, fell on pastry and bakery 'Da Giuliano', located in the Chaoyang district, which was recommended by several people for the excellent quality of the ingredients.

half a teaspoon of powdered phycocyanin was added to each 445 ml bottle.[17] The savory crackers are meat-free and suitable for vegans and vegetarians. The pretzels, softer or crunchier, are made with Parmesan cheese and/or spinach, with added *Spirulina* powder in the dough. The same goes for the biscuits, covered with dark chocolate and characterized by intense green color. Much space has been given to the creativity of the chef, who managed to enhance the flavor of *Spirulina*, without disguising it. The chef also worked on the colors and intensity of the green, trying to make the product palatable but also visually appealing.

The participants were able to express their preferences through a short survey, scanning a QR code with their smartphones. They were asked to judge each recipe on a Likert scale from 1 to 5, where 1=very bad and 5=very good. The aspects to be evaluated were the appearance, the smell, and the taste. The participants also expressed an overall subjective opinion and added qualitative comments, after confronting themselves with their group members. The facilitators did not influence their choices.

The results were encouraging for the next design phases. Contrary to previous convictions, the participants positively evaluated the parameters of smell, taste, and appearance of each recipe tasted, with a high number of answers that were ‘good’ or ‘very good’.[18] All participants except for 1 person also declared that they are willing to prepare these recipes at home or to eat them again in a restaurant. The tasting phase lasted for about 30 minutes, after which the second part of the workshop began.

8.3.3 Growing session

This intermediate phase of the workshop lasted for about 20 minutes and was particularly engaging. The aim was to demonstrate that growing your own *Spirulina* is overall easy. It was also a way for responding to the online surveyed who had shown interest but also raised doubts about the actual feasibility of home cultivation. Furthermore, this activity was a way to explain how to take care of *Spirulina*, by sharing the personally encountered obstacles during the first experimentation. Each group, composed of 3 people, was provided with a ‘Microalgae Growing Kit’, including 2 empty 100 ml bottles, 1 100 ml bottle with alive *Spirulina* inoculum[19], 1 380 ml Nongfu water bottle, and 1 small nu-

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17 C100 lemonade, a well-known local brand, was purchased.

18 Concerning lemonade, the judgment was ‘good’ or ‘very good’ for 93% of respondents. Many have observed that the taste was not so different from that of a normal lemonade. The bright blue color was particularly liked. The taste of the pretzels had a judgment higher or equal to 4 for more than 73% of the interviewees. Chocolate and *Spirulina* biscuits were the most appreciated.

19 For this event, a certified Chinese supplier was found on Taobao. It was more economical than the one used during the first phase of experimentation and the quality

trient bag (Zarrouk medium formula). The microalgal cultivation process was divided into 5 parts (inoculum, nutrients, stirring, control, harvest). The first three were performed during the workshop. Each group followed the directions given in this order:

1. Inoculum: Each participant took a bottle. The one with the bottle full of *Spirulina* shared the content with the other group members, dividing the inoculum into 3 equal parts.
2. Nutrients: Altogether, they put the nutrient salts into the drinkable water bottle provided.
3. Stirring: They shake the water bottle vigorously until all the salts were dissolved. Then, poured the nutrient-rich water into each participant's bottle, to get a healthy *Spirulina* culture. Each participant got her/his own bottle to bring home.

The last two phases have only been illustrated in a video for easy replication at home. These are:

4. Control: Leave the bottle exposed to the light, but not directly to the sun. High temperatures may kill the culture. Remember to remove the cap, so that it can breathe. Shake often.
5. Harvest: After around two weeks, the culture will be ready to harvest. It will have a darker green color. It can be dried in an oven or consumed fresh.

The biomass provided was certified for food use. However, since it would not have been possible to verify the appropriateness of the culture conditions at home, it was suggested to eat the biomass only after a chemical analysis, to avoid possible contamination. At the end of the activity, a few minutes were left to the participants for answering a short survey. 15 people or about 60% of the participants were interested in trying to grow *Spirulina* at home, while only 2 people would not want it. 9 people were inclined, but only under particular conditions (safety of the device, automation of some processes, etc.). This data is much higher than the ones of the previous online survey. This is to confirm that the young participants selected to attend the workshop have a much higher level of interest in this type of activity.[20] However, there is still skepticism about the interest of the communities. This implies and highlights new design challenges and possibilities, many of which will be subsequently addressed by the groups.

8.3.4 Design session

This part of the workshop was probably the most important and the one with the longest duration. Participants were greatly involved and it was possible

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was rather high.

20 In the online survey, only 26% of respondents wanted to grow *Spirulina* at home, almost as many as those who would not.

Figure 8.9. The three mood boards. Attendees were asked to rate them, to define the most suitable look for a microalgae production device.

to receive substantial insights, valuable for the design of a Product-Service System including microalgae and to activate a fruitful dialogue on this topic.

A brief lecture on innovative ways of cultivating *Spirulina* at home or in open spaces in cities took place. The most recent product design experimentations and urban installations were further presented. A focus was also made on PBRs, their main characteristics, and their functions. Subsequently, participants were asked to express their opinion on the features that a *Spirulina* production device should have[21], and on the type of functions that they would like to be automated (based on the operations performed during the growing session). Participants were also asked to tell what they would expect to know more about in future projects or events (e.g. environmental sustainability of *Spirulina* production; health benefits and nutritional values; new recipes and instructions for cooking; technical aspects of production devices). Moreover, to identify the most suitable look and feeling for possible designs, attendees were presented three mood boards[22] and asked to rate them on a scale 1 to 5 (Fig. 8.9).

The next two activities were aimed at designing a system map of a hypothetical microalgae production/distribution service first, secondly to sketch a device that would fit in it. For the service design phase, a set of small adhesive cards was provided to the groups. These were intended to be placed on an A3 sheet and to be connected according to the guidelines given. The set included 42 cards (see Appendix: Workshop cards) divided into six categories, namely:

- Production place: Home, residential community, school, university, office, restaurant, bar/café, public space, other.
- Primary product: Fresh *Spirulina*, dry *Spirulina*.
- Processor: Food/drink factory, restaurant, pharmaceutical company, community, bar/café, home, other

21 They were asked to order by importance the following features: aesthetically pleasant, functional, safe to operate, economical, easy to use, highly productive, fashionable and cool, integrated with furniture.

22 Mood board 1: neat, modern, simple; Mood board 2: technological, digital, futuristic; Mood board 3: familiar, analog, warm.

- Processed product: Human food, animal feed, drinks, pharmaceuticals, cosmetics, biofertilizers.
- Payment methods: Electronic payment, cash, in-kind contribution, redeem code/voucher, other.
- Final customer: Individuals, local entrepreneur, community, public bodies, hospital, canteen, gym, local market, supermarket, restaurant, pharmacy, small shops, other.

The card set was designed specifically for the event. The toolkit was instead devised by Emili (2017) for his doctoral thesis and was taken as a model. It has been simplified in some parts and adapted to the context.[23] The tool proved to be effective and easy-to-use.

Later the groups made some sketches, hypothesizing design devices for microalgal cultivation and that could fit their previous system. In the beginning, the design session was supposed to last for around 30 minutes. However, as in most of the workshops, the groups needed more time to complete their tasks. This resulted in significantly better results. Each group presented the outcomes of their work and an engaging open dialogue took place. This design session has been enriching both personally and professionally because participants were brilliant and skilled. They were also eager to know more about design and microalgae, and happy to actively contribute to this research. The outcomes of the workshop are illustrated in detail in the next section.

8.3.5 Workshop outcomes

The workshop provided compelling quantitative data through brief surveys. These have already been presented. Furthermore, thanks to the design session, qualitative data was collected. The analysis of these was useful in the subsequent definition of the design parameters. The original tables can be found in the Appendix: Workshop group outcomes. The ideas of each group are listed and described below:

- **Group n. 0** (刘新, 钟芳)
  Description of the Product-Service System Map: A microalgae-growing device to be placed on a university campus that can absorb carbon dioxide while purifying the air. It is an art installation capable of producing food and generating electricity. It provides healthy biomass, which is processed by the relevant departments of the school. It is then sent to internal canteens and cafeterias, and transformed into foods and beverages.
  Description of the Product sketch: An installation made with transparent flexible tubes, in which *Spirulina* grows. The top part is mainly decorative.

23 Emili conceptualized three tools for designing PSSDs applied to Distributed Renewable Energy Systems and tested them in several workshops. Given the adaptability of the design framework and the cards, these were used as a reference for this simplified card deck.

The base hosts all the functional equipment.

- **Group n. 1** (宋佳珈, 王渤森, Daniel Gockler)
  Description of the Product-Service System Map: A *Spirulina* farming device can be placed in a home or a bar to produce fresh or dry biomass mainly used for beverages. Consumers can buy drinks online and redeem them at the closest bar.
  Description of the Product sketch: This piece of equipment is supposed to be placed in a bar. Its double-spiral shape resembles the structure of *Spirulina* or DNA. The light fixture is used both for illuminating the cultivation and to create a nice atmosphere.
- **Group n. 2** (洪力飒, 黎书, 梁茹茹)
  Description of the Product-Service System Map: A *Spirulina* culture equipment that can be placed in a home or bar to produce fresh or dry *Spirulina*. Individuals can purchase ready-made drinks at the bar or bring their own *Spirulina* for getting a discount.
  Description of the Product sketch: A dance station and spinning bikes are placed in a gym-like space. The kinetic energy is converted into electricity, to provide light for the *Spirulina* production. Visual feedbacks are given in real-time to the users. The higher the score, the more *Spirulina* is obtained. This is then converted into healthy food that is rewarded to users.
- **Group n. 3** (苌彬, 邬梓桐, 李天)
  Description of the Product-Service System Map: 'High Protein Spirulina Food' is the name of the project. A device for dry *Spirulina* production is placed in residential communities or university campuses. This is processed into high-protein beverages by third-party processors and distributed to supermarkets and gyms.
  Description of the Product sketch: The fish pond-like structure is placed in residential communities and university campuses. This is surrounded by a device that can accumulate *Spirulina*, connected to a central transparent glass tube. The central pipeline rises to collect the microalgae, and the filtered water is used for aquaponics. The bottom of the structure is polished, to show green light at night and increase the photosynthetic activity.
- **Group n. 4** (黄孙杰, 王金钰, 花生豆)
  Description of the Product-Service System Map: The service consists of the realization of microalgae-based beauty products. Microalgae production pieces of equipment are installed in beauty salons and SPAs, to purify the air while being used for face masks. If the production exceeds the needs of the salon, fresh *Spirulina* is sold to pharmaceutical plants which can realize, for example, slimming products ultimately sold to consumers.
  Description of the Product sketch: Autonomous-drive, environmental-friendly mobile beauty salons produce *Spirulina* while collecting carbon dioxide around the city. They offer face masks and other cosmetic treat-

ments. The surplus of the production is processed into foods and sold to final customers through a mobile platform.

- **Group n. 5** (廖卓颖, 陈瑶, 康婧)
  Description of the Product-Service System Map: The university is the microalgae production site. Students and campus staff can grow *Spirulina*, which is turned into food by some internal processors. This is distributed to the canteens, the students, and the families living inside or around the campus. By getting involved in the community, it is possible to get these products at no cost.
  Description of the Product sketch: A small self-service beverage distributor can be placed in the campus canteens. The beverages can be chosen and *Spirulina* added according to the tastes, to get healthy and nutritional drinks. Larger vending machines are placed outdoor on the campus.
- **Group n. 6** (田润泽, 陈祉璇, 高歌)
  Description of the Product-Service System Map: A school-based *Spirulina* culture with educational features, that provides edible *Spirulina* foods and drinks for human students and teachers.
  Description of the Product sketch: Three hypotheses are presented by the group. An algae-growing pipe that can be installed indoor (e.g.: staircases); algae-growing cube-shaped huts where children can play; the 'Algae Canteen', an entire building dedicated to science and teaching, where students can also eat and grow microalgae.
- **Group n. 7** (李博功, 张雨生, 贺小易)
  Description of the Product-Service System Map: Following the popular trend of sharing services, this system permits to grow *Spirulina* inside shared bikes, that are made of transparent material. After scanning the code, users can check how much carbon dioxide is purified by their ride and get tokens. Points can be redeemed for *Spirulina* drinks. The main purpose of this product is to foster the adoption of *Spirulina* while promoting healthy living and sustainable transportation.
  Description of the Product sketch: The frame of the bike is hollowed and used for cultivating *Spirulina*. During the daytime, photosynthesis purifies the air. At night, the illumination increases the safety of the riders. All the components of the bikes are easy to repair and/or disassemble, in the attempt of containing the maintenance costs of the bike company.
- **Group n. 8** (白俊慧, 韦家柳, 严泽腾)
  Description of the Product-Service System Map: The *Spirulina* production device, which is a sort of gazebo, is used by the community as a gathering and science education space. The biomass generated is added into drinks, ultimately given to the community residents and local gyms. Dry biomass can be sold to nearby supermarkets.
  Description of the Product sketch: The gazebo uses sunlight to grow mi-

croalgae. A flexible roof can be moved accordingly, to increase or reduce the amount of necessary light. Below the gazebo, there are some chairs, for people to meet and talk about science and biology.

The experience was particularly rewarding. The participants were happy to have been attending the workshop and left their contacts for being updated on further developments. Some students have hypothesized to research this topic in their theses. Others have experimented with rudimentary photobioreactors once they have returned home, to best cultivate the *Spirulina* that was given to them. The debate continued even after the workshop, on a dedicated WeChat group.

Table 8.5. Summary of the considerations on the workshop. Pros and cons marked with +/-.

Considerations	**+/-**
Successful event	+
Appreciated tasting session	+
Gained qualitative insights	+
Envision of PSSD	+
Lack of western participants	−

8.3.6 Considerations

The workshop was necessary and thus a particularly important step in the research: the goals that were set have been achieved. It was also a significant moment for research dissemination. Useful feedbacks were obtained from the participating professors but also from the students, who asked various smart questions.

Spirulina was proven to be a food with great potential, appreciated by almost all participants. The stereotypes that emerged from the survey and some previous fears were immediately overcome after having tasted it. It was possible to transform a not-so-common ingredient into foods with a more familiar appearance and taste. The participants will remember this tasting experience and, expectedly, will be willing to share their new perspectives with others. It is also hoped that some people could utilize the *Spirulina* inoculum that was donated to them, to scale up their microalgal production and to activating a sort of original micro-network of urban growers. This may be a bottom-up approach for educating and sharing knowledge with a wider public, somewhat similar to the Spiruliniers in France.

This first collaboration with 'Da Giuliano' bakery was fruitful. They were shown the positive results related to the palatability of the products, and the owner said that he would like to try selling some Spirulina-based food and drinks (G. Movio, personal communication, December 9, 2019). Their clients, mainly expatriates and middle-class Chinese, could be particularly interested in buying new, healthy baked goods made with natural ingredients. Moreover, the survey showed that the attendees would like to receive information about the environmental sustainability aspects related to the production of *Spirulina* (such as, for example, the levels of CO_2 removed), the health benefits, and its nutritional values. Numerous people would like to know more about new recipes and instructions for cooking. Future projects could, hence, allow users to know this easily.

Regarding the work of the participants, despite the widespread opinion that residential communities would not be interested in cultivating *Spirulina*, several groups have instead suggested solutions of this type. As many as 5 out of 9 proposals involve schools, universities, or residential communities, even with volunteering activities and engaging experiences. Most of these projects require the production of *Spirulina* for human food consumption, and only one is focused on cosmetics. Almost all the projects necessitate the use of electronic payments or a mobile application. One group's core mission is to teach children in schools, with dedicated science and biology lessons, and spaces where to grow and eat microalgae (Group 6). Group 7 instead is focused on designing new behaviors, by promoting healthy living and sustainable transportation. These two groups slightly differ from the others in terms of educational content.

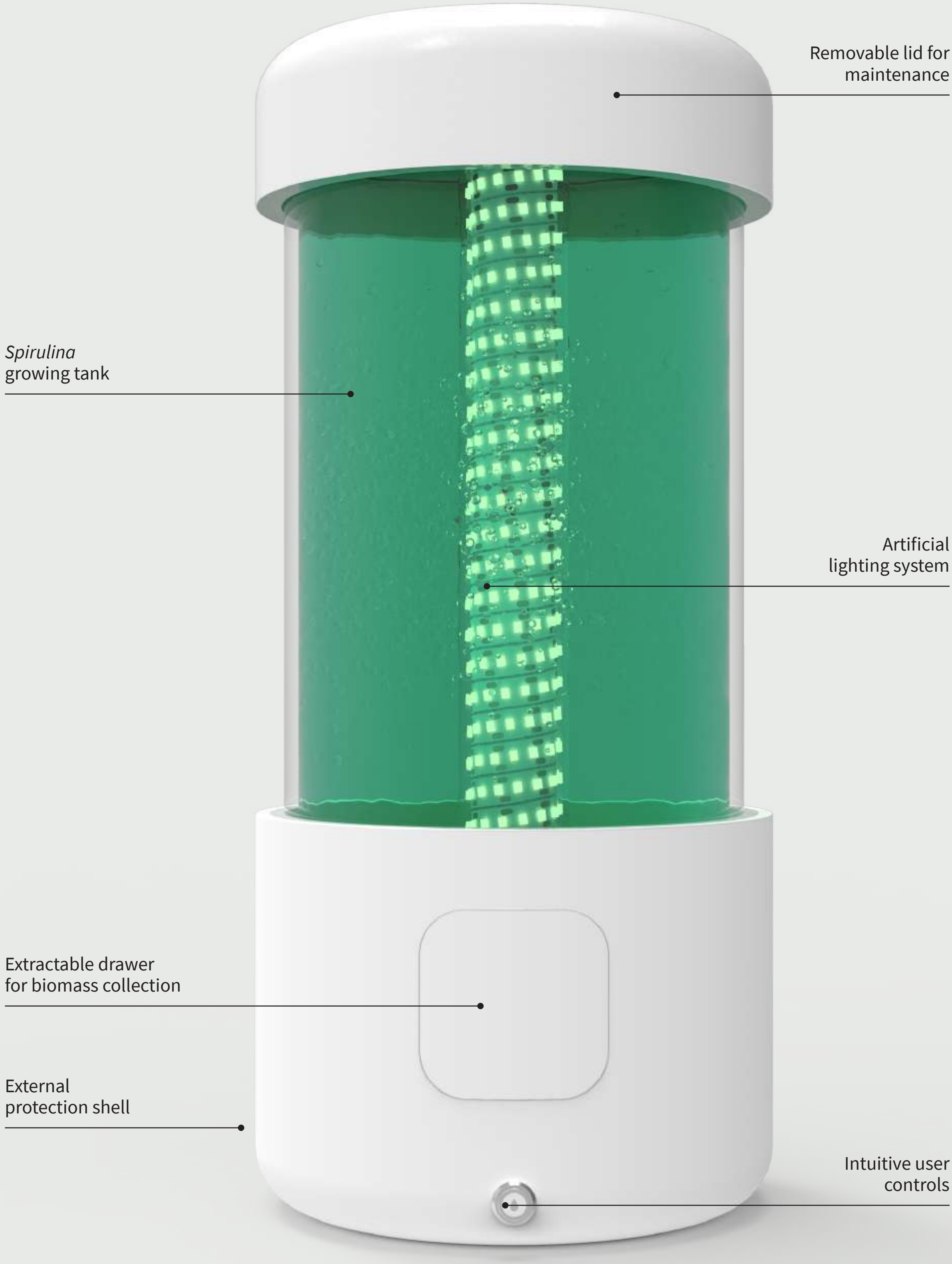
Given the cultural background of the participants, the ideas presented are strongly contextualized to a Chinese modern metropolis. However, some projects are more futuristic, while others are more likely to be implemented. The considerations made until now remain valid, given the fact that if the workshop was conducted elsewhere, it would probably have led to different results, albeit with similarities. A limit of the event was, unfortunately, the scarce participation of foreigners: only three participants from Italy, France, and Hungary attended.[24] The design output of this thesis is partly based also on the analysis of the results of the workshop and the work of the participants. Therefore, thanks to all those who participated and contributed, even indirectly, to the success of this event. Considerations are summed up in Table 8.5.

8.4 Product development

Product development is a salient step in the research process. This phase started in the first week of November 2019 – immediately after the analysis of the workshop results – and lasted until approximately mid-February 2020, with the tests and validations by users. The analysis and classification of the case studies, the results of the online survey, and the outcomes of the workshop were the starting points for the design: the already-implemented projects confirmed the existence of an audience interested in the use of Spirulina-production devices; the results of the survey were positive as they highlighted the willingness of the youngers to grow microalgae in a domestic environment; the innovative Product-Service Systems that were developed by the workshop participants included disparate stakeholders and, despite the initial skepticism about the involvement of communities, multiple groups suggested solutions that went in this direction.

For these reasons, the product development phase of this research includ-

24 The number was supposed to be higher to represent the percentile of foreigner survey respondents. However, several people declined the invitation shortly before the event for diverse reasons.


Removable lid for maintenance
Spirulina growing tank
Artificial lighting system
Extractable drawer for biomass collection
External protection shell
Intuitive user controls

ed the design of two distinct artifacts, namely the 'Algae Grower', a home-device which produces fresh *Spirulina* for personal and family use, and the 'Algae Station', a modular distributor of both fresh biomass and various Spirulina-based food products, which can be placed in public indoor and outdoor spaces. The two projects have multiple points in common, nonetheless, they cover different dimensional scales. The first device is designed to educate *Spirulina* daily consumption within the home, also stimulating the creation of new recipes. The second serves mainly as an aggregative fulcrum for a wider public, being an urban furnishing element in all respects. The complementarity of these projects allows spreading interest and different types of information on various levels, making knowledge of microalgae accessible to the masses. The products are not ending in themselves, but allow the activation of new use scenarios and sustainable business models that are suitable for an urban context, but not limited. These will be analyzed later.

Practice-based research has made it possible to create two products that modestly and partially bridge the limits of the previously-analyzed case studies, by verifying the first design hypotheses, drawing a theoretical framework and, above all, to define the design guidelines useful for those who want to pursue similar projects. However, the devices still have specific technical limitations, which deserve to be further explored. The next paragraphs document and analyze in detail the processes of product development, prototyping, testing, limits, and trace further considerations in this regard.

Figure 8.10 (Facing page).
Rendering of the Algae Grower, a home device for the production of fresh *Spirulina*.

8.5 The Algae Grower

The Algae Grower is a home device for the production and semi-automatic collection of fresh *Spirulina* (Fig. 8.10). This can produce about 5 grams of biomass per day in ideal conditions, which is enough to satisfy more than the needs of an average adult and/or that of a small family.[25] The device is intended to be used in the kitchen and is easy to operate thanks to the limited number of control buttons. The Algae Grower draws inspiration from existing projects such as Farma (paragraph 7.1.12) and Spirugrow (paragraph 7.1.17) and adopts the same working principle of a photobioreactor. Although the similarities may appear to be many, the device differs from them because of its contained dimension, the large surfaces that allow users to see *Spirulina* as it grows dense, and a few other characteristics. These differences are explained in detail in paragraph 8.5.9.

The *Spirulina* produced can be consumed fresh without further processing, ensuring high nutritional values. The surfaces of the device are easy to clean

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25 There are no fully-scientific recommendations for the daily intake of *Spirulina*, but 1 to 3 grams divided into doses are advised as standard, while up to 10 grams can be eaten for mass nutrition. It is recommended to have a balanced diet and multiple sources of nutrients, thus even lower quantities of *Spirulina* per day are enough.

and made with food contact materials (FCMs). The realization of the Algae Grower was done parallelly to that of the Algae Station. It was a fun project but decidedly demanding in terms of time and effort. During the process, it was possible to use various processing techniques, even in first person: among these 3D printing, saw cutting, CNC milling, and laser engraving. Most of the electronic components and materials used were purchased online on Taobao and tested empirically. The design was conducted together with Sun Yu-Chi, M.Sc. in Mechanical Engineering at Beijing Information Science & Technology University in Beijing (BISTU), and who was primarily responsible for the product engineering.[26] The Algae Grower is now a functional and working prototype.

8.5.1 Ideation phase

The ideation phase took a relatively longer time than the others, to conceive solutions that could best meet the needs of users. These solutions have been preliminarily compared taking into consideration a series of factors including:

- Main functions of the device;
- Fundamental components;
- General functioning scheme;
- Main dimensions;
- Amount of *Spirulina* to be produced;
- Use case scenarios.

The previous analysis of the design case studies was proven to be particularly useful as it allowed to immediately understand which could be the best technical solutions to be adopted. Numerous publications from the areas of engineering, biology, and chemistry were also helpful in this phase. The sketches in Fig. 8.11 show only some of the first design ideas. As you can see some of these are simpler, others more complex. Some are aimed at optimizing processes and energy consumption, others instead are aimed at guaranteeing a satisfactory and somehow familiar user experience. All these preliminary solutions include artificial light (in combination with the natural one) to control and maximize yields and are characterized by the use of tubular reactors, which are easier to clean rather than the regular tanks (the microalgae production experiment at home highlighted the difficulties in cleaning some surfaces of the aquarium, especially the corners).

As for the overall look, this was partly based on the preferences that emerged from the workshop. It was decided to use clean, modern and neat forms, similar to those of the products that can be found in present-day kitch-

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26 Prof. Liu Xin recommended Sun Yu-Chi as an outstanding young graduate passionate about industrial design and competent about mechanical and structural engineering.

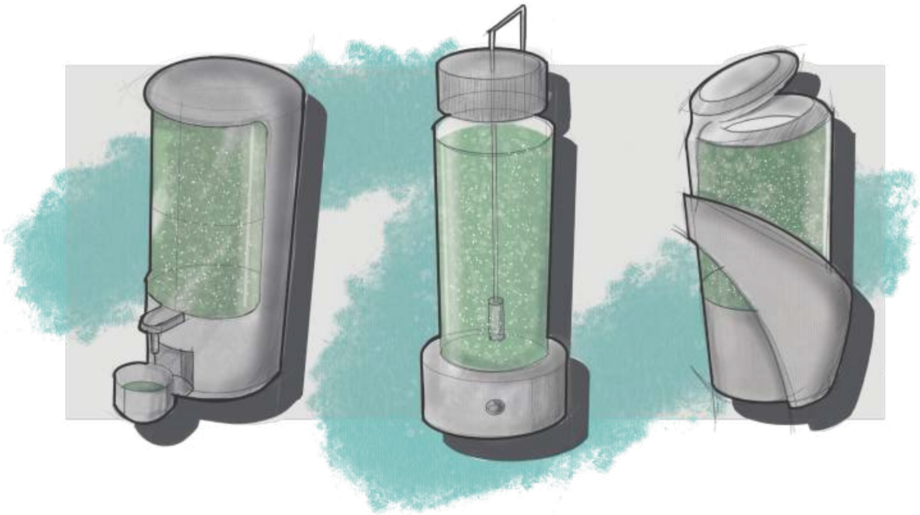


Figure 8.11. Preliminary sketches and first design ideas.

ens. The light colors convey a feeling of hygiene and cleanliness: stains and dirt are also more visible. The target audience for this product is young people accustomed to technology, who care about environmental issues and who prefer to eat healthy food. This type of user is not intended to be unique: in the design phase solutions that could also meet the needs of a wider audience were adopted. The ideation phase permitted to skim some ideas in favor of others. In the subsequent design phase, the product's use, operation, production, and environmental requirements were analyzed in detail, defining its features and shapes.

8.5.2 Definition of spatial context

The global market is full of household devices with different functions, users, and features. When it comes to home devices, however, it is good to understand which particular space they are meant for. The spaces inside the house change considerably among them: how they are lived, the moments in which they are used, the difference between intimate and shared spaces, and so on. A microwave oven or a blender is a small appliance with well-known functions, designed to be used mainly in the kitchen. In the same way, a design furnishing object (e.g., a table lamp, a chandelier) or an aquarium, perhaps find their place in the living room. On the other hand, a plant can be put almost everywhere.

An innovative device like the Algae Grower, without well-recognized functions by a large audience yet, needs to be contextualized and narrated. The device, which is pleasing to the eye, could be used as a mild green mood lamp, possibly in a living room. However, the intensity of the light would be insufficient to evenly illuminate the spaces or for certain tasks and would follow an alternating cycle not always aligned with the needs of the inhabitants (the production of microalgae requires to follow light-dark cycles as in nature).

Given the main purpose of the device – the production of biomass for food use – it was decided to contextualize it in the kitchen. The kitchen is a room that is lived by all the occupants of the house differently. It is also a space where people learn how to cook and get to know more about food culture. It is the place where other small appliances are usually placed including water boilers, juicers, rice-cookers, and other devices that are semantically similar to the Algae Grower. Studies have also demonstrated that usually in the kitchen there are higher levels of carbon dioxide and distinct pollutants, compared to other rooms, and these are harmful to health (Fluckiger, Seifert, Koller, & Monn, 2000; Lee, Li, & Ao, 2002; Parrott, Emmel, & Beamish, 2003). The microalgal production, releasing oxygen, would allow improving the air quality in this environment. The device is equipped with pumps for bubbling – necessary elements to facilitate the circulation and aeration of the water – and is quite silent. Nevertheless, the protracted noise could be disturbing for some, especially if positioned in other rooms such as the living room, the study room, or the bedroom. To maximize the photosynthetic activity, the inner light could also be turned on at night. The choice to place it in the kitchen is thus reasonable, as this space is rarely used after dinner.

8.5.3 Definition of users

As mentioned earlier in this chapter, the reference users for this project were defined using data collected through the online survey. The various responses of the surveyees were interpolated and from these, it emerged that young people are more interested in growing *Spirulina* at home than adults. Therefore, the target identified consists of young people aged 18-35 years old, well educated and conscious of environmental issues. Students or young professionals, they live in a big international city and have a propensity to try new foods. They have heterogeneous eating and purchasing habits, and most of them desire to improve their diets. Although attention is paid to this type of user, the device has universal design features that make it usable by everyone. The simplified user interface, characterized by a few buttons and limited interaction possibilities, makes it easy-to-control even by the children and the elderly, with due considerations.

Based on the identified target, the possible users of the Algae Grower (personas) were hypothesized. Personas are human archetypes, as well as representative models of specific users. Personas are effective and widespread tools in the collaborative design of products and services. Research has confirmed that with the support of this tool, practitioners and students were able to produce designs with superior usability characteristics (Long, 2009). Three personas have been hypothesized: among them a young employee, a dad who lives with his wife and young daughter, and an exchange student (Fig. 8.12). For each one, the age,the occupation, the interests, and the relationship they have with food – particularly with microalgae – are indicated. These personas represent only some of the potential users of the Algae Grower. The same ones will be used to explain the functions of the Algae Station and its related services. Bear in mind that these personas are immersed in the Chinese context: however given their characteristics, they could be also adapted to other western metropolises.

8.5.4 Conception phase

The conception is a research phase that involves the intellectual process of transforming an idea into a real-world product. During this phase, several meta-design aspects were taken into consideration, particularly:

- Feasibility: the general feasibility of the project both in terms of economic budget, and based on the professional and personal hard skills necessary to carry it out.
- Practicability: the duration of the visiting period, the production processes that can be done independently, and the suppliers which – alternatively – should be reached were taken into consideration.
- Product functions: compared to the ideation stage, where the main characteristics were just drafted, this phase went into detail with a comprehensive and precise analysis.

A so-called 'requirement chart' was drawn up. The requirement-performance analysis consists of interpreting the needs of the users into technical features. Defining these needs is of fundamental importance as it allows designers to take objective decisions related to technical, but also stylistic and semantic

Figure 8.12. Su, Wang, and Magda, three potential users of the Algae Grower and the Algae Station.

Su, the young accountant

26 years old, Female
Chinese, Beijing

Recently graduated, working as account manager in a private company. She enjoys eating meat, and going shopping with her friends. Has a boyfriend and not a lot of free time.

"My diet is not good and I want to eat more fresh and sustainable food. Microalgae are a great solution!"

Wang, the creative

32 years old, Male,
American-born Chinese, Shanghai

Freelance photographer and graphic designer. Loves to share food pictures on social media. He is a tech-addict. Lives with his wife and daughter and has a flexible working schedule.

"This is the food of the future! It is cool to produce at home and my followers enjoy to see my posts!"

Magda, the exchange student

23 years old, Female
French, Beijing

Exchange student in engineering. Vegetarian since many years, loves to go to the gym and practice yoga. She is single and has a very detailed time schedule

"All my classmates are very interested in my Spirulina culture. We sometimes eat it fresh together!"

Table 8.6 (Facing page). The requirement chart of the Algae Grower.

aspects of the project. The design theories of Ciribini[27] (1995), Italian academician and professor Emeritus of Technology of Architecture, were observed.

The requirement chart (Table 8.6) is structured according to requirements for use, operation requirements, production requirements, and environmental requirements. For each of these sections, the user needs are highlighted, to which the object responds with specific performances. As for the requirements of use, the Algae Grower guarantees sufficient yields, ensuring the freshness of the biomass. Its solid structure is visibly light to the sight and is made of materials with a familiar look. The product is also easy to operate, therefore disassemblable in its parts, and easily washable. Particular attention is also paid to the total weight of the device, its ergonomics, and the user control interface.

Regarding the production of the prototype, this takes into consideration the use of hygienic materials in contact with food (FCMs). There are distinct sections for water pipes and electrical components, to avoid eventual water leaking and guarantee high safety standards. These principles are particularly valid for eventual mass production, in which the simplicity of the manufacturing processes also allows to lower the total cost of the device. The product takes into account environmental factors. Long-term resistant materials are used, as well as parts that are easy to replace if broken, recycled materials, and low-energy consumption components. Trouble-free end-of-life disposal is facilitated. The prototype meets this list of requirements, albeit with small limitations. These will be filled when – and if – the device undergoes a mass-production.

8.5.5 Development phase

The development phase was characterized by diverse empirical endeavors, practical experiments and unconventional hands-on, aimed at ensuring that the product performances were best met (Fig. 8.13). The main components for the device were researched, including air pump, water pump, harvesting net, water pipes, water joints, LED, and glass pipes: the selected components were purchased online. Subsequently – and considering the necessity of keeping the overall dimensions contained – detailed technical drawings were produced using professional 3D modeling software (Rhinoceros, AutoCAD). The parts were tested to verify the tolerances and the correct functioning of the moving elements. If problems were found, the pieces were modified accordingly or re-engineered from scratch.

It took more than two months to complete the final prototype of the Algae

27 Giuseppe Ciribini is considered the Italian father of the discipline of architectural technology. After World War II, Ciribini taught at Politecnico di Milano and Politecnico di Torino.

	Requirements	Performances
Requirements for use	Safe	No sharp surfaces
		No water leakage
		Stable structure with solid joints
	Simple	Elementary to control (limited number of buttons)
		Use of few colors and materials
		Easy to harvest
	Productive	Guarantee enough yields
		Assure freshness
	Light	See-through feeling
		Balanced contrast between functional parts
	Multifunctional	Use both for growing and harvesting
		Mood light
		Air cleaning
	Ergonomic	Easy to handle, nice feeling while touched
	Intuitive	Limited operation buttons
		Easy to understand the main function
	Pleasant	Harmonious shapes
		Premium feeling
	Contextualized	Familiar look
		Ordinary materials
	Connected	IoT features
Operation requirements	Disassemblable	Simple to separe into parts
	Washable	Clear or light materials without rough surfaces
		Proper dimensioning to facilitate cleaning
	Reliable	Correct and immediate operational feedbacks
		Well balanced configuration
	Repairable	Easy to fix even single components, standardized and strong parts
	Handy	Easy to fill and remove the water
		Effortless to grab
Production requirements	Safe	Use of higienic food contact materials
		Compliance with electrical high safety standards
	Simple	Use of basic production techniques and pieces of machinery
	Economic	Cheap to manufacture in small and large-scale productions
		Possibility of distributed manufacturing
	Replicable	Use of standardized manufacturing techniques
Environmental requirements	Efficient	Low energy consumption
	Ethical	Use of non-polluting materials and processes
		Safe-for-health product and outcomes
	Durable	Long-lasting and strong, hard to damage materials
	Dismantlable	Trouble-free end-of-life product disposal
	Recyclable	Use of reusable and recyclable materials

Fig. 8.13.1

Fig. 8.13.2

Fig. 8.13.3

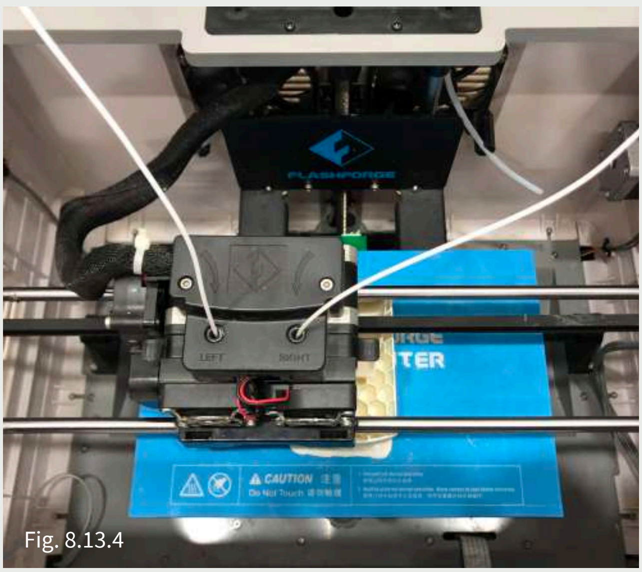


Fig. 8.13.4

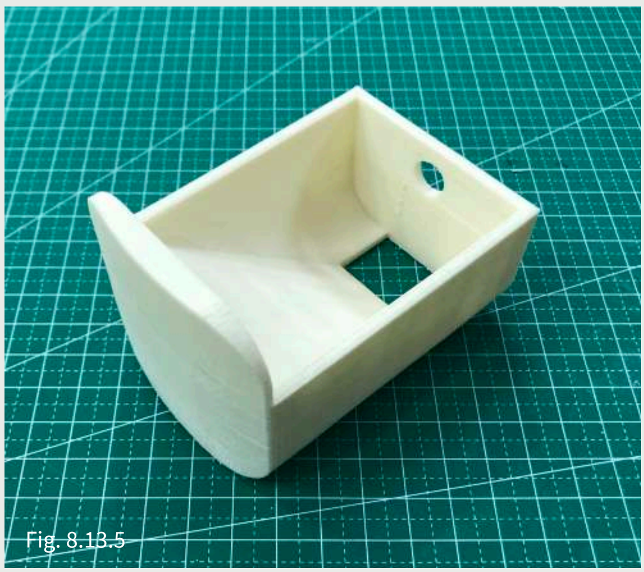


Fig. 8.13.5

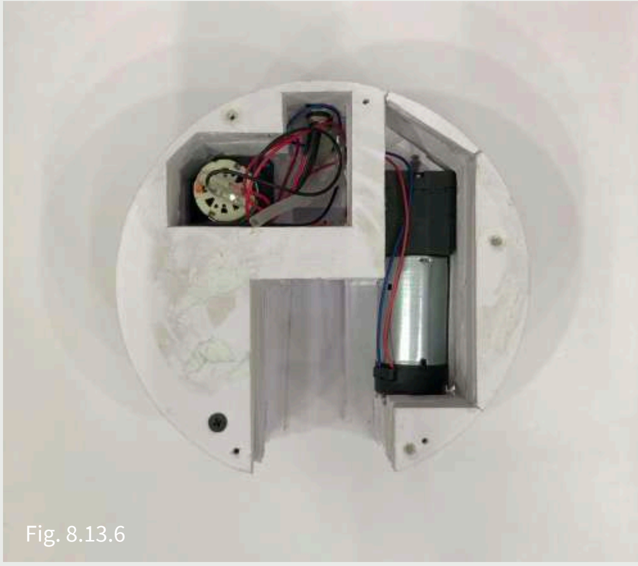


Fig. 8.13.6

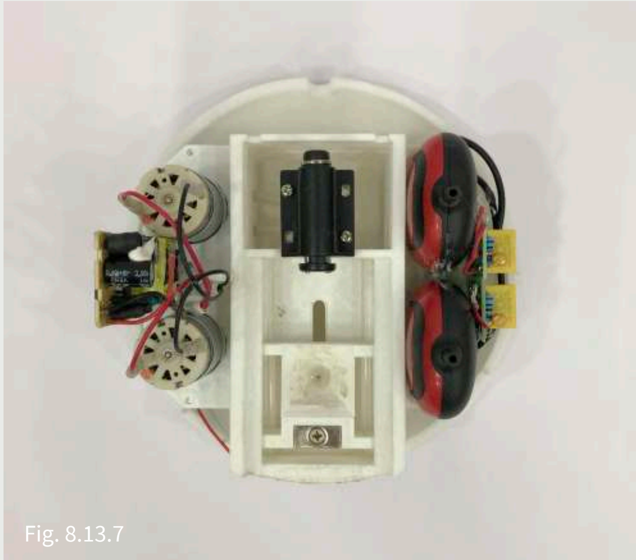


Fig. 8.13.7

Fig. 8.13.8

Fig. 8.13.9

Figure 8.13. Diverse empirical endeavors, practical experiments and unconventional hands-on during the product development phase.

1. Nozzle water outlet test;
2. Lighting and bubbling test;
3. Shaping and dimensioning of the top body;
4. 3D printing of some internal parts;
5. A preliminary version of the harvesting drawer;
6. The arrangement of the internal components of the first version of the Algae Grower 1.0;
7. The arrangement of the internal components of the Algae Grower 2.0;
8. Assembly of the Algae Grower 2.0;
9. The high-fidelity prototype under construction at Beijing Hongfan Ruihe Technology Co., Ltd. (more pictures in the Appendix).

Grower. Multiple production techniques were used and three distinct models were built, each with different characteristics and incremental levels of detail. The first two models – still imperfect and under construction – were tested in their functions and shown for the first time to a group of professors and design students at THU at the end of December 2019. The students were very curious and asked several questions mainly about the operational requirements. Qualitative feedback related to ergonomics and usability was also received, which was useful for the improvement of the project. The next paragraph describes and compares the first two versions. A dedicated paragraph illustrates the characteristics of the final functional prototype, including a detailed list of the components that were used.

8.5.6 Algae Grower 1.0 and 2.0

The practice-based research permitted to experiment with different production techniques by putting them into practice: it was, therefore, a particularly enjoyable and engaging stage of the research. However, the design process was not linear but required several corrections during its course. For this reason, two prototypes were made (Fig. 8.14), before the final version.

Version 1.0 is visually rougher. It is made up of PVC layers that have been cut by hand or with a hole saw. PVC is a versatile, rigid, durable and inexpensive material, ideal for prototyping. The choice to work with multiple overlapping levels was dictated by the characteristics of the material (0.5 and 1.5 cm thick panels were used), and the necessity of quickly make small extemporary modifications (holes for the buttons, grooves for the cables, etc.). The PVC layers were screwed or glued together. As for the internal components, this version included a considerably powerful air pump[28], to guarantee high bubbling density. To obtain a pleasing effect, the use of an aquarium stone air diffuser was initially envisaged. The air pump, however, proved to be decidedly noisy and oversized, therefore not suitable for a home device. Concerning the biomass harvest system, only one pump was utilized. The initial solution exploited gravity rather than a second pump, to collect fresh *Spirulina* in an extractable front drawer. However, this layout was not optimal as it would have required the use of highly resistant gaskets, which would have hindered the opening of the drawer. The upper part of the device has not been particularly taken into consideration in this version, along with the lighting system. This prototype has obvious limitations: the following version, which is much more similar to the final one, fills these gaps.

Version 2.0 has a much higher level of detail, and the internal and external structures were completely redesigned. 3D printing was used to prototype them quickly. The air pump has been changed in favor of two smaller and quieter

28 High pressure miniature air pump mod. THOUSAND MERCURY 12V550.

Figure 8.14.
The Algae Grower 1.0 (left) and 2.0 (right).

ones; the resulting free space permitted to add one more water pump, therefore improving the *Spirulina* extraction system. A front button was also added to activate the pump. The internal structure was divided into distinct spaces for electrical components and for water pipes, to avoid possible short-circuits. In this phase, an already assembled LED lamp with a matte surface finish was used for lighting. The lamp was placed inside a transparent tubular profile in the center of the photobioreactor. Although the lighting effect was pleasant, the intensity seemed not to be sufficient to ensure maximum illumination of the culture. The top of the device has been improved too: a small removable lid was designed to allow the addition of nutrients and facilitate the inspection, without the need to raise the top cover.

The device is still imperfect in some parts (e.g., surface finishes). The 3D printed structure proved to be more solid than expected but this technique would not be adequate in case of mass-production. Despite these small details that may deserve further improvements, the Algae Grower 2.0 is a fully-functional prototype.

8.5.7 High-fidelity prototype

This final prototype is characterized by premium finishes and a high level of engineering. For the production of the structure, the technical drawings were provided to a small local factory.[29] The structure is in ABS, an easy-machined,

29 Beijing Hongfan Ruihe Technology Co., Ltd. located in Beijing, Chaoyang district, Jinzhan Village Industrial Park. The factory has been collaborating with THU – Department of Industrial Design on several projects.

high-impact strength, and low-cost rigid plastic material. The ABS was CNC milled and coated with a washable, water-resistant white paint. The structure is composed of:

- An upper cover to protect the culture from external contamination and minimize evaporation, on which the Algae Grower logo is silkscreened. The lid also includes a small removable cap for routine operations;
- A support base for the tank, perforated in some points to allow the passage of water and air;
- The supports for the internal components (air and water pumps, electric boards, etc.). This part consists of 5 different pieces, connected by interlocking. It also holds the drawer for *Spirulina* collection;
- The drawer, which can be split into parts, and its track slides;
- The outer shell of the lower main body, with openings for the buttons and the drawer.

As for the other components, this prototype includes:

- n. 1 high-quality transparent acrylic tube with external diameter 160 mm, length 250 mm, thickness 5 mm;
- n. 1 high-quality transparent acrylic tube with external diameter mm 35, length mm 270, thickness mm 2;
- n. 1 matte white PVC tube with external diameter 25 mm, length 280 mm, thickness 1.5 mm;
- n. 1 warm white adhesive LED strip (18W/m), around 2 m;
- n. 2 12W peristaltic water pumps suitable for food use (mod. KAMOER NK-PDCS10);
- n. 2 1.5W ultra-quiet aeration pumps (mod. SUNSUN QB-104B);
- n. 3 one-way check valves for water and air pumps;
- n. 4 quick-screw pipe connectors (straight-through and T-type);
- n. 1 magnetic buckle 48-58 mm stroke (mod. QUFEN 156484486389635);
- n. 2 high-quality transparent acrylic rods with diameter 5 mm, length 94 mm;
- n. 4 electric boards (1 for the LED strip, 1 for the peristaltic water pumps, and 2 for the aeration pumps);
- n. 3 self-locking waterproof metal button switchers (mod. RONGYUHUAFU 2016010305922942);
- n. 1 DC power plug socket connector (mod. TELESKY DC-099);
- n. 3 high-strength neodymium magnets with M5 screw hole;
- n. 1 nylon mesh filter cloth (38/106μm mesh);
- n. 1 silicone gasket (2 mm thick);
- Various M5 screws and bolts;
- Various soft plastic waterlines and airlines (diameter 5 mm);
- Various cabling and electric connectors.

The axonometric exploded view in Figure 8.15 shows all the components. The total cost of the parts purchased online is approximately ¥ 800.00 (around € 105.00). The factory manufacturing of the structure costs ¥ 4,500.00 (around € 590.00).

The multiple efforts and the countless hours of work have made it possible to create a rather simple and intuitive device, despite the technical complexity. The tank has a volume of 4 l. Its tubular shape ensures a good recirculation of air and water flows – uniformly moving the culture – and allows easy cleaning of the surfaces, both external and internal. This solution, as already seen in the first part of the thesis, is commonly adopted in the design of photobioreactors. For the pipes, the acrylic was chosen over the glass (that offers better quality and guarantees a high refractive index) because it is a cheaper and more resistant material. The lighting of the culture is provided by an LED strip wrapped on a tube and placed in the middle of the tank. This positioning allows for uniform illumination. The top cover protects from possible external contaminations (e.g., dust). For quick inspections, such as checking the density of the culture with a Secchi stick or for adding nutrients, it is possible to use a special cap, without the need to lift the whole lid. The two air pumps provide a regular flow of oxygen and CO_2, fostering the growth of microalgae. A water pump allows the extraction of fresh biomass from the tank, which is collected in a drawer located underneath. The second pump operates simultaneously, but with an inverse flow enabling the filtered water – still rich in nutrients – to get back into the tank. The front drawer is composed of several parts for an effortless replacement – in case of damage – of the filter cloth. The drawer is entirely removable from the main body, for comprehensive cleaning. The functions of the prototype can be controlled just with three switches. The front one is for operating the water pumps to collect *Spirulina*. The rear buttons are for switching the lighting and the air system on and off. On the back, there is also the power socket. To facilitate the understanding of the buttons, flat design icons are laser engraved on them.

The overall size of the device is 40 cm high by 18 cm wide. Fig. 8.16 shows the main dimensions and sections of the product. It is estimated that the device can produce, under ideal conditions, approximately 5 grams of fresh biomass per day. The design of this device responds well to the characteristics that, according to most of the survey respondents and workshop participants, a *Spirulina* home-production device should have: functionality, safety, ease of use and maintenance, aesthetic (Fig. 8.17). Detailed pictures of the prototyoe can be found in the Appendix: The Algae Grower – High-fidelity prototype.

8.5.8 Validation tests

The validation tests of the Algae Grower were conducted from 5 June to 25

Figure 8.17. The characteristics that a *Spirulina* home-production device should have, according to the 504 respondents of the survey. Multiple choices, ordered by importance.

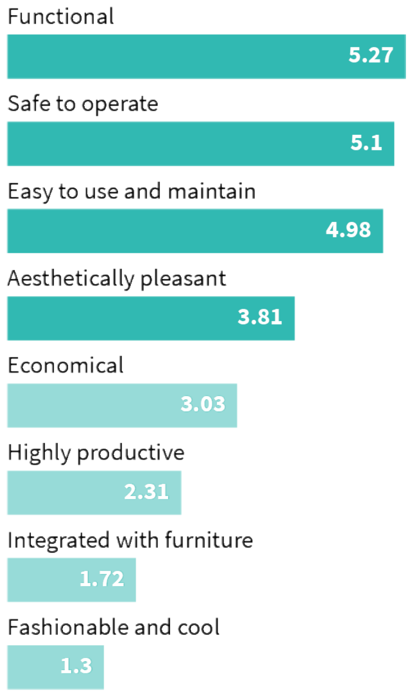
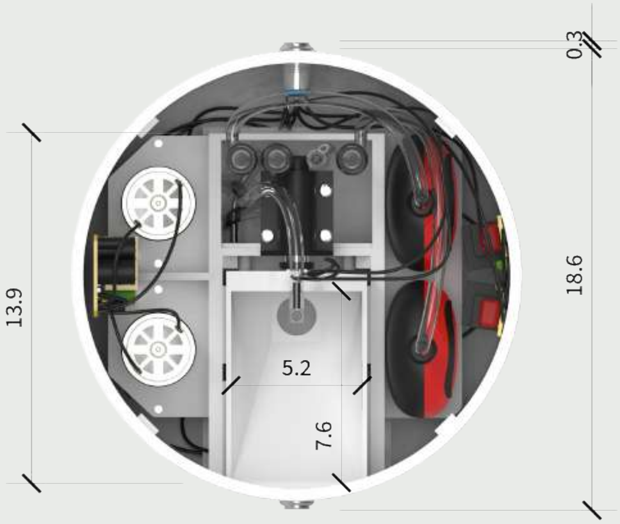
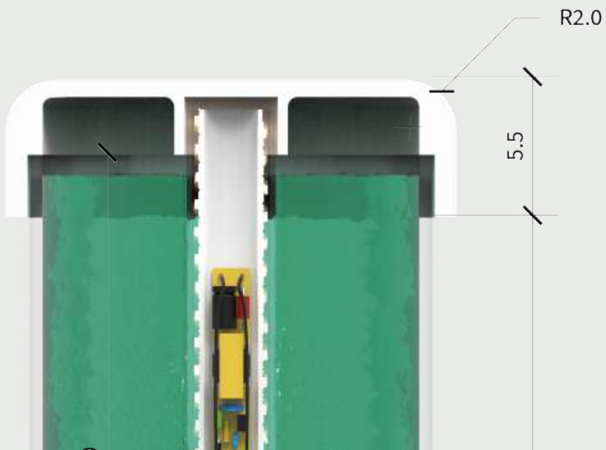


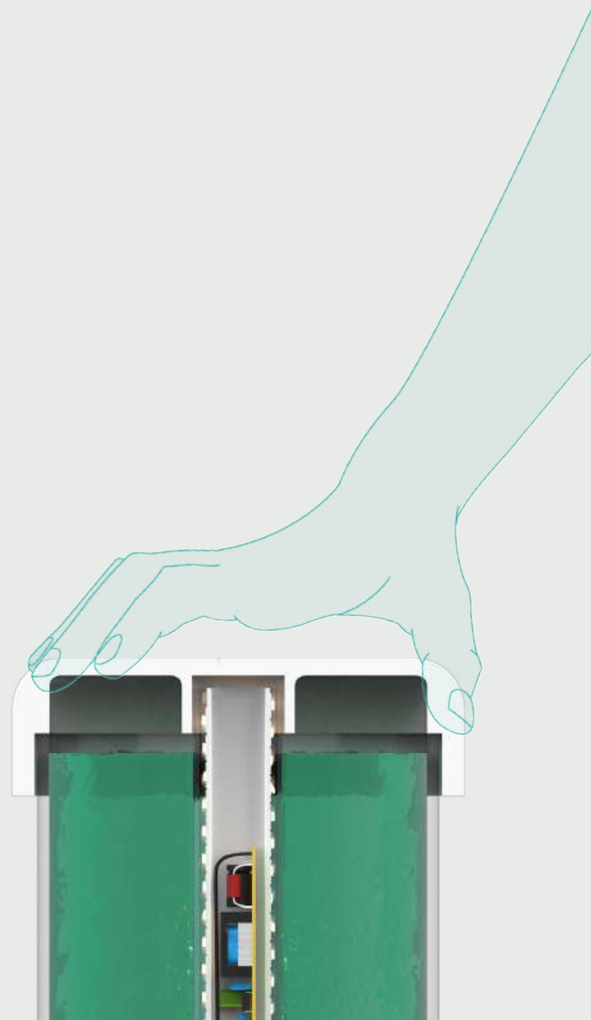
Figure 8.16. Front, back, top views and sections of the Algae Grower.

SCALE 1:3
Quotes in cm



SECTION B-B’





SECTION A-A’

SECTION C-C’

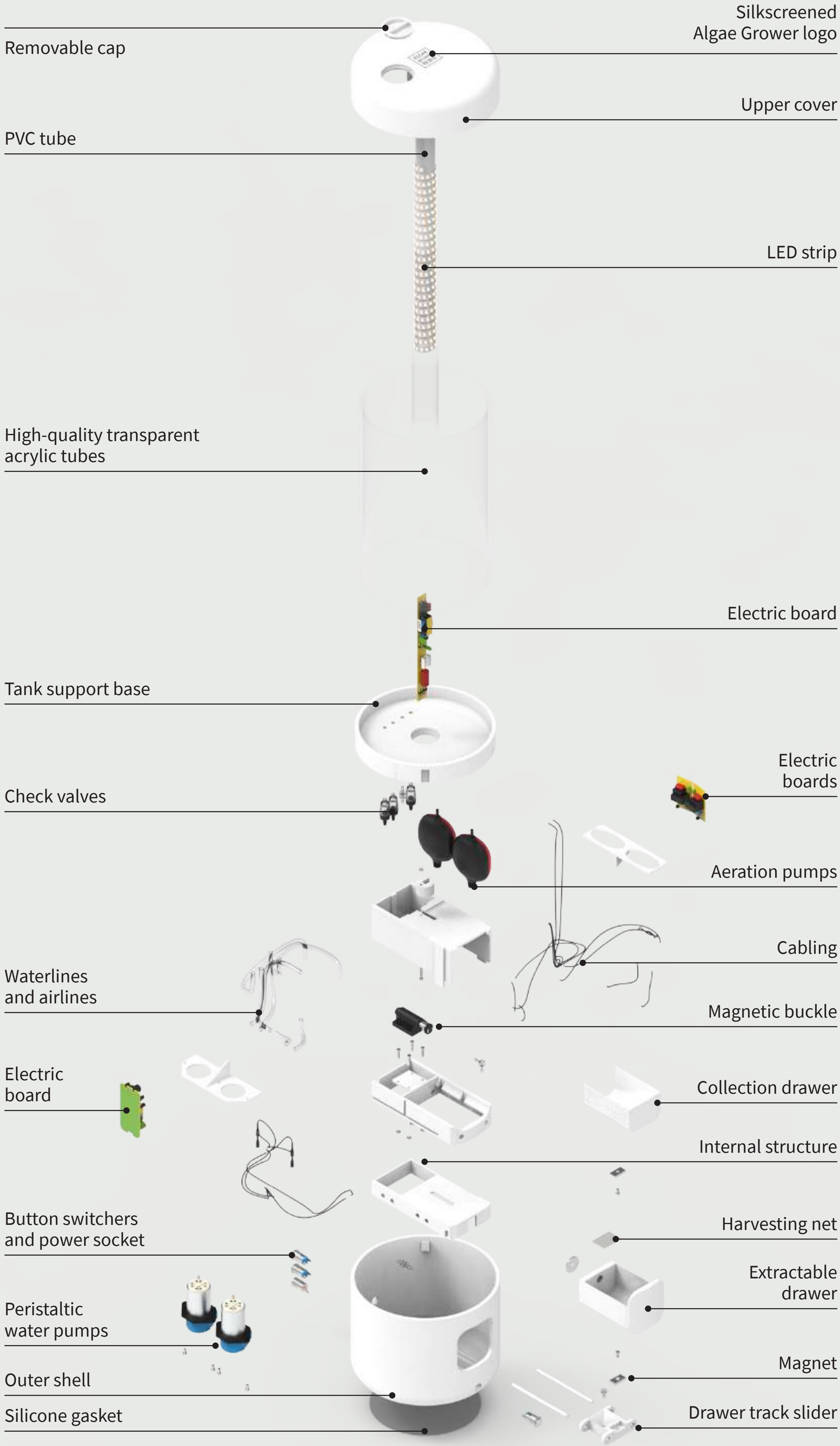

Removable cap
Silkscreened Algae Grower logo
Upper cover
PVC tube
LED strip
High-quality transparent acrylic tubes
Electric board
Tank support base
Electric boards
Check valves
Aeration pumps
Cabling
Waterlines and airlines
Magnetic buckle
Electric board
Collection drawer
Internal structure
Button switchers and power socket
Harvesting net
Extractable drawer
Peristaltic water pumps
Magnet
Outer shell
Drawer track slider
Silicone gasket

Figure 8.15 (Facing page). Axonometric exploded view of the Algae Grower.

June 2020.[30] The purpose of this phase is to validate the results of the product experimentation and verifying the effectiveness of the device itself. The main objectives are:

- Test all the functions of the Algae Grower;
- Verify the ability of the device to produce and collect fresh biomass, with the expected methods and quantities;
- Check that the digital and mechanical components of the device work correctly in normal daily operations;
- Gaining user interaction feedbacks;
- Evaluate the overall user experience; Identify limits and possible improvements.

The first test that has been carried out consisted of growing and harvesting *Spirulina* in the high-fidelity prototype, and it took 21 days. The test simulates a hypothetical real-word daily use. The device was placed in a domestic environment, away from direct sources of intense sunlight to avoid photo-saturation and compromise the reliability of the experiment. An attempt was made to keep the lighting and bubbling cycles constant throughout all the test period (it has been assumed that around 4 hours each day would ensure sufficient time for the culture to thrive). The same goes for temperature. Daily variations indicate the authenticity of the test and reflect what could happen if an 'amateur' uses the device.[31] The tank was filled with 4 liters of Nongfu Spring water, including the alive *Spirulina* inoculum (the same high-quality *Spirulina* strain utilized for the workshop – see paragraph 8.3.3). The parameters of illumination and bubbling time, temperature, pH, evaporation, culture density, amount of *Spirulina* harvested were checked daily.[32] Data are available in Table 8.7. On day 11, the optimal culture density was achieved (around 100% culture density), and *Spirulina* was ready to be harvested. A culture is thick when the

30 The test phase was scheduled earlier. The delay in the production of the prototype due to the COVID-19 pandemic implied modest changes in the test modalities. Preliminarily, it was hypothesized to carry out an engaging test session in February 2020 in Beijing with about 10 participants (selected by age, food habits, propensity to try new recipes). They would have been required to interact with the device, providing qualitative feedback. A second part of the event would have included the preparation of simple Spirulina-based recipes, made by the participants. Thanks to Sun Yu-Chi for helping in the coordination of the tests remotely.

31 The initial design could not take into account the heat dissipation of the LED strip. Prolonged use of the device caused the transformer circuit board to overheat, and the LED to turn off automatically. Therefore, the lighting time in the first five days is notably less, as well as the temperature and the consequent growth rate. On Day 6, the 24W transformer was replaced with a 60W transformer to carry more power and heat.

32 A ruler was applied to the external surface of the tank to monitor evaporation. Evaporation level on day 1 is 0 mm. Water was refilled daily. The density was measured with a Secchi stick. The data in Table 7.7 refer to the visible millimeters on the ruler: an 80% dense culture shows about 13 mm, while a 100% culture shows about 8 mm.

Day	Illumination	Bubbling	Temperature	pH	Density	Evaporation	Harvests
1	1h 20 mins	4h	29.8 °C	10.4	33 mm	1 mm	-
2	1h 20 mins	4h	28.7 °C	10.5	33 mm	1 mm	-
3	1h 20 mins	4h	27.5 °C	10.4	32 mm	1 mm	-
4	1h 20 mins	4h	29.7 °C	10.2	29 mm	1 mm	-
5	1h 20 mins	4h	27.6 °C	10.6	27 mm	1 mm	-
6	6h	6h	37.3 °C	10.4	25 mm	2 mm	-
7	6h	6h	37.5 °C	10.8	18 mm	1 mm	-
8	6h	6h	37.4 °C	10.8	13 mm	2 mm	-
9	6h	6h	37.6 °C	11.0	10 mm	2 mm	-
10	4h	4h	37.2 °C	11.1	9 mm	1 mm	-
11	4h	4h	37.1 °C	11.3	8 mm	1 mm	-
12	4h	4h	37.3 °C	11.1	4 mm	2 mm	5.2 g
13	4h	4h	37.4 °C	11.2	3 mm	1 mm	5.3 g
14	4h	4h	37.2 °C	10.9	4 mm	2 mm	5.0 g
15	6h	6h	37.8 °C	10.8	4 mm	1 mm	5.7 g
16	6h	6h	37.9 °C	11.1	5 mm	1 mm	5.3 g
17	6h	6h	37.7 °C	11.2	4 mm	2 mm	5.5 g
18	6h	6h	37.5 °C	11.1	5 mm	1 mm	5.2 g
19	6h	6h	37.8 °C	11.1	4 mm	2 mm	5.2 g
20	6h	6h	37.7 °C	11.1	5 mm	1 mm	5.0 g
21	6h	6h	37.5 °C	11.1	5 mm	1 mm	5.7 g

Table 8.7. The Algae Grower: daily parameters collected during the growing and harvesting test.

color becomes a dark green, and visibility is poor. With that density, even the LED light inside the tank is difficult to see from the outside. From day 12 and for the following 10 days, about 5 g of fresh biomass was collected every day.

This test showed that the device is capable of producing a modest amount of *Spirulina* daily, as expected. By keeping the values of light, bubbling, temperature, and pH constant and in the right ranges, it is possible to have a self-sustaining production. The *Spirulina* culture had no external contamination, and it should be safe for food use. The water evaporation was minimal; nevertheless, with more prolonged use of the device, it may be necessary to add a little water from time to time. A higher temperature could have ensured greater yields; however, this prototype does not have a heater. The test was instrumental in confirming the device's potential.[33] It would have been appropriate to test the device for a more extended period – perhaps more than 30 days. Due to logistical reasons, this was not possible.

33 A control culture was set up with the same ambient temperature and light. After 21 days, the growth of the two cultures was significantly different. The *Spirulina* coming from the Algae Grower showed a density of 5 mm, while the control culture showed 29 mm. The control culture was almost unchanged.

The second test was conducted simultaneously with the first one. This test aims at highlighting technical problems arising from the regular use of the device. It focuses on the product's structure durability, mechanism, and functions, taking into consideration all its components: outer shell, LED strip, electric boards, check valves, aeration pumps, water pumps, waterlines, airlines, cabling, drawer, harvesting net, buttons, connections, and power socket. The eventual problems encountered, and the solutions adopted (or possible) for each component are sum up in Table 8.8.

In this prototype, the structure turned out to be pretty solid and had no particular issues. The electric system, electric boards, buttons, and power socket worked correctly throughout the test. Despite intense use, air pumps never overheated, but the transformer of the LED strip needed to be replaced with a more powerful one. The heat also caused the inner acrylic tube to crack slightly, but this was not a big issue. A critical factor in the design phase was the possibility that there could be water leaks. The glue used has held up very well: nevertheless, in eventual mass-production, particular attention must be paid to waterproof junctions. No relevant problems with the airlines were encountered. Instead, waterlines tended to accumulate *Spirulina* in some sections, especially in the pipe that releases the biomass. *Spirulina* may dry out in pipes, but this is not a severe problem if *Spirulina* is collected daily. In case of non-use for a lengthy time, it would be advisable to fill the tank only with water and let it get out from the pipe, in order to eliminate excess jammed *Spirulina*. Other connections and joints, including the drawer and the harvesting system, have worked as expected.

The results of this test are particularly encouraging because they demonstrate the functionality, reliability, and safety of the Algae Grower, three important factors from the users' perspective, and that were taken into consideration in the design phase. The apparent limitations of this prototype can be overcome in the future.

The third – and last – validation test addresses usability issues and collects qualitative perceptive and psychological/cognitive data. User testing of the high-fidelity prototype assures that the design is in the right direction. Five people – at different times – were involved in the test. Among them, three are target female and male users aged 18-35, mainly students or young professionals, and two are extreme users: a teenager, and a senior lady.[34] Since the Algae Grower is an object to be utilized at home, they are also two likely users. The test was rather informal and lasted around 20-30 minutes per person. Before the test, participants were informed that they would use a proto-

34 Engaging with extreme users is a design methodology to represent edge case uses. Typically, extreme users perform activities differently from average users. Their involvement highlights some usability aspects to make the design more inclusive.

Table 8.8. The Algae Grower: problems encountered and solutions adopted during the technical test.

Element	Problem	Solution
Outer shell	-	-
LED strip	Overheat if used for a prolonged time, causing the circuit board not to work correctly	Replace it with a more performing transformer
Acrylic tubes	The difference in temperature inside and outside the acrylic tube may cause it to crack	Replace with glass tubes and eventually increase their thickness
Electric boards	-	-
Check valves	-	-
Aeration pumps	-	-
Water pumps	-	-
Waterlines	Dry *Spirulina* residues in the water lines if the device is not used for some time	Clean the lines periodically by letting water flow inside them
Airlines	The heavy tank can pinch the airlines and influence the airflow	Shorten the airlines and assemble with care
Cabling	-	-
Drawer	The lower part of the drawer is not perfectly sealed	Add silicone and improve the quality of the prototype
Harvesting net	Liquid and biomass can get stuck	Increase the dimension of the hole
Buttons	-	-
Power socket	-	-

Figure 8.18. A participant interacts with the high-fidelity prototype of the Algae Grower during the user validation test.

type and that some functions would be limited (e.g., temperature control and heater). The test was moderated: participants were not alone interacting with the product, so they could ask questions and receive immediate feedback and explanations from the moderator. The main uses of the product were briefly described: attendees then had time to spontaneously interact with the device (Fig. 8.18). Participants were asked a few open-ended questions, and the moderator took notes on user behavior and non-verbal cues. The open questions can be found in the Appendix: The Algae Grower – User validation test (Open questions).

The testers' answers/considerations – the most noteworthy ones – are summarized in Table 8.9. The interviewees generally believed that the product's design matches its purpose. However, almost all users found it counter-intuitive to open the front drawer for three main reasons: the opening mode is not clearly indicated; the harvesting button could be mistaken for the opening button; the drawer is a little hard to press. A transparent drawer could also help in providing feedback on the harvesting status. The youngsters used the device effortlessly because it reminded them of a tech device (e.g., Bluetooth speaker), and even the most senior users had no particular problems. Everyone has particularly appreciated the icons engraved on the front and back buttons, but they may be too small to see for some. The behavioral observation shows that it would be advisable to provide simple instructions to tell users how to grow, take care, and collect *Spirulina* properly, since this device may have a hidden affordance.[35] Generally speaking, the test confirmed that the insights from prototyping worked out the way expected, and provided useful information on how to improve user experience. All the participants

35 Affordance is a term coined by psychologist James Gibson as an approach to perception. Donald Norman suggested in the late 1980s that design discipline could take advantage of it. Unlike a pair of scissors, whose design is simple and the function is evident, the Algae Grower is a more complex product and, therefore, requires greater cognitive effort to be fully understood.

Question	Noteworthy considerations
#4	Some marks to check the water level on the tank would be convenient. Not sure if the small removable cap is very useful.
#5	If the drawer is transparent I can see the harvesting process.
#6	I like it! It reminds me of my Bluetooth speaker!
#8	The icons on the buttons are too small and hard to see for some.
#11	I will recommend this product to a friend.
#12	It is very easy to operate. This is an ornamental, practical, and innovative farming device.
#13	I am bit worried that the water could touch the electric components. The buttons on the back are a bit hard to operate.

Table 8.9. Noteworthy considerations regarding the usability issues of the Algae Grower. Answers from the testers.

would recommend this product to a friend or a relative. Further considerations can be done on the back buttons' position and the insulation of the electric components.

8.5.9 Product comparison

As mentioned, the Algae Grower draws inspiration from other products. However, The Algae Grower stands out for its small size, good usability and maintainability, and high educational value. Also, unlike other goods designed for commercial use, the Algae Grower blueprint and parts list have been made available online for free. Thanks to this operation and from an open-source perspective, it is possible to replicate the device and spread its use.

Table 8.10 shows an accurate comparison of the Algae Grower with selected products, namely: Algae Curtain, Eco-friendly Lamp, Living Things, Farma, Spirugrow, Symbiont, and The Coral. These seven products were chosen from the 20 innovative small-scale solutions previously analyzed in chapter 7.1 – Design experimentations. The selected products fall within the sphere of product/furniture design and are made for domestic use. All these devices have a modest biomass production capacity and are semantically similar to the Algae Grower. It should be noted that the Algae Grower does not compete commercially with other products in a particular market niche but works in a complementary manner. Different product features were taken into consideration to provide an objective comparison. Some features have been quantified on a scale of 1-4, where 1 is generally very poor, while 4 is very good.

- Main scope: The primary function of the device;
- Dimensions: The physical dimensions of the product, ranging from contained to substantial where 1=substantial and 4=contained;
- PBR shape: The shape of the production tank (flat-panel, tubular, tank, etc.);
- Production system: Whether the system is open or closed;
- Harvesting system: Typology and mechanism of the harvesting system;
- Productivity: Not in absolute value but the relative amount of biomass produced in a given timeframe;
- Usability: Ease of use and if the product has a good user interface. Usability also refers to whether the product has high-grade performances and functionalities;
- Maintainability: If the product can perform for a designated period with minimum maintenance, or if the maintenance operations are easy to accomplish (e.g., cleaning the tank);
- Cost-effectiveness: The production/manufacturing/replicability price given the biomass productivity;
- Open-source: Whether the project is available in open-source collaboration and peer-production is encouraged;

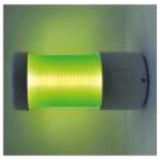
	Algae Curtain	Eco-friendly Lamp	Living Things	Farma	Spirugrow	Symbiont	The Coral	Algae Grower
								
Main scope	biofuel	CO_2 capture	food/biofertilizer	drugs	food	CO_2 capture	food	food
Dimensions	●	●●	●●	●●●	●●●	●●	●●	●●●
PBR shape	tank/various	tubular	various	tubular	tank	tank	flat-panel	tubular
Production system	closed	closed	closed	closed	closed	closed	open	closed
Harvesting system	manual	semi-automatic	manual	semi-automatic	semi-automatic	manual	manual	semi-automatic
Productivity	●	●●●●	●●	●●●	●●●	●	●●	●●●
Usability	●	●	●●	●●●	●●●	●●	●	●●●●
Maintainability	●	●●●●	●●	●●●	●●●	●	●●	●●●●
Cost-effectiveness	●●	●●●●	●	●●●	●●	●	●	●●●
Open-source	no	no	no	yes	no	no	no	yes
Educational value	●●	●	●●●	●●●	●●	●●●	●●●●	●●●●

Table 8.10. Comparison of the Algae Grower with selected product design experimentations.

● = very poor ●●●● = very good

- Educational value: The values behind the product and the educational message that the device (or its daily use) conveys to users (e.g., the possibility of seeing microalgae growing, periodical maintenance activities needed, etc.).

Although these considerations may seem trivial, they are fundamental to understand, at a glimpse, the areas in which the primary practical outcome of this thesis stands out. The differences may, in fact, not appear evident at first.

8.5.10 Considerations, limits, and future steps

The Algae Grower is an innovative and futuristic device that has drawn the interest of users, engineers, biologists, designers, and even chefs and educators (see Appendix: A chat with Lee Yi-Wen; Q&A with Wikifactory; The Algae Grower Plus with Beatriz Castelar). Nowadays, however, the cultivation of microalgae is not popular and very rare at home. For this reason, its utility may not be immediately appreciated: many users may not even feel the necessity of using it, resulting in limited adoption. The self-production of genuine and sustainable foods is not something new though, and the present and future trends bode well. In the '90s for example, bread-baking machines were widely used by the American and European middle class. Nearly thirthy years later, bread machines are practically non-existent, but more and more health-conscious people – especially young consumers, attentive to physical health and environmental issues – are rediscovering the advantages of these devices, to know what goes into their food and to produce gluten-free bread (Bautista, 2017). Present-day devices can also make pizza, pasta, and other delicious recipes. The same goes for yogurt machines, that enable concerned consumers to produce low-fat yogurt with no added sugar. Some of these devices even permit the production of personalized probiotic- and prebiotic-filled yogurts (Hancocks, 2020).

Table 8.11. Summary of the considerations on the Algae Grower. Pros and cons marked with +/-.

Considerations	**+/-**
Innovative device	+
Easy to use	+
Positive user feedback	+
Uncommon houseware	–
Needs improvements (e.g., LED)	–
Technical limitations	–

Kitchen counter devices such as bread-baking machines, yogurt machines, juice extractors, but even microwaves and toasters were unthinkable in the past. Therefore, the current needs of individuals and societies lead to imagine new devices, new functions, new rituals of use, and decentralized models for the production of healthy and sustainable food. The Algae Grower, hence, fits into this context and operates in a particular niche market. Although the main purpose of the device is the algal production, the Algae Grower has a high educational value. *Spirulina* is a living organism that responds to external stimuli: the production process is almost automated but requires periodic checks, to ensure the correct and healthy growth of the culture. Information on how to take care of the culture and some recipes can also be provided to users. Learning how to cook delicious and healthy recipes with fresh and locally-produced ingredients would teach new generations, facilitating the transition toward a more conscious and sustainable society. The environmental impact of an individual device is also positive. With a harvest of 5 grams per day, it is estimated that about 0.7 kg of CO_2 could be absorbed every year.[36] This data is not huge, but if the Algae Grower is utilized by a larger pool of users, these numbers would increase significantly.

The Algae Grower, at present, still has many limitations mainly due to time, budget, and resource constraints. The amount of *Spirulina* produced may not be sufficient to cover the needs of larger families: the design of the device can be slightly changed by increasing the dimensions of the tank (height or diameter) while maintaining the internal functions and the overall look unchanged. A series of Algae Growers, suitable for other contexts (living room, office, etc.), can also be envisaged. To create ad-hoc recipes, the collaboration with a chef and a nutritionist is crucial: a small *Spirulina* cookbook can be designed or they can be consulted through a smartphone application. The app would also serve to monitor the status of the cultivation, the values of temperature and pH, and to control the cycles of light and aeration, even remotely.

Figure 8.19. The 3D-printed shell that includes temperature and pH sensor, to be used for monitoring the parameters of the culture.

From a technical point of view, the device would need some improvements too. Sensors for monitoring the pH, the temperature, and density of the harvest could be integrated within the device, without the need of using analog instrumentation (Fig. 8.19).[37] It would also be advisable to include a heater to maintain the optimal constant temperature at 35–37°C, especially in winter when the home environment is colder; this prototype, being completely made of plastic, did not provide for the use of heaters.

There are a few important things to address when choosing the 'best' lighting system. Photosynthesis in cyanobacteria works slightly differently from plants. For this reason, there should be minimal issues providing *Spirulina* with monochromatic light, with wavelengths as high as 730 nm. Photons are the driver of photosynthesis: if the goal is getting optimal lighting in terms of energy, both the efficiency and the efficacy (number of photons per J of electrical energy) have to be taken into account (P. Kusuma, personal communication, April 19, 2020). Red and blue lights may significantly improve algal biomass growth (da Fontoura et al., 2020; Park & Dinh, 2019; Prates, Radmann, Duarte, Morais, & Costa, 2018), but it may be odd for some people to put

36 This calculation only takes into account the amount of CO_2 subtracted through photosynthesis. It does not take into consideration the environmental cost of the electricity used to run the device, which could vary from place to place. It is assumed that: harvest occurs 300 times a year; 1 kg of dry algal biomass can fix 1.83 kg CO_2, and that the conversion rate fresh/dry biomass is 0.25.

37 To remedy this lack, a container was designed to accommodate a digital temperature sensor, a pH sensor, and a small display for reading data. The shell is 3D printed and is also useful for organizing the cables. If including the sensors inside the device is too complicated or expensive, this additional device could be supplied together with the Algae Grower. For the moment, though, this is only a temporary solution.

these colors of light in their homes. A warm white LED – as in the prototype – could be a good design compromise. Finally, the light source could eventually be modified to provide both light and heat.

To facilitate cleaning, the tank cylinders could be screwed on the structure, therefore guarantee an easy removal if necessary. The Algae Grower can be finally supplied with a small growing kit, including for example nutrients, *Spirulina* inoculum, spare parts for the harvesting net in case of breakage, a spoon, Secchi stick, or other tools useful for cleaning and maintenance.

This prototype is the outcome of an articulated design research process, but only the first step of a medium-long term project. Deficiencies will be perfected in the near future. Partner companies will also be sought for targeted market analysis, product development, optimization of engineering for mass production, promotion, and marketing. It will also be necessary to obtain food use and electrical certifications (unfortunately, the current prototype does not guarantee food safety). These operations will require considerable efforts to make this product a reality. At the same time, the technical drawings of the product will be published online and made available free of charge to those who want to replicate it. Table 8.11 sums up all these considerations.

8.6 The Algae Station

Meeting the needs of cities and citizens requires an inclusive approach: it was, therefore, necessary to act on different dimensional scales and fields of application with complementary design projects. The Algae Grower is a consumer product that is used in private domestic spaces. The Algae Station instead, is designed to fill the lack of similar urban products – but especially services. It is a modular installation for the production and distribution of fresh *Spirulina* and the distribution of other microalgae-based food products and meets the needs of a larger number of people. In its basic arrangement, it has the size of a regular vending machine. The device can be configured to suit a community space, a shopping center, a school, etc. It can be installed in both indoor and outdoor spaces.

The Algae Station can also act as an aggregative fulcrum, providing real-time information about the amount of *Spirulina* produced and the quality of the air that is purified through photosynthetic activity. The full development of the Algae Station is currently underway. The rough drawings of its parts and a scale model were made. Three scenarios have also been hypothesized, also identifying possible associated service-systems. With due considerations, the Algae Station can be adapted also to other non-urban contexts.

8.6.1 Ideation phase

The ideation phase was fundamental for planning the following design stage. The various technical solutions adopted by designers and engineers – illustrated in the case studies – were taken into account, concluding that a tubular photobioreactor could be an effective solution in technical, productive and maintenance terms. Based on this consideration, and bearing in mind that the installation should have been adaptable to multiple situations, its main characteristics were drawn: modularity and easiness of combination. These two features are essential for adapting the project to the needs of different clients, for scaling it according to the production required, and for giving it more dynamism.

In this phase, also the overall sizing was drawn, taking inspiration from vending machines and parcel drop-off points (Fig. 8.20). Both vending machines and parcel drop-off points are extremely popular in large cities. In Beijing, for example, almost all residential compounds have one or more points for collecting parcels. These points are also found in offices or supermarkets. The same goes for vending machines, often equipped with touchscreens and commonly used for the purchase of various types of products by scanning a QR code. These devices have a familiar style and are commonly used by many people of different ages and backgrounds. In the ideation phase, it was also decided to limit the project to a concept, without going into specifics stylistic or functional details. The topic of urban furniture is very broad and this thesis deals with it only marginally.

Figure 8.20. Cainiao parcel drop-off point in a residential compound in Beijing, November 2019.

8.6.2 Definition of spatial contexts

In urban contexts, microalgae are grown with different methods and in diverse areas, for example on rooftops, on the facades of buildings, in abandoned or temporarily-unused fields, and near large infrastructures (viaducts, highways, etc.). The workshop participants also suggested unusual alternative places, such as gyms and university campuses. The production of microalgae in the city is therefore quite versatile and moderately simple to maintain. The modularity of the Algae Station would, therefore, allow its adaptability to different places. A smaller version could be installed in a bar or a restaurant, while a larger one in a park. Some possible places are residential compounds, university campuses, offices, schools, shopping centers, supermarkets, bus stops, subway, public or privately managed spaces, gardens. The list of places may be longer.

Since the sizes of the individual parts of the Algae Station do not exceed that of a vending machine, this modular installation is also straightforward to transport. As emerged from the temporal analysis, many projects have limited duration over time: after the events, they are dismantled or decommissioned after some years. This is not the case with the Algae Station[38], which can be

38 During the winter, if too cold, the Algae Station may not be productive. The station could be temporarily moved indoors, where the temperature is constant.

	Requirements	Performances
Requirements for use	Safe	Smooth edges and corners
		No water leakage
		Anchored stable structure
	Simple	Easy to interact with and efficient payments handling system
		Optimized showcase of products and features
		Use of few colors and materials
	Productive	Guarantee high yields while assuring freshness
		Periodically refilled
	Modular	Possibility for multiple configurations
	Versatile	Suitable for both indoor and outdoor environments
		Act as gathering point
	Intuitive	Limited and guided interaction
	Pleasant	Harmonious shapes
		Distinctive features to make it noticeable
	Contextualized	Peculiar but familiar look
	Educative	Arouse curiosity of people
		Provide environmental benefits information
	Shared	Multiple ways of use, universal accessibility
	Connected	IoT integrated features
		Social activities facilitator
Operation requirements	Movable	Easy to transport the single parts
		Facility to assemble and disassemble on-site
	Maintainable	Simple growings operations and products refill
		Washable in all parts and locations
	Repairable	Easy to change components
		Easy to fix broken parts on-site
	Reliable	Correct and immediate operational feedbacks
		Well balanced configuration
Production requirements	Safe	Compliance with public safety regulations and certifications
		Use of impact protection materials
	Simple	Easy to assemble and to transport
		Use of basic production techniques and pieces of machinery
	Economic	Cheap to manufacture even in small-scale, local productions
	Resistant	Materials and finishes resistant to all weather conditions
		Use of vandal-resistant solutions
Environmental requirements	Efficient	Integrated systems for energy control and self-sustainability
	Ethical	Use of non-polluting materials and processes
		Safe-for-health product and outcomes
	Durable	Long-lasting and strong, hard to break materials
	Dismantlable	Trouble-free end-of-life single components disposal or reuse
	Recyclable	Use of reusable and recyclable materials

disassembled and re-assembled in different areas of the city and even at certain times of the year. The technical solutions adopted would also allow a quick arrangement. The relationship of The Algae Station with its users changes according to the scenario in which it is placed. The characteristics of the project are analyzed in detail in the following paragraphs.

Table 8.12 (Facing page). The requirement chart of the Algae Station.

8.6.3 Conception phase

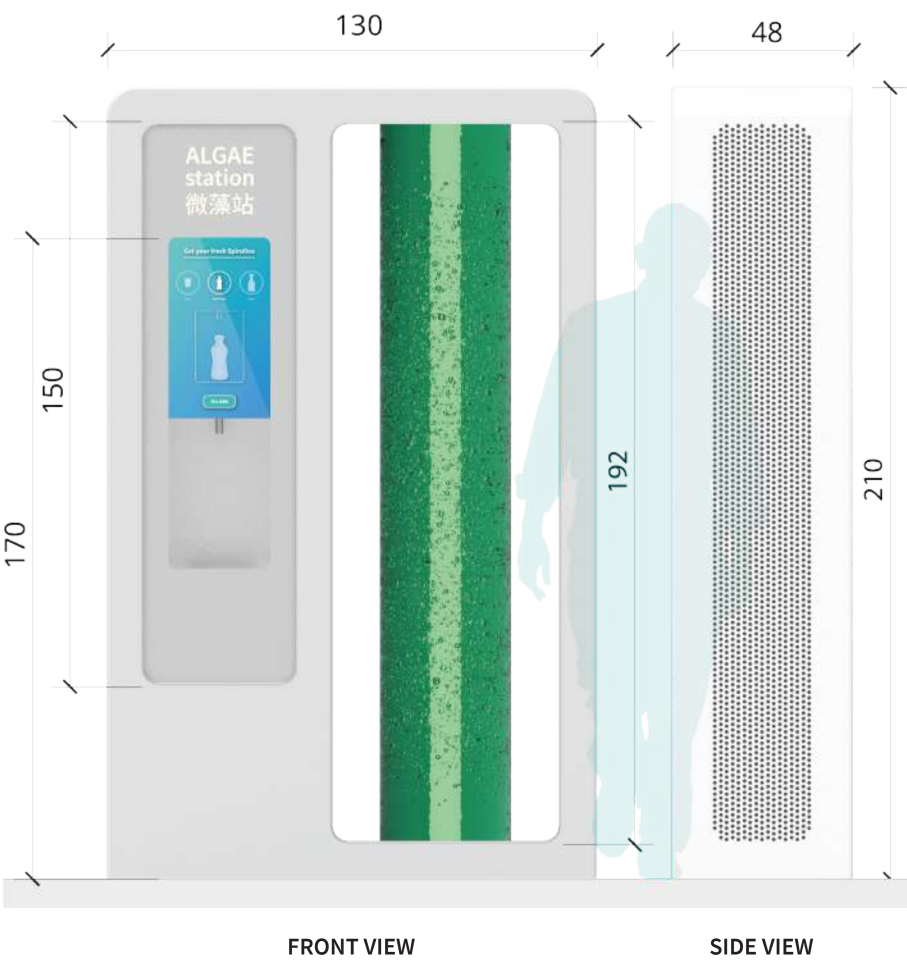
The meta-design aspects of this project were analyzed, particularly the detailed functions, features, operability, and interaction. The requirement-performance chart was drawn up (Table 8.12): it is divided into requirements for use, operational requirements, production requirements, and environmental requirements. The user needs are partly similar to the ones identified for the Algae Grower, but the way the Algae Station responds to them in terms of performances is rather different.

The Algae Station is a modular and versatile device for both indoor and outdoor settings and can be arranged into multiple configurations. Its shapes are simple and it is easy for users to interact with it. The station ensures the production of a certain amount of fresh high-quality *Spirulina*, therefore large tanks that protect the culture from external contaminations are necessary. The Station is immediately recognizable and eye-catching, with a peculiar but familiar look. It also has an educational value with an optimized showcase of products and features, stimulating people's curiosity to be more interested in environmental issues and providing information on the sustainability of microalgae production. The product, in some landmark-like configurations, can act as a gathering point and become a social activities facilitator. As regards the operational requirements, the Algae Station is movable, easy to transport in parts, easy to assemble and disassemble on site. In support of the maintenance personnel, the device is designed to be washable and repairable in all the parts.

Taking into account a future mass-production, the Algae Station makes use of affordable materials that can be machined with basic production techniques and tools. In this way, the station can also be manufactured in smaller scales and by local suppliers. The materials and finishes are resistant to most of the weather conditions and, supposedly, vandalism. The product uses integrated systems for energy production and control, non-polluting, reusable and recyclable materials, and sustainable production processes. The product is designed to be usable in the long-term and not to become obsolescent in a few years. The Algae Station is just a concept. More studies on ergonomics, safety, use scenarios, appeal, colors, materials, contextualization, and identity of the product would be deserved. The current solutions are mainly suggestions. During the implementation/production phase many parts will have to be critically reviewed and improved.

Figure 8.21. Orthographic front and side views of a configuration of the Algae Station, with one Fresh Spirulina vending machine and one PBR module.

SCALE 1:20
Quotes in cm



8.6.4 The Algae Station: A modular and versatile system

As already seen, the Algae Station is not a static product, but a modular system of different parts designed to change over time and operate in different contexts, responding to the needs of multiple users. The modules have dimensions not exceeding 210 cm in height, 60 cm in width, and 48 cm in depth (Fig. 8.21). These dimensions reflect those of similar objects for public use (vending machines, parcel drop-off points), which have excellent portability. The three main modules are presented below, essential for the minimal operation of the installation, i.e., the production and distribution of fresh *Spirulina* or processed products. Each module has distinct characteristics (Fig. 8.22)

A) Dry Spirulina vending machine: this module has the function of distributing dry Spirulina-based food products, like a regular vending machine. The products sold are processed by third parties (restaurants, bakeries, and other local businesses). The products are stored inside the module: users can choose the product they like most through the intuitive graphic interface of a front touchscreen (it is assumed that the machine can contain products such as pasta, croissants, chocolate bars, biscuits, pills, but also drinks). The module, connected to the Internet, permits to make transactions with electronic payments. The selected product is withdrawn from a compartment below. When not in use, the monitor shows educational videos in the loop, which illustrates the benefits of microalgae and the positive effects of urban production. The module can be quickly inspected and filled with products by workers, through a side or rear opening. This module can operate independently and is the minimum configuration of the Algae Station.

B) Fresh Spirulina vending machine: the function of this module is to distribute fresh *Spirulina*. The module works alongside one or more photobioreactors (module C). The external appearance is very similar to that of module A: the functions of the touchscreen are almost the same, except for the possibility of selecting the quantities of fresh *Spirulina* (a glass, a bottle, or a larger bottle). The compartment below allows the bottle to be placed on a grid during the filling operation. Internally, an automatic pump system picks up the algal biomass and separates it from the water, rich in nutrients, through one or more filters - the operation is very similar to that of the Algae Grower. The user, therefore, fills the bottle only with fresh *Spirulina* and not with water (fresh biomass is abundant in intracellular water). The sidewalls of the module are microperforated. This solution allows the air needed to grow algae to enter and to release the oxygen produced by photosynthesis.

C) Photobioreactor: the functioning of this part guarantees biomass production. The module consists of a large tubular pipe in high-quality transparent glass. Its height is 190 cm, and its diameter 35 cm for a total volume of approximately 150 l. Inside each tube is installed a low consumption lighting system, which provides light and heats the culture when necessary. This system can be turned on and off to compensate for the shortage or excess of natural light and heat. Multiple photobioreactors can be placed side by side if more biomass production is required. The photobioreactors are not connected in series with each other to have the possibility to manage the cultures separately and to have backups in case one cultivation could go wrong. The photobioreactors are covered to avoid contamination and minimize evaporation. The tanks are connected with tubes to module B, which also contains the electronic components needed for their operation. The upper part of the module allows it to be opened to facilitate internal inspection, the addition of nutrients, and the cleaning of the tank. Figure 7.21 shows a Fresh Spirulina Vending Machine and a photobioreactor module. Compared to the space given for cultivation, the station has a relatively small size.

Concerning the three main modules, other parts have also been conceptualized and are of secondary importance. Figure 8.23 shows some hypothetical types of seats (D, E, F) that can be added to the production core and create alter-

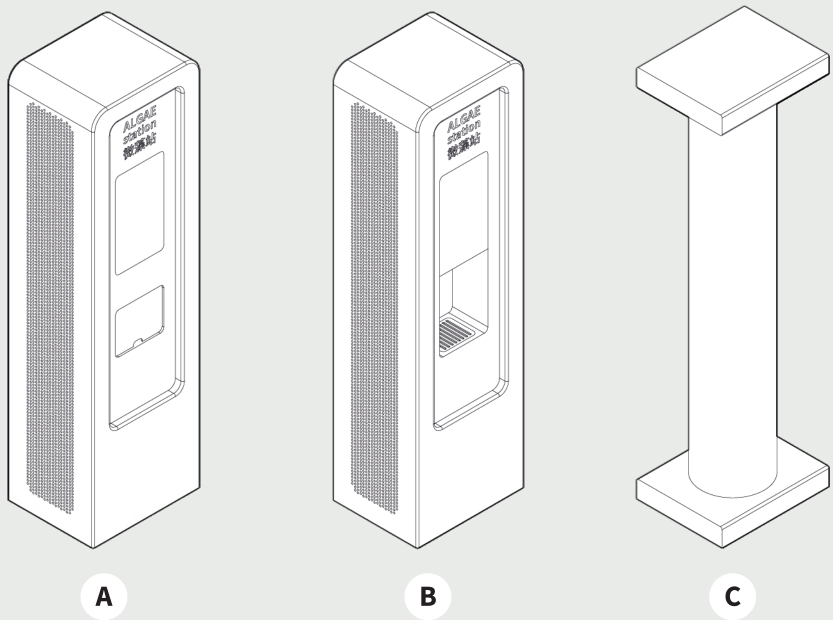


Figure 8.22. Main composing elements of the Algae Station.

A. Dry Spirulina vending machine
B. Fresh Spirulina vending machine
C. PBR module

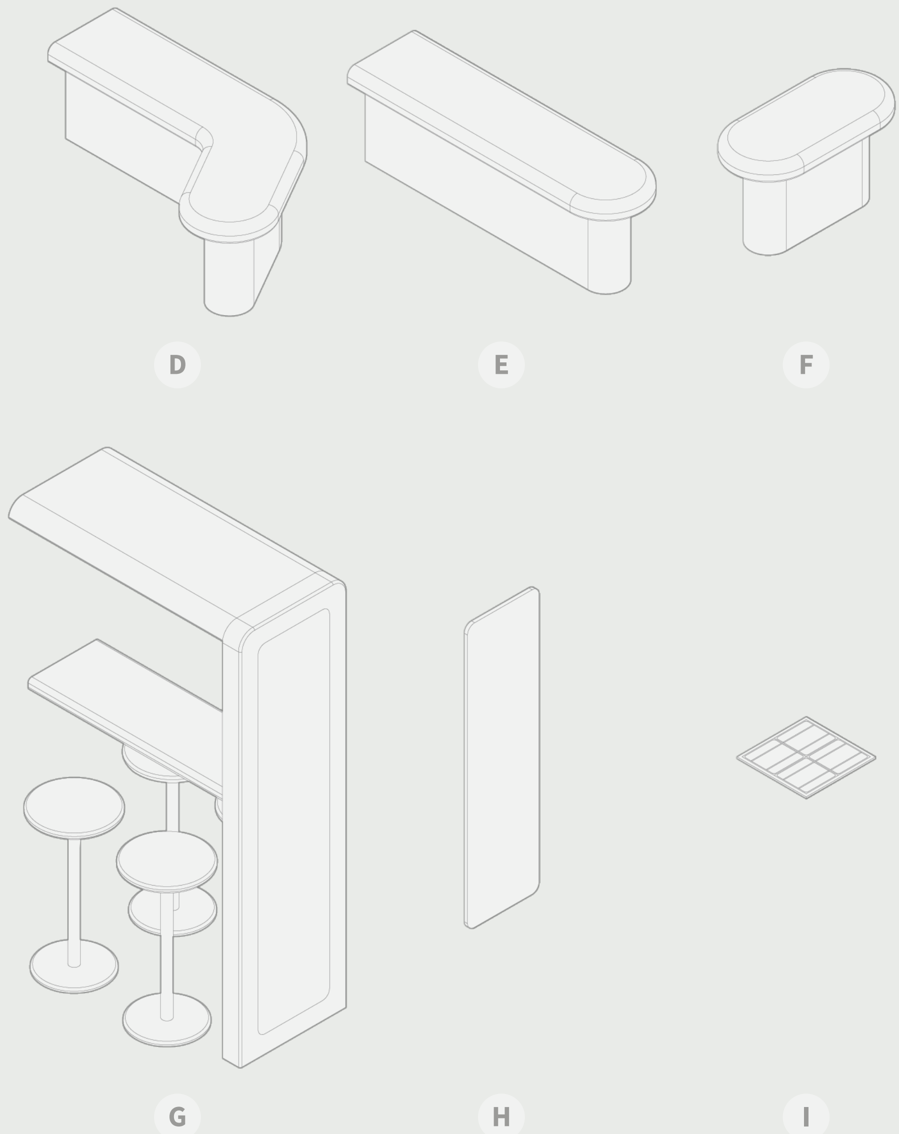


Figure 8.23. Hypothetical extra accessories for the Algae Station.

D. Bench type n. 1
E. Bench type n. 2
F. Bench type n. 3
G. Table
H. Educational/Advertising billboard
I. Modular photovoltaic panel

Figure 8.24. Possible configurations for the Algae Station.

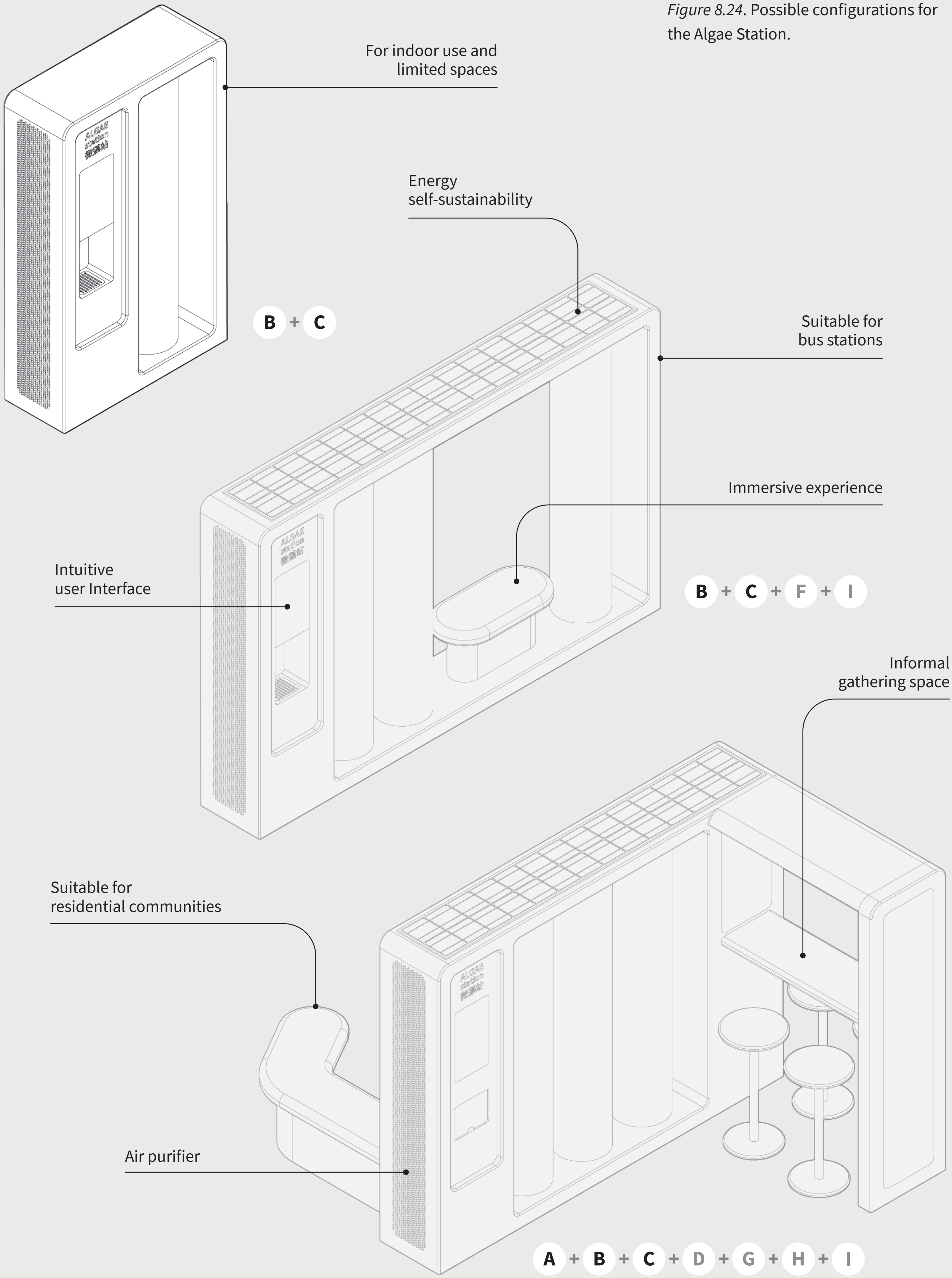
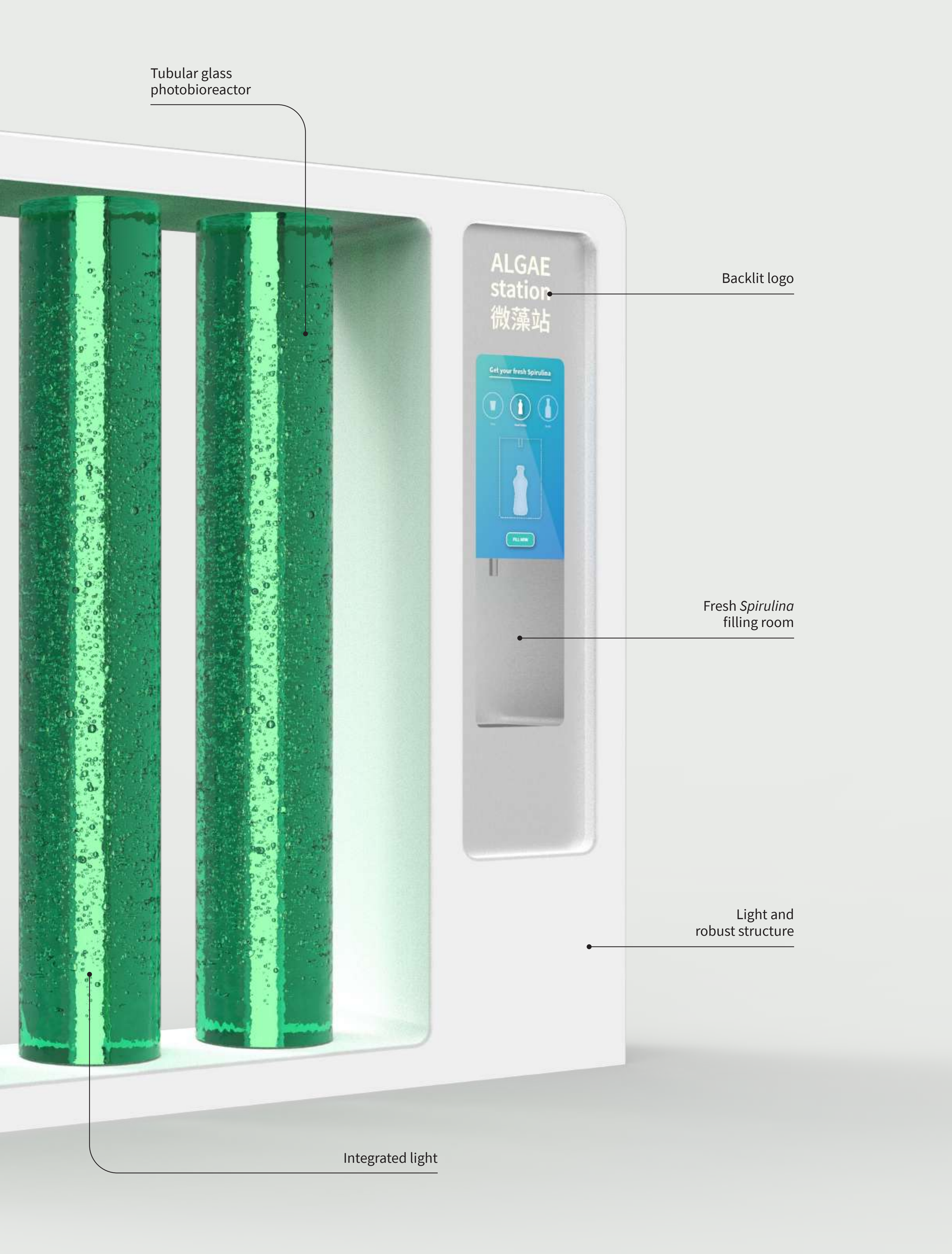


Figure 8.25. Rendering of the Algae Station, with one Fresh and one Dry Spirulina vending machine, and three PBR modules. This configuration may be suitable for public spaces.


Tubular glass photobioreactor
Backlit logo
ALGAE
station
微藻站
Get your fresh Spirulina
Fresh *Spirulina* filling room
Light and robust structure
Integrated light

native meeting spaces. These spaces can be used by groups of people waiting at the bus stop, or for chatting with the neighborhood. A table has also been hypothesized, where perhaps people can sit to consume the products just purchased from the machine. Easily washable colors, materials, and finishes have been used for the Algae Station: they provide a clean look and are welcoming. The external surfaces can be entirely or partially covered with graphics (H) referring to educational values, environmental sustainability, the benefits of *Spirulina*, and the cultivation of microalgae in the city. They can also be targeted and ethical advertisements, such as those of the project partners, investors, or universities involved. The profits from advertising would serve to partially or fully cover the installation and the management costs.

The Algae Station is almost entirely automated: this system is very efficient for production and distribution. At the same time, jobs are created (maintenance, inoculation, device production, research, partners, etc.). Modular photovoltaic panels can be installed above the modules to produce clean energy used to power the device. The configurations of the Algae Station are innumerable (Fig. 8.24). Fig. 8.25 shows only one of the possible ones.

The details and the dimensions of each module can be found in the appendix: The Algae Station – Technical drawings of the modules. A 1:10 scale non-functional model was also realized with the help of a local factory, to understand better the proportions of the parts, the materials to be used in the production, and the overall potential look (Appendix: The Algae Station – Scale 1:10 model).

8.6.5 Envisioning urban Product-Service Systems

In this paragraph, some possible scenarios for microalgae production in urban areas are proposed using the Algae Station in different configurations: on a university campus, in a coworking office, in a residential compound. These scenarios are plausible but need to be verified and tested, in combination with a robust business model. The proposals are supposed to be achievable in large cities, perhaps with high housing density. Nevertheless, these examples can also be adapted to other contexts: smaller municipalities, towns, but also suburban and rural areas, with due considerations. The three scenarios described below are the result of the detailed elaboration of some solutions – or combinations between them – presented by the participants in the 'Food for the future' workshop held in November 2019.[39] To describe these three hypotheses, the typical tools of Product-Service System Design were used: a Service-System map, the definition of personas (the same users previously hypothesized for the Algae Grower: see paragraph 8.5.3 and Fig. 8.12), and user storyboards.

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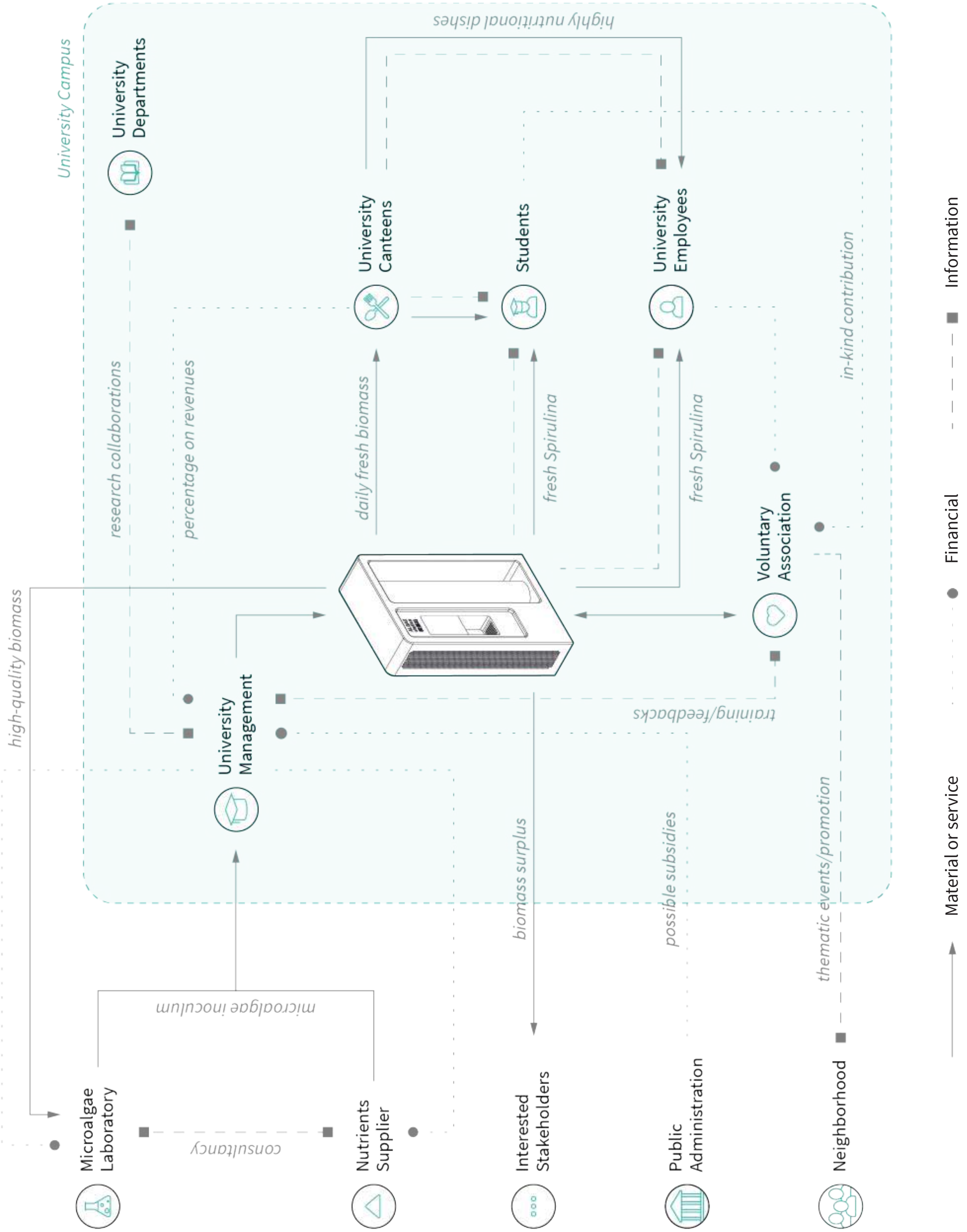
39 Thanks to Gao Ge and Liao Zhuo-Ying for helping me with part of the visual representation of the storyboards, within the framework of their design studies.

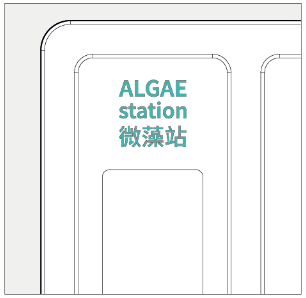
- **Fresh Spirulina production in a university campus** (Fig. 8.26): The university management handles the installation and maintenance of the Algae Station within the school. The Algae station can be configured with a Fresh Spirulina vending machine and PBR module (B+C). One or more Algae Stations can be installed in places where many students are passing by. External (or internal) laboratories at the university provide consultancy, together with the algae inoculum and the certified nutrients for food use. University departments can cooperate on the project. The designers, for example, can take care of the promotional part, the design and implementation of ad-hoc configurations, and the graphical user interface of the system. Engineers may be responsible for the control of the production, biologists for periodic microbiological verification. The fresh biomass produced is sent to the canteens daily, which prepare delicious recipes with high nutritional values for students and employees. For those who wish, *Spirulina* can also be purchased directly from the vending machine. Any excess biomass could be sold to other interested stakeholders (food companies, residential compounds, schools, and universities, etc.). Curious individuals can also join an association of volunteers with the responsibility of monitoring the cultures around the campus and collecting *Spirulina* once ready. They can get academic credits or *Spirulina* as a reward. The association also organizes thematic and educational events, also with the neighborhood: public administration could provide subsidies for the promotion of these activities and the launch of the project. Fig. 8.26 also illustrates Magda's user journey, a French exchange student in engineering. She lives on the campus of a Chinese university, and she has been a vegetarian for many years.
- **A dry Spirulina vending machine at the office** (Fig. 8.27): This service does not include the direct production of *Spirulina*. External activities produce fresh *Spirulina* and sell it to processors, such as food and drink factories or pharmaceutical companies, which process it and add it to food products (crackers, biscuits, chocolate, pasta, etc.), or in pills and supplements. The external Spirulina-producing activities may also be partner universities and residential compounds. The management in charge of the Algae Station buys the products (or holds them on consignment) and supplies the vending machines periodically. The vending machines (module A) are placed in strategic points, such as a coworking space, available to as many people as possible. From the vending machine, customers can also order Spirulina-based products, freshly prepared from neighboring bars and restaurants, which are delivered with food delivery services. Coworkers can purchase Spirulina-based products and consume them in the office or at home. Neighboring businesses such as pharmacies, gyms, or small shops can also purchase them. The persona identified for this storyboard is Su, a

Figure 8.26. Fresh *Spirulina* production in a university campus. System map and user storyboard.

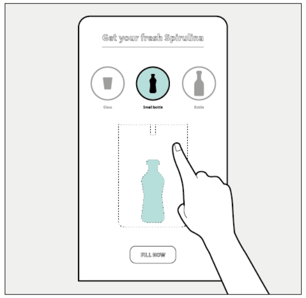


in the campus

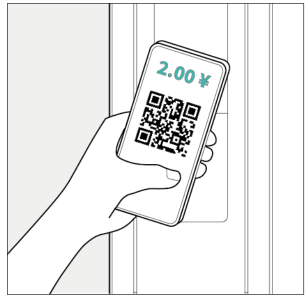
While I am going to the dormitory, I notice that a new eye-catching device is installed on the campus…



I cannot believe it distributes *Spirulina*! It is not easy to be a vegetarian, and I am always struggling to buy it in shops.

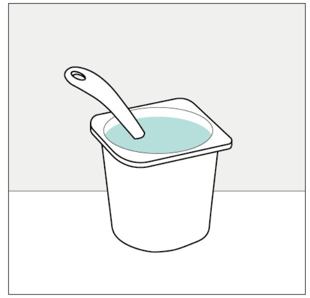


The interface is easy-to-use and bilingual. I decide to purchase a bit of *Spirulina*: I use to eat it fresh in my country and I want to compare it.



I pay a small fee through the phone, by scanning a QR code. I fill my own bottle: I always bring it with me! I receive some information about the CO_2 that was subtracted today.

in the room

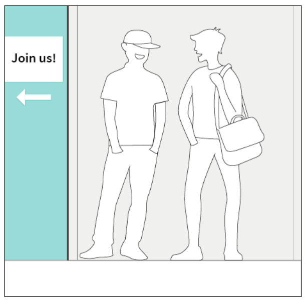


When in my room, I add fresh *Spirulina* to some yogurt. It tastes delicious! The quality is controlled and certified by a microbiology lab.

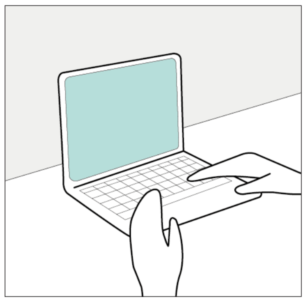
in the canteen

The day after, at the main canteen, I could taste other recipes made with *Spirulina*. I talk about this with my classmates.

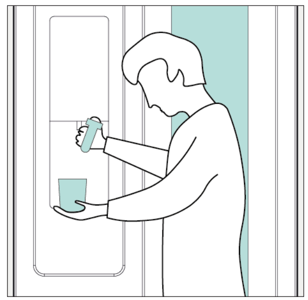
in the campus



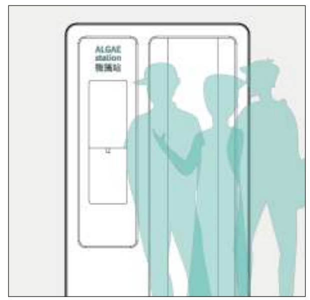
I soon realize that this is a very cool project. Thus, I decided to join the Voluntary Association, to be directly involved.



I make new friends and collaborate with the Microbiology and Engineering departments on a research project. I am considering writing my thesis on this topic.

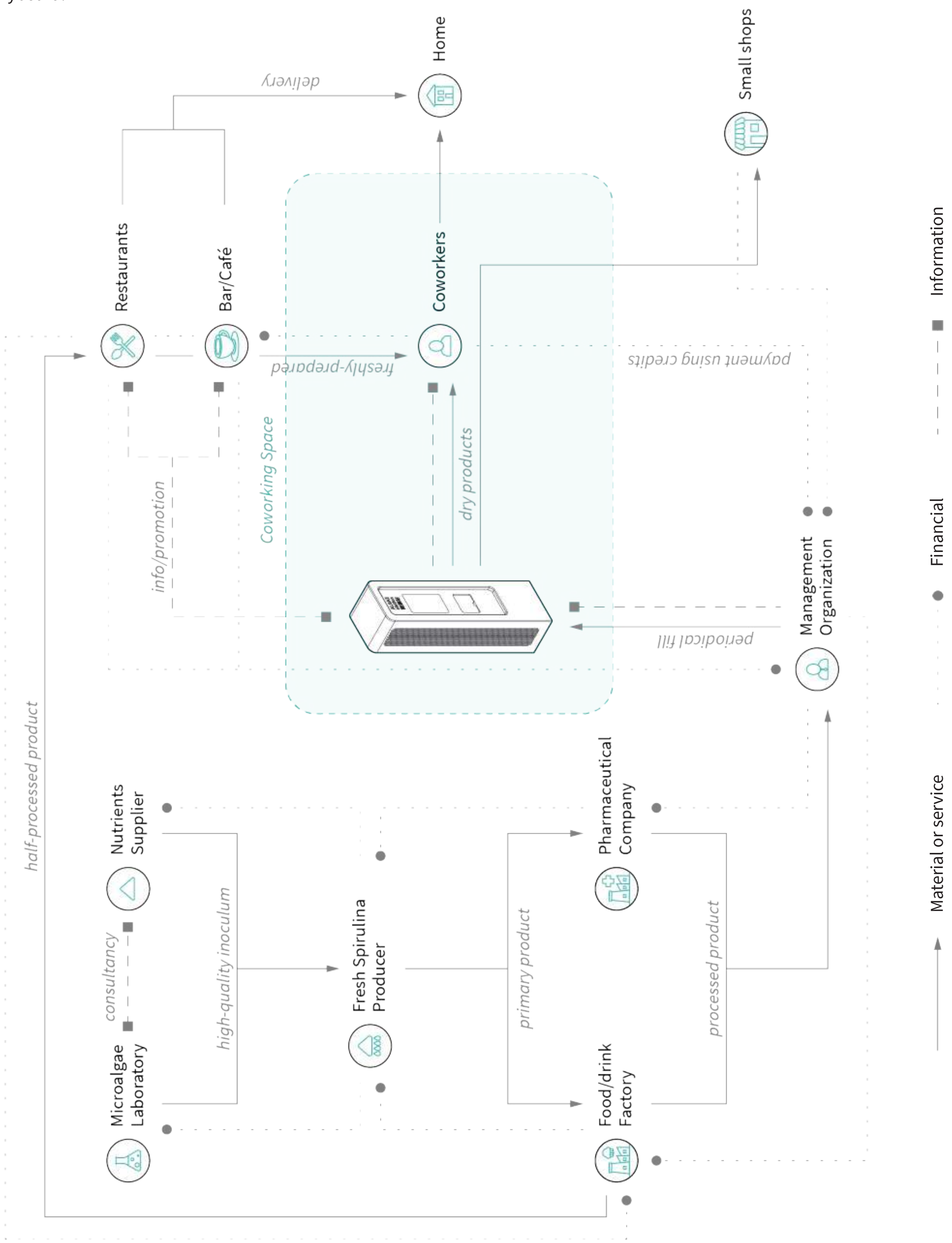


I am trained to take care of the *Spirulina* cultivation. Together with some experts, I dedicate a few hours a week to this project. I also get student credits and fresh *Spirulina* for free.

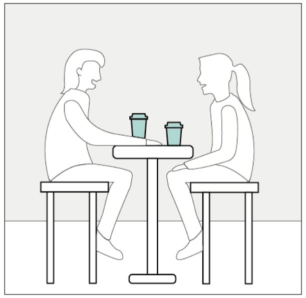


I try to involve other students in this project. I am proud of contributing to the environment while learning more about healthy food and sustainability.

Figure 8.27. A dry *Spirulina* vending machine at the office. System map and user storyboard.

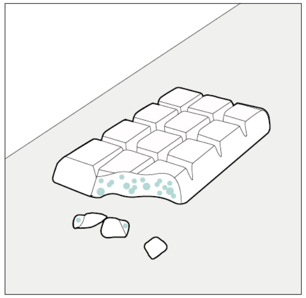


in the office



It is 10:00 AM and I decide to have a coffee break with my colleagues.

In the common area of our coworking space, they have recently installed the 'Algae Station'.



I purchase a Chocolate and *Spirulina* energy bar. It is low in carbohydrates and high in protein. Perfect for my diet!

My colleague also wants to try a fresh *Spirulina* smoothie. It is not available at the moment, but she easily orders it from the display. It is made by a nearby café.

in the café

The café prepares the smoothie and the order is delivered to the office within 30 minutes.

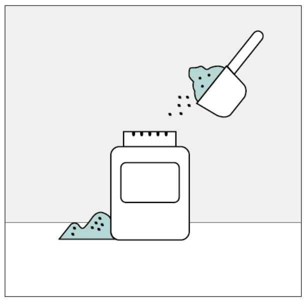
in the office

The smoothie tastes great! It is made with locally-produced fresh *Spirulina*. She writes a positive review online.

in the gym

The office also has a gym. Especially during lunchtime, a lot of people buy some healthy snacks before or after training.

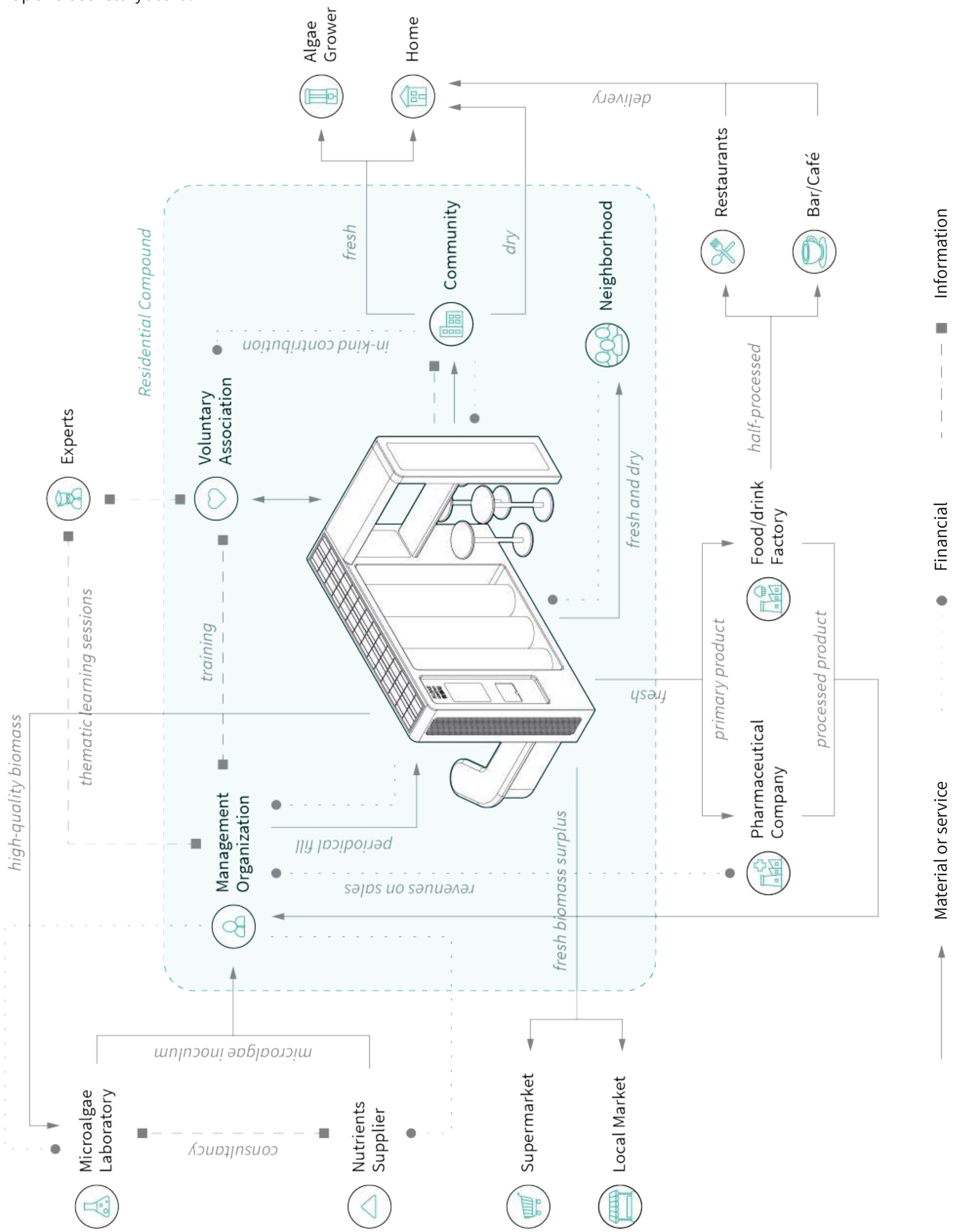
at home



It is time to go home. Before leaving the office I decide to bring some *Spirulina* powder home. I would love to make some recipes with it.

With my boyfriend, we prepare *Spirulina* dumplings. We both like them and we will surely make them again!

Figure 8.28. Gathering and harvesting *Spirulina* in a residential compound. System map and user storyboard.

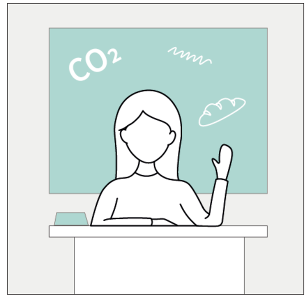


in the compound

During the last meeting with the neighbors, we decided to install the 'Algae Station' in our residential compound. I strongly supported this initiative.

It fits well in the common space of our community. It helps to purify the air and a lot of people are usually gathering around it.

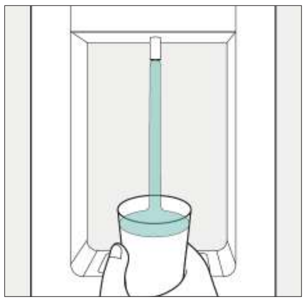
I am also a volunteer. At the weekend I spend a few hours to check the status of the device: I got trained by the management and I teach my daughter too.



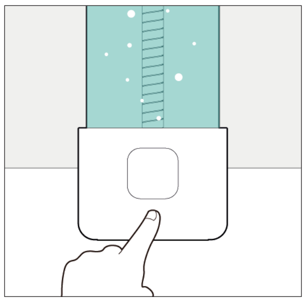
Periodically, we organize events with experts from different fields, to illustrate the benefits of *Spirulina* and of harvesting it in our compound.

I use to get dry *Spirulina* powder from the vending machine. When at home, I add it to my recipes. I learned many of them online.

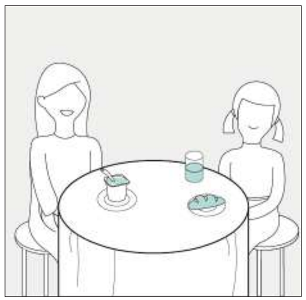
at home



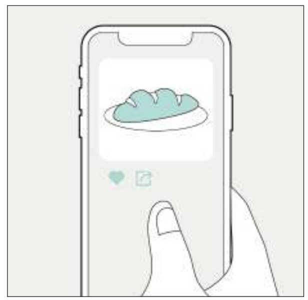
I am now willing to harvest *Spirulina* at my place. The Algae Station can provide high-quality fresh *Spirulina*, perfect for starting a home culture.



I finally got my 'Algae Grower' and I am happy to test it! All I have to do is adding the inoculum and turn the device on. *Spirulina* will grow healthy and vigorous.



The quality of this *Spirulina* is very high. It is perfect for me, my wife, and my little daughter. We use it fresh daily and provides proteins, essential fatty acids, and vitamins!



I usually share the pictures of my recipes on social media. My followers love them! They ask questions and give precious advices.

nearby

The surplus biomass produced by the Algae Station is sold to nearby supermarkets. This business model is great. Many people can benefit from this service.

young accountant in a private company, who would love to eat more fresh and sustainable food. She thinks that eating microalgae could be great for her diet.

- **Gathering and harvesting Spirulina in a residential compound** (Fig. 8.28): This solution is complex but apparently with great potential because it seems to be scalable and replicable in many other places. The compound management is responsible for leading the service. The Algae Station in this configuration allows both the production and distribution of fresh biomass and the distribution of Spirulina-based dry products. An external laboratory (eventually a university) supplies high-quality inoculum for food use. The photobioreactors of the Algae Station optimize the growth of microalgae, providing sufficient biomass for the whole neighborhood. An association of volunteers made up of young people, adults, and elderly residents take care of the daily maintenance of the device. In return, they receive a substantial discount on the purchase of *Spirulina*. The most challenging maintenance operations are entrusted to a team of skilled technicians. Some benches and refreshment areas can flank the Algae Station: the station thus becomes a place for meeting and discussion, where educational activities are also organized. External experts can moderate thematic learning sessions and workshops. Surplus biomass can be sold to neighboring markets and supermarkets, ensuring an additional source of income for the community. Considering that some may wish to use the Algae Grower at home, it would also be possible to take the inoculum needed to start the domestic production directly from the Algae Station. Neighboring restaurants could also use the fresh biomass, creating highly nutritional and protein recipes, which could be purchased by residents and delivered home with delivery services. For this storyboard, the journey of Wang, a 32-years old American-born Chinese freelance photographer who lives in Shanghai with his wife and daughter, is presented.

8.6.6 Product-Service System assessment

Considering that the development of the Algae Station is still in a preliminary concept phase, it is hard to test the different parts and functions of the device, which could also change significantly. Moreover, due to the countless configurations that the Algae Station may assume – and the contexts in which it could be placed – even an assessment of a particular service would not be very relevant, at least at the moment. With these premises, this paragraph presents the various tests that will be done when the project is more mature. The tests will focus on both the device and the service in its entirety.

From a technical point of view, the tests – similar to those already carried out for the Algae Grower – will serve to monitor the amount of *Spirulina* produced by the device, and confirm that it is sufficient for a given number of people. At the same time, they will verify that the internal mechanical distribution system (still to be developed) is efficient and functional. More user tests will also be necessary to understand and improve the interaction both by customers (e.g., interface, distribution mode), and operators (e.g., ordinary and extraordinary maintenance, cleaning). These tests could also be done with inexpensive and straightforward mockups during the engineering process and will include interviews and observations. The educational impact will also need to be addressed: for this reason, an open workshop/survey could be organized.

The product-service assessment will be done through the SDO toolkit to evaluate the improvements in relation to existing reference systems (see paragraph 2.3.3). It will take into consideration the environmental (e.g., system life optimization, transportation/distribution reduction), socio-ethical (e.g., employment and working conditions, enhancement of local resources, social cohesion, integration of marginalized strata, responsible and sustainable consumption), and economic sustainability (e.g., market position and competitiveness, macro-economic effect, partnership cooperation, long term business development/risk, added value for customers). Regarding the medium-long term profitability, a model business plan has already been developed, with the help of finance experts, and described in paragraph 8.2. Further tests will be conducted if deemed necessary.

8.6.7 Values beyond the physical product

The Algae Station is unquestionably an innovative product installation with technical features that rely on engineering and biological expedients to maximize microalgal biomass production for food use. However, the value of the Algae Station does not only lie in the product itself. The Algae Station is a change maker: it assumes an important role that goes far beyond the tangible. Its role is intangible but perceptible. This modular device can be placed just about everywhere: in a city, as well as in a rural area. Because of this flexibility, it is possible to create aggregative hubs from scratch – even in the poorest and most degraded areas – favoring social communities' creation and acting as a local landmark. Being actively involved in the Algae Station management is a

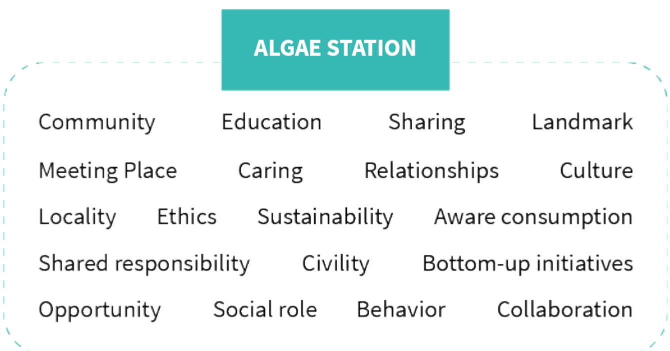


Figure 8.29. Values of the Algae Station beyond the physical product itself.

vocational job opportunity or a volunteering activity for locals: the activities can help build social relationships between neighbors. A positive attitude to collaboration lays the foundation for successful bottom-up initiatives.

Well-educated people assume more responsible behaviors because they are also aware of their significant role in civil society. The awareness of producing and eating healthy, nutritious, and locally-sourced food also brings gains in environmental sustainability, with cascading benefits both in the short and medium-long term for the people involved in the system and for others. Figure 8.29 sums up the values that the Algae Grower incorporates.

8.6.8 Considerations, limits, and future steps

Like the Algae Grower, the Algae Station is an innovative device that is not yet present on the market. The technologies selected are well-known and widely used, but the adoption of microalgae is still limited, and the installation of the Algae Station in the common spaces of residential compounds, in city squares, or the subway cannot be yet justified. The adoption of the Algae Station will undoubtedly find much resistance, at least at the moment. The characteristics of the device are, however, remarkable. The captivating but familiar look stimulates people's curiosity; the displays provide highly educational information, as well as advertisements with ethical and environmental values. Modularity allows excellent versatility of the device, that can be placed in vastly different contexts. It is for these reasons that the Algae Station could play an essential role in the transition toward an urban, sustainable, and decentralized *Spirulina* production.

The high degree of automation, especially for biomass production and distribution, could be a negative aspect for some, as technology is increasingly replacing jobs. In reality, the benefits of technology and automation are embraced by many: technology is increasingly present in our daily lives. It is something we are already accustomed to, especially in modern western and Asian cities, where the propensity to use of new technologies is high. The future will most probably be defined by automation as well. The automation of the processes also allows optimizing production and minimizing contamination from external polluting agents. The choice to use an automatic vending machine derives from the fact that in the history of the last two centuries – and even more today – these devices have played an essential role in our societies and have been increasingly adopted, with reasonable client and sellers satisfaction (Segrave, 2002). The project, although automated in some parts, would create, for instance, even more collaborations. In order to start and sustain such a project over time, it is undoubtedly necessary to cooperate between several parties. The Algae Station project is not only made of by mechanical components, glass, and metal sheets, but by people who establish relationships. Universities could offer great support in research, design, and engineering, as well as private research institutions. An amount of data could be obtained on microalgal production in city areas, at different latitudes and geographic contexts. Public bodies and government spin-offs could support the promotion of the initiative and provide funding for starting the business. People would become more aware, and numerous jobs would be created: management, production, maintenance, delivery and transportation, accounting, promotion, suppliers, etc. The tank of the PBR module is quite large, and the scalability of the project could guarantee an abundant production of *Spirulina* for many people. It is estimated that if each device could produce around 30 kg of biomass on average per year, it could subtract about 14 kg of CO_2 from the atmosphere.[40] The numbers will multiply if more devices are going to be installed in the city.

At the moment, the Algae Station is only a concept. The budget, time, and resources for building a first fully-functional 1:1 scale prototype are limited. Initial investments are required for a possible mass-production. It will, therefore, be necessary to find financing partners to start a pilot project. The partners could be private companies, start-up incubators, institutions, public bodies, associations, foundations, or banks. Before the realization, it is necessary to consult other phycology experts for obtaining relevant suggestions (how to optimize the production parameters, which types of lamps to use, proper sizing of the pipes in relation to the illuminated area, and so on). Also, from a design point of view, the Algae Station needs numerous improvements. Remember that in this research phase, only suggestions are provided: the final goal is not only the design of an urban furniture product, but it is a research through design. Here are some technical details that could be taken into consideration at a later time. Some design suggestions are also provided:

- To ensure a product with a universal design and easy to use even by the elderly, children, and the disabled, attention should be paid to the interaction screens. For some users, these may be too high. Lowering their height or making the screens movable can be a solution. A smartphone application may also be used to interact with the Algae Station.
- The stools near the table (module G) are a barrier, an obstacle for some users. They may be removed, at least on one side. The table can also be redesigned with two distinct heights.
- The Algae Station has a distinct appearance and is alien to some contexts. In a modern city, in a subway station or an airport, it fits quite well. In historic city centers (for example of some European cities), it may be inappropriate. The station may have different finishes, alternative structures, colors, and materials, to better suit the different landscapes in which it will be placed.

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40 Please refer to footnote 36 in this chapter and the Appendix: The Algae Station – Economic analysis, for the data used for this calculation.

Table 8.13. Summary of the considerations on the Algae Station. Pros and cons marked with +/-.

Considerations	+/-
Very versatile device	+
Intuitive language	+
Urban landmark	+
Jobs creation	+
Still a concept	–
Technical limitations	–
Needs a solid business model	–

- The user interactions are different during the day and night. Even the identity of the Algae Station could change at different times: mixed-use of light is recommended. Lighting could also increase the feeling of security in the evening.
- At the moment, there are no particular roofing solutions. Some roofs could be useful to protect the users and the structure from rainstorms, or the displays and the culture in case of intense solar radiation. High temperatures may have adverse effects on algae cultures and quickly reach photosaturation levels.
- Other minor solutions in the design of the structure and the modular benches may be adopted, i.e., drain water in case of rain. More detailed studies need to be done to counteract vandalism. Special paints for surface treatment could be used (smooth and continuous surfaces are more easily vandalized). The theme of urban furniture design is extensive and will undoubtedly have to be taken into consideration later when the project will be in a more advanced phase.

The current limits of the Algae Station are not only related to the design but also the feasibility and economic sustainability of the overall project. The previously suggested service-systems are plausible and detailed. Tests could show, albeit in part, the validity of these models. Nevertheless, only the implementation of a pilot project and the definition of a robust business model would be able to guarantee the success of the project also in the medium-long run. In the upcoming months, it will take time and resources to promote the Algae Station, hoping that the right partners will be found for the engineering and production of the device and the start-up of the project. Some public events will be organized where the potentiality of the device will be illustrated to possible investors and users, including real estate companies and municipalities. Scientific publications on design journals and participation in multidisciplinary conferences will also follow. Considerations on the Algae Station are summed up in Table 8.13.

8.7 A decentralized microalgae production network

The Algae Grower and the Algae Station are devices with many similarities on a technical and stylistic level – including the essential functions and materials – even if they are designed to operate in diametrically different contexts. The Algae Grower is used at home to produce fresh *Spirulina*, educate on healthy food habits and recipes. The Algae Station is used to produce and distribute fresh algal biomass and dry-processed products. The target users of the two products are similar. In urban contexts, both the Algae Grower and the Algae Station may have significant diffusion. In order to start cultivating *Spirulina* at home, users need a small inoculum of fresh microalgae. Similarly, the Algae Station also needs an inoculum, but in larger quantities. At the moment, certified companies and research centers in the field of algal biotechnology can supply the biomass, as also suggested in the previously described service-system maps. These companies have several microalgal and cyanobacterial strains. Sometimes microalgae cultivations may die from various causes (i.e., too much lightning, few or wrong nutrients, water stagnation, contamination with external agents, poor maintenance). For these reasons, it may be useful to have backup cultures in order to replace them easily or to restart with new inoculations. A network of connected devices in cities could then be conceived. Volunteers and users of the Algae Grower and Algae Station may be invited to join in an online and offline community of growers-consumers, the so-called 'prosumers'.[41]

The community would be active in the exchange of inoculations – to start or restart the cultivations – but also for exchanging bits of advice related to the production, the preparation of recipes, the organization of thematic events, and periodic meetings. The community could agree on control guidelines, as the Fédération des Spiruliniers de France has been doing for some time in France. The advantages of acting locally are clear. Unlike large algae producers, small local producers even with higher production costs "*can capture 100% of the retail value*", and they can sell fresh biomass because "*fresh Spirulina is not easily commoditized by large distant producers*" (Henrikson, 2013, p. 39). The 'algaepreneurs' model could also be successful in urban contexts.

Central management could develop an online application, a place where the community can meet and coordinate purchase and sale operations, The application is a sort of O2O platform for the sale of microalgae-based products, but not only. It would allow promoting the culture of sustainability as well as educational notions on general biology and chemistry.[42] The application could be used directly from a smartphone. Users could easily find the closest Algae Stations on a map and reach them using navigation functions. The map would also indicate the amount of biomass available for each station, as well as nearby restaurants and partners. The graphic user interface could be somewhat similar to the ones of bike and car-sharing applications. From the app (or directly the screens on the Algae Station), it will be possible to check the values of the CO_2 subtracted in real-time, and the overall biomass pro-

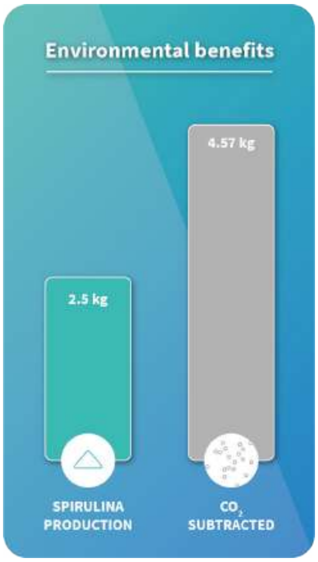

Figure 8.30. The Algae Station can show, for instance, the amount of CO_2 subtracted in real-time, and the overall production of algal biomass. This has a high educational value.

41 The term 'prosumer' was coined for the first time by businessman Alvin Toffler in 1980. Prosumer refers to a person who consumes and produces a product. For more information, it is recommended to read: Kotler, P. (2010). The prosumer movement. In B. Blättel-Mink & K. U. Hellmann (Eds.), *Prosumer revisited* (pp. 51–60). Wiesbaden: Springer VS.

42 There are already various applications with similar functions. Among the many, the Turin-based Italian startup AWorld – selected by the United Nations for the ActNow campaign – is worthy of note, which encourages virtuous daily behavior through collective challenges and gamification (Mac, 2020).

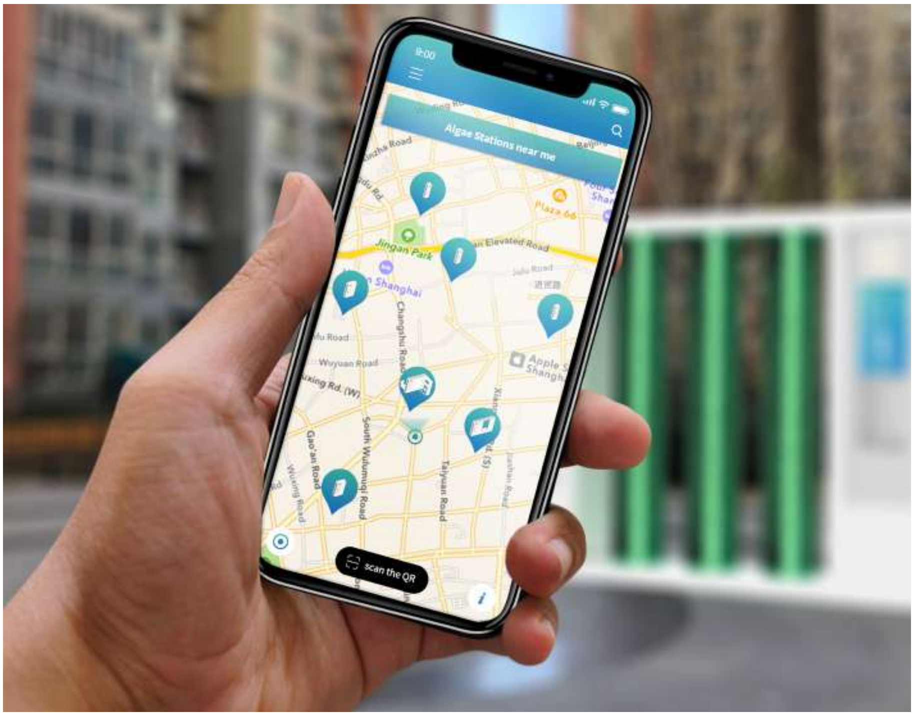

Figure 8.31. Algae Stations and Algae Grower users play an important role in a productive urban network. They can connect online and offline.

duced by the devices in the network (Fig. 8.30). A sort of win-win competition would, therefore, take place between various communities and individuals; they would compete to achieve goals and obtain badges, with a gamification process. The race is not a real competition, but rather a collaboration since the goal of reducing emissions and contributing positively to the environment is common (Fig. 8.31).

The production of microalgae, which now takes place in large plants in the countryside, would thus be decentralized, creating a resilient system of small and medium urban producers. Algae Growers and Algae Stations represent only two of the types of devices that could become part of this network. The possibility of having other devices created by third parties is not excluded. The value of a network is undoubtedly more considerable than that of individual devices. *"A system is more than the sum of its parts"* (Meadows, 2008, p. 12). A connected system like the one described favors job creation, helping people who are in need of economic support and contributing directly and indirectly to mitigating climate change. Not only oxygen is introduced into the atmosphere making the air cleaner, but also people's nutrition changes, perhaps with the reduction of the consumption of proteins from animal sources, with evident environmental and health improvements in the short, medium, and long term. The educational value of this system is high because the projects enter the communities and there is firsthand involvement, generating an intangible and invaluable value for urban communities, which could rediscover a sense of belonging that has been lost. There would also be many synergies in the area. In the near future, this model will be possibly tested in multiple cities, and it is hoped that it can find a positive response from those who adopt it.

8.8 Concluding remarks

The product development phase was significant in this research because it made it possible to verify, with practical hands-on, the gaps identified in the case studies analysis. It also laid the foundations for outlining future design guidelines useful to researchers and practitioners – which until now were only hypothesized – and identify a new theoretical framework for similar projects to thrive. It was an opportunity to experiment, to put into practice previously-acquired academic and working knowledge, but also to learn something new, by collaborating with people with varied educational skills and cultural backgrounds.

The two products will possibly find their niche market in the future. This is good because it shows the topicality of the research project and the theoretical-practical connection of academia with the real world. For the moment, the products have attracted the interest of potential customers and investors. Dissemination of research results will follow both in scientific conferences and through online channels and design competitions. The products will be given adequate media coverage, also to convey educational messages, such as design guidelines. By doing so, it is expected that more designers and the civil society will gain sensitivity on the subject, facilitating the transition toward a future in which microalgae will be more widely adopted. A higher number of researchers in the field of chemistry and biology could be curious about this approach, and these projects and the advancement of research and discoveries in both disciplinary fields would, therefore, be encouraged.[43] Beatriz Castelar, Brasilian researcher and oceanographer at University of Turin is already heading in this direction (see Appendix: The Algae Grower Plus with Beatriz Castelar).

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43 The paper Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019 which consists mostly of review and analysis of case studies, has already been shared on the online portal of Politecnico di Torino, Google Scholar, ResearchGate, and Academia, arousing the interest of a considerable number of readers worldwide and from different disciplinary fields, not only designers. The number of papers on this topic is still limited.

CHAPTER 9

Research outcomes

This chapter summarizes and discusses the research outcomes obtained by research through design.[1] These modest results conclude the doctoral thesis and are the starting point for further research and practice. The knowledge produced with the analysis of the case studies and the project's exploration defined the research results, which are separated into three categories – of equal importance and academic interest – which are: product/service, knowledge, theory (Fig. 9.1).

- **Product/Service:** includes the artifacts produced during the development phase of the project (the Algae Grower and the Algae Station) and the hypothesized added services. Each design phase has been appropriately documented and reported. Some considerations are also made regarding the models for the production and distribution of these devices.
- **Knowledge:** lessons learned during the research phase – as well as the design one – re-proposed in the form of a set of actionable principles and universal design suggestions for the design of small-scale urban products or

1 Part of the work described in this chapter was also previously published in: Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019; Vrenna, M., Crétier, M., & Landén, S. N. (2019). Participative urban air quality monitoring using open source devices. *Agathón*, *2019*(5), 167–174. doi:10.19229/2464-9309/5192019

Figure 9.1. Research outcomes: design, knowledge, and theory.

installations, to be used and adapted with due considerations.

- **Theory:** a theoretical framework is proposed, within which design projects involving the use of microalgae can thrive. The technical, social, economic, and environmental implications of the projects are also illustrated. This framework could be used as a reference by other designers.

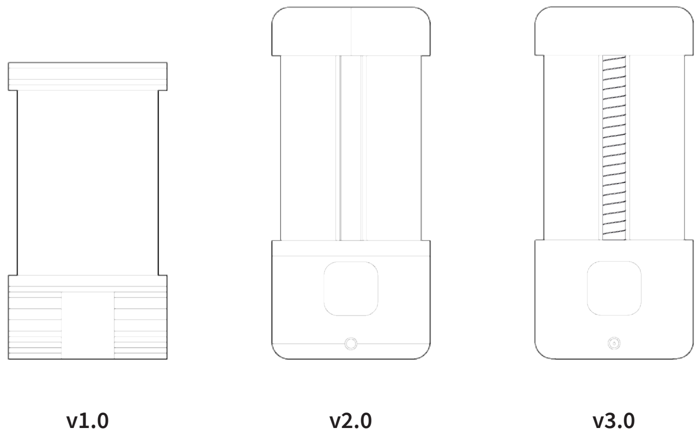
The topics covered in this section are organically linked to the previous chapters. This part is also an introduction to the final chapter, where some more general considerations are addressed.

9.1 The home device

The project development process is described in detail in chapter 8. In the attempt to act on different urban scales (micro/macro, private/public, home/district), and meet the needs of an assorted public, two products have been developed: one for domestic use and one for public spaces. Three versions of the prototype of the home device have been produced, each with incremental refinements. Version 1.0 is rudimentary but functional in all parts. Version 2.0, whose structure is 3D printed, is cost-effective and technically optimized. The high-fidelity prototype (version 3.0) has excellent finishes, highly efficient components, and better overall user experience (Fig. 9.2).

The construction of these prototypes was challenging and educational. Hopefully, many people will be using the Algae Grower, with positive results on their health and the environment. Two complementary strategies could be adopted to increase the user pool: one strategy does not exclude the other (Fig. 9.3). The first and more traditional hypothesis follows a business-as-usual logic, which consists in involving a company for product development, mass-production, and marketing. This operation could also involve one or more crowdfunding rounds. This strategy is undoubtedly valid and consolidated, which would probably lead to good sales results (thanks to the coordination of the marketing and promotion department), guaranteeing a high-quality standard of the device. The production would most likely be located in selected regions, according to market policies. Logistics, often polluting, would be another factor to consider. It is assumed that manufacturers of household appliances, household items, but also tech-companies may be interested in the marketing of this product. Therefore, it will be appropriate to connect with them in

Figure 9.2. The three versions of the Algae Grower developed during this study.



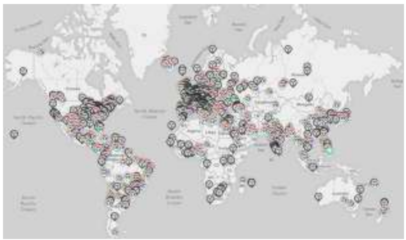


Figure 9.4. Fab Lab map: there are 1830 Fab Labs worlwide, in every continent except for Antarctica. Data as at November 2019.

the near future to understand potential ways to collaborate. Given the work of many people involved, and the profit margin, Spirulina-home production devices produced this way may not be cheap to buy.[2]

The second strategy, which perhaps would guarantee a more widespread diffusion of the product, is self-production. An emerging phenomenon is the so-called ‘open design’. Even though it does not have a broadly accepted definition, it can be intended as the *“free revealing of information on a new design with the intention of collaborative development of a single design or a limited number of related designs for market or non-market exploitation”* (Raasch, Herstatt, & Balka, 2009, p. 383). Open design applies to software and product design and has led to concrete results and successful implementations (Howard, Achiche, Özkil, & McAloone, 2012). The project demonstrated that it is possible to self-produce a Spirulina-harvesting device at home: a few documents (a manual for self-production, DIY kits, technical drawings, list of the components) could be made available online to download for free. The device could be independently produced by users, who could make use of the resources available, including receiving support from their local Fab Labs (Fig. 9.4).[3] The finished

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2 In the European market, a similar premium product could have a consumer price ranging from € 50,00 to € 150,00 – a price aligned with other kitchen table-top devices (e.g., yogurt machines, juice extractors). A higher price could result in poor sales. In-depth market research in collaboration with expert consultants, as well as an analysis of mass-production techniques, is necessary.

3 A Fab Lab – short form for ‘fabrication laboratory’ – is a small-scale workshop offering digital fabrication to individuals and companies. Usually, a Fab lab is equipped with analog and digital tools to make almost anything. Each Fab Lab is autonomous but they form a worldwide network of local laboratories – currently around 1800. The network offers practical, pedagogical, technical, financial, and logistical assistance, which surpasses a single laboratory’s capabilities. The concepts and projects developed in the Fab Labs are in the public domain and can be used by everyone (Menichinelli, Bosqué, Troxler, Raspanti, Schaub, & Neves, 2015). Events and workshops are held periodically. More information about Fab Labs at https://www.fablabs.io

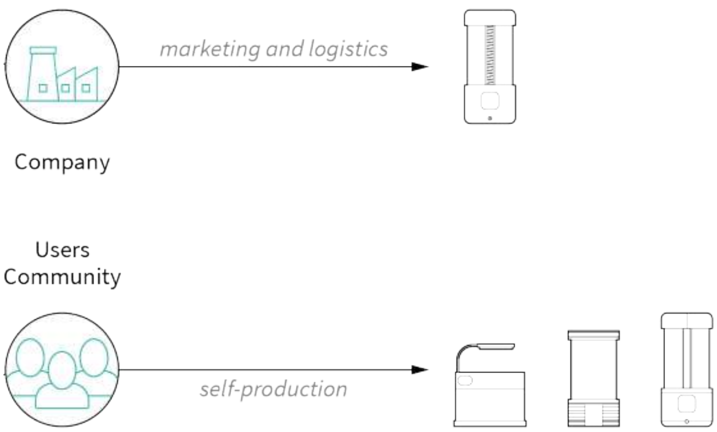


Figure 9.3. Hypothetical and complementary distribution strategies for the Algae Grower. Users may self-produce their device or buy a ready-made, high-performing one.

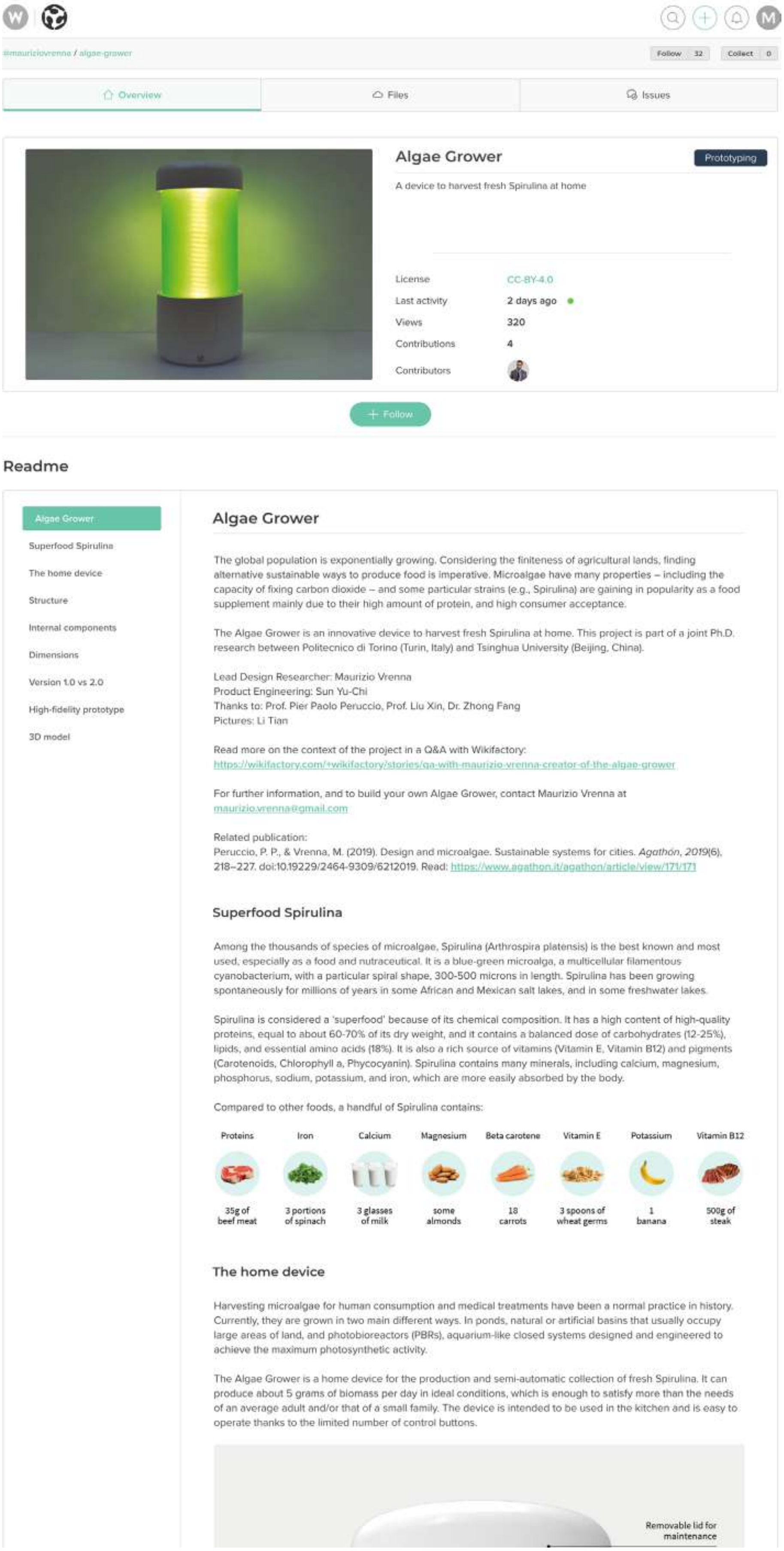
product would be more rudimentary – probably similar to version 2.0 of the Algae Grower – and with a much more contained price. Users would also have the option to improve some components and add or remove features based on their needs (some may even opt for minimal configurations, such as the setup adopted for the experiment).

Based on these considerations, the instructions for the self-production of the Algae Grower have already been published online on Wikifactory, a social platform for collaborative product development made for open source communities, designers and product companies (Fig. 9.5).[4] These open platforms provide handy tools and methodologies to collaboratively improve and share documentation toward the democratization of the knowledge. Makers from all over the world can download the files, ask questions, start discussions, and actively contribute to the projects' development. The documentation was uploaded on 5 July 2020. Since then, the project received 320 views and got 32 followers (data as at 13 September 2020). It has also been included in the 'featured projects' section, and a dedicated post with an interview was written by Nicolò Gnecchi, Wikifactory Community & Partnerships Lead (see Appendix: Q&A with Wikifactory). Users from Ghana, India, Michigan, Nigeria, Portugal, and Spain, also connected with direct emails to ask for more information. Besides, blog articles about the project have been published on international design and lifestyle websites such as Designboom, Tabi Labo, Trend Watching, and Beautyspot.[5] The feedback obtained so far are encouraging. Hopefully,

4 Instructions, list of the components, and technical drawings are available for download at https://projects.fablabs.io/@mauriziovrenna/algae-grower

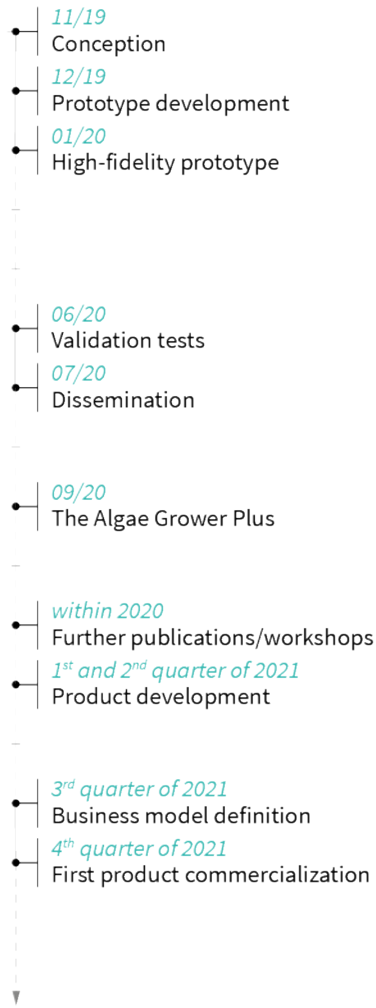
5 It is suggested to read: Katsikopoulou, M. (2020, July 13). Algae Grower home device can satisfy average adult's daily nutritional needs [Blog post]. Retrieved from https://www.designboom.com/design/algae-grower-home-device-average-adult-daily-nutritional-needs-07-13-2020/; Tabi Labo. (2020, July 27). 食糧問題解決の鍵！「スピルリナ培養キット」が発表 [For stylish interiors! 'Spirulina culture kit' that you can do at home] [Blog post]. Retrieved from https://tabi-labo.com/296358/wt-algae-grower;

Figure 9.5. The instructions for the self-production of the Algae Grower published on Wikifactory and the Fab Lab website. Data as at 13 September 2020. Retrieved from https://projects.fablabs.io/@mauriziovrenna/algae-grower



the project will achieve greater involvement of the international maker community through the organization of thematic workshops, better if in person. For instance, a first workshop could be held in Fab Lab Torino (F. Alessio, personal communication, July 6, 2020). Given the mediatic buzz, Beatriz Castelar demonstrated interested in working on a second version of the Algae Grower, intending to scale it up and include a comprehensive aquaculture system (see Appendix: The Algae Grower Plus with Beatriz Castelar). While maintaining the principles of open design, it would also be possible to refine the business models and the partnerships with companies and institutions (e.g., Fab Labs and universities), which would play a key role in the promotion and acquisition of an extended pool of users. They would generate a community of aware citizens: the willingness to act together toward sustainability and a high level of public awareness could pave the way for other kinds of technical solutions. For the sake of clearness, the road map of the project is illustrated in Fig. 9.6.

Figure 9.6. The road map of the Algae Grower project from November 2019 to October 2020 and beyond.



9.2 The public device

The second design output of this research is the Algae Station, a device to be placed in public spaces. The design of the Algae Station is inspired by that of the urban installations analyzed in the case studies – some more visually appealing while others more efficient from an engineering perspective.[6] Moreover, the Algae Station has many visual, dimensional, and technical similarities with other common elements found in cities, such as parcel drop-off points and vending machines. The Algae Station aims to improve the experience of growing, harvesting, and distributing *Spirulina* in the city, in the attempt of optimizing shapes, spaces, and various functions. Furthermore, in some particular configurations, it could act as a landmark or an aggregative fulcrum, gaining substantial social value for entire communities. The Algae Station is a unique product, one of a kind. It has important dimensions and a firm identity, which certainly does not make it go unnoticed. With its modularity, it can be assembled in many configurations and adapted to the most disparate contexts: in the previous chapter, only three possible scenarios were described, but these could be many more.

The Algae Station – at present – is still a concept. The scale model is purely

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Mennen, R. (2020, July 24). Innovation of the day. Algae Grower [Blog post]. Retrieved from https://info.trendwatching.com/innovation-of-the-day-the-algae-grower-simplifies-the-process-of-growing-spirulina-at-home; Mennen, R. (2020, July 29). Natuurlijke ingrediënten worden alsmaar populairder [Natural ingredients are becoming increasingly popular] [Blog post]. Retrieved from https://www.beautyspot.nl/kennisbank/natuurlijke-ingredienten-worden-alsmaar-populairder/

6 Particular reference to Algaegarden (paragraph 7.2.2), Urban Algae Canopy (paragraph 7.2.6), The Carbon Sink (paragraph 7.2.14), the Algae Dome (paragraph 7.2.15), WaterLilly 3.17 (paragraph 7.2.17), and BioUrban 2.0 (paragraph 7.2.18).

illustrative and only gives an idea of a plausible look of the final product (see Appendix: The Algae Station – Scale 1:10 model). For budget and time constraints, and partly also because of the sanitary emergency, it was not possible to reach the same level of detail of the home device. In the near future, the intent is to design and engineer the product in all its parts. On paper, the Algae Station is undoubtedly an exceptional and game-changing device, but the tests were not sufficient to validate all its features. The limitations of the product are evident, as well as its potential. The Algae Grower is meant to be used in the medium-long term and is not a temporary installation. A managing company or an association of people could deal with periodic and extraordinary mainte-

Table 9.1. The Algae Station: assumptions regarding construction, monthly operating costs, and monthly biomass production.

	Element	**Unit price**	**Total**
Construction costs	Structure	€ 900.00	
	Tubular glass	€ 600.00	
	Hydraulic system	€ 400.00	
	Electric system	€ 400.00	
	Pneumatic system	€ 300.00	
	Screen	€ 200.00	
	Photovoltaic panels	€ 300.00	
			- € 3,200.00
Operating costs (month)	Medium	€ 30.00	
	Electricity	€ 37.00	
	Labour	€ 360.00	
			- € 427.00
Biomass (month)	Spirulina	€ 220.00/kg	**+ € 660.00**

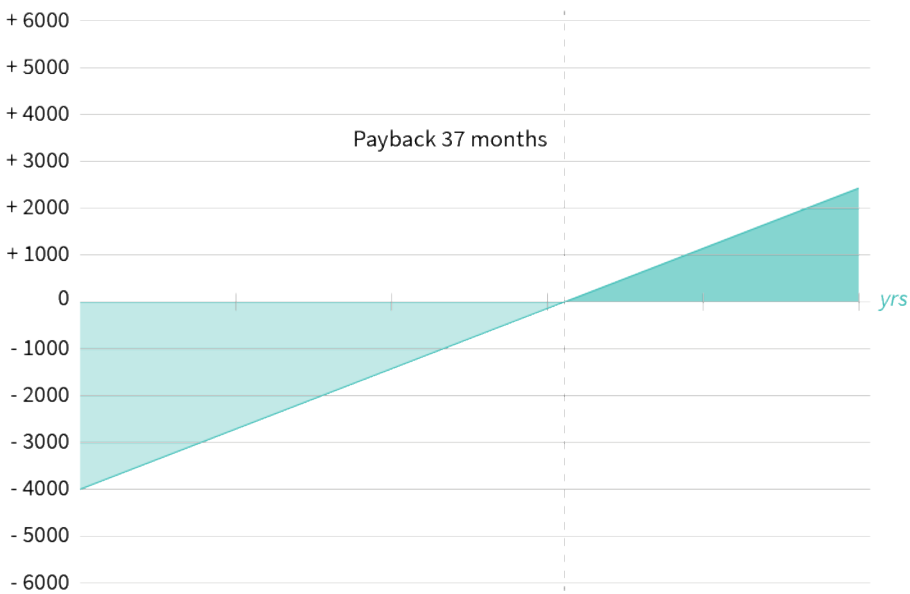


Figure 9.7. The Algae Station: break-even graph over five years. The payback period is estimated at 37 months.

nance. Its use could generate employment in the city, as already happens in less developed countries in Africa, and similarly to the model adopted by EnerGaia in Thailand and Bangladesh (see paragraph 7.2.3 and the Appendix: A conversation with Ehsanul Karim).

The 'algaepreneurs' business model, adapted to an urban context, could be successful with an estimated payback period at around three years. This time is not very short, but it must also be considered that the project is designed to have an extended duration. Figure 9.7 shows the break-even graph based on the assumptions from Table 9.1, over a period of five years. A detailed project analysis can be found in the Appendix: The Algae Station – Economic analysis. The analysis has been conducted with the supervision of Fabrizio Galliano and Federico Giuliato, two finance analysts experts. The construction costs (€ 3,200) are only guesstimates for a configuration of the Algae Station B+C (Fresh *Spirulina* vending machine and one PBR module). The consumer sale price of the biomass is lower than the Italian average. Other assumptions that have been taken into consideration are: starting cash € 4,000; low operating costs; ordinary maintenance costs; cost for the work of a part-time employee; Italian tax system; slight inflation over the years; limited – or zero – biomass production in colder winter months (production may also vary based on the location of the device). The analysis draws inspiration from the study by Griffa and Vissio (2018) regarding the medium-long term economic sustainability of WaterLilly 3.17, in which they hypothesized a corollary of activities to ensure the sustainability of the project. The indirect benefits of the Algae Station on job creation and health improvement are difficult – if not impossible – to quantify with scientific rigor. A constant, albeit modest, income could also be the driving force for incentivizing citizens to urban self-production and creating communities of cohesive people aware of environmental issues. The project is self-sustaining but not lucrative. The system could be economically viable if the labor expense is part of the community activities or if it is shared with other activities, such as building management.

It is clear that the economical production and installation costs of the Algae Station vary according to the configurations and the number of modules that will be used. However, the structure certainly has a considerable price, given the use of various technical-technological elements. The materials used in the concept are not cheap, starting from the glass for the photobioreactors, as well as the air and carbon dioxide pumping systems, the lighting apparatus, the automatic biomass distribution mechanism, and the touchscreens. The Algae Station outer casing could be covered with advertisements to balance running costs and reach a payback point faster. It would be an ethical and selected advertisement, at affordable costs and mainly based on the promotion of local activities, partners of the system, and sustainable practices – which reflect the values of the entire project. It would also be possible to design rudimentary, economical, but less-appealing versions of the product, with low-cost materials. These versions would be similar to the photobioreactors patented by EnerGaia, or to the ponds cultivation of African microfarms. These versions would most likely have limited productivity but greater diffusion. The use of a basic version would not exclude the use of the 'premium' one since they would be placed in very different places and contexts. Payback time could also be shortened by including revenues from the sales of dry *Spirulina* vending machine products. In fact, vending machines can be highly profitable if the business is adequately structured and positioned in the right places (VendTech Media, 2020).

Without a pilot project, however, it is impossible to verify how – and if – the Algae Station can be successful. It can be assumed that it could attract more interest in Asia than in Western countries because the management of public and private spaces is different, and the population density is much higher. Also, in China, common goods' vandalism is rarer than in Europe or America (LePetit, 2016).

9.3 Design guidelines

This paragraph draws the guidelines – or better say some design suggestions – for the design of integrated adaptive products, services, and systems. These are useful for the implementation of projects which involve the use of microalgae as driving forces for fostering economic profitability, environmental sustainability, and eventually social inclusion primarily in urban areas, but also everywhere.[7] These indications are mainly for the design of products or small-scale urban installations, although they can be valid – with due consideration – for interventions on an architectural scale too (Table 9.2). Firstly, it is necessary to critically examine the unique contexts of operation, to identify the critical factors for facing the problems with full knowledge of the facts and scientific rigor. However, microalgae production must not be an imposed option, but rather an adequate response to the circumstances. The study of microalgae is fundamental to understand how they function, without the need to enter deeply into the domains of competence of other subjects.

Based on the project needs, it is necessary to identify the most suitable algal species for the particular case, planning that if they have to be used as food, they must be cultivated in clean waters. Designers should divert attention from the sole material component of the project, focusing on the definition of relat-

7 I have been lucky enough to spend time on research and design. These are not guidelines to be followed literally or a particular methodology, but rather general suggestions, the result of some considerations I have made during the work. I think that this approach can be useful to colleagues designers who are dealing with microalgae for the first time, but also to more experienced researchers and practitioners who are working on cutting-edge studies and projects.

1	Examine the context
2	Gain knowledge on microalgae
3	Focus on the product but also on connected services and experiences
4	Provide general notions to the audience
5	Collaborate with professionals from other fields
6	Involve communities and institutions
7	Assess the sustainability of the project
8	Facilitate the replicability
9	Think big, act small
10	Create impact and value

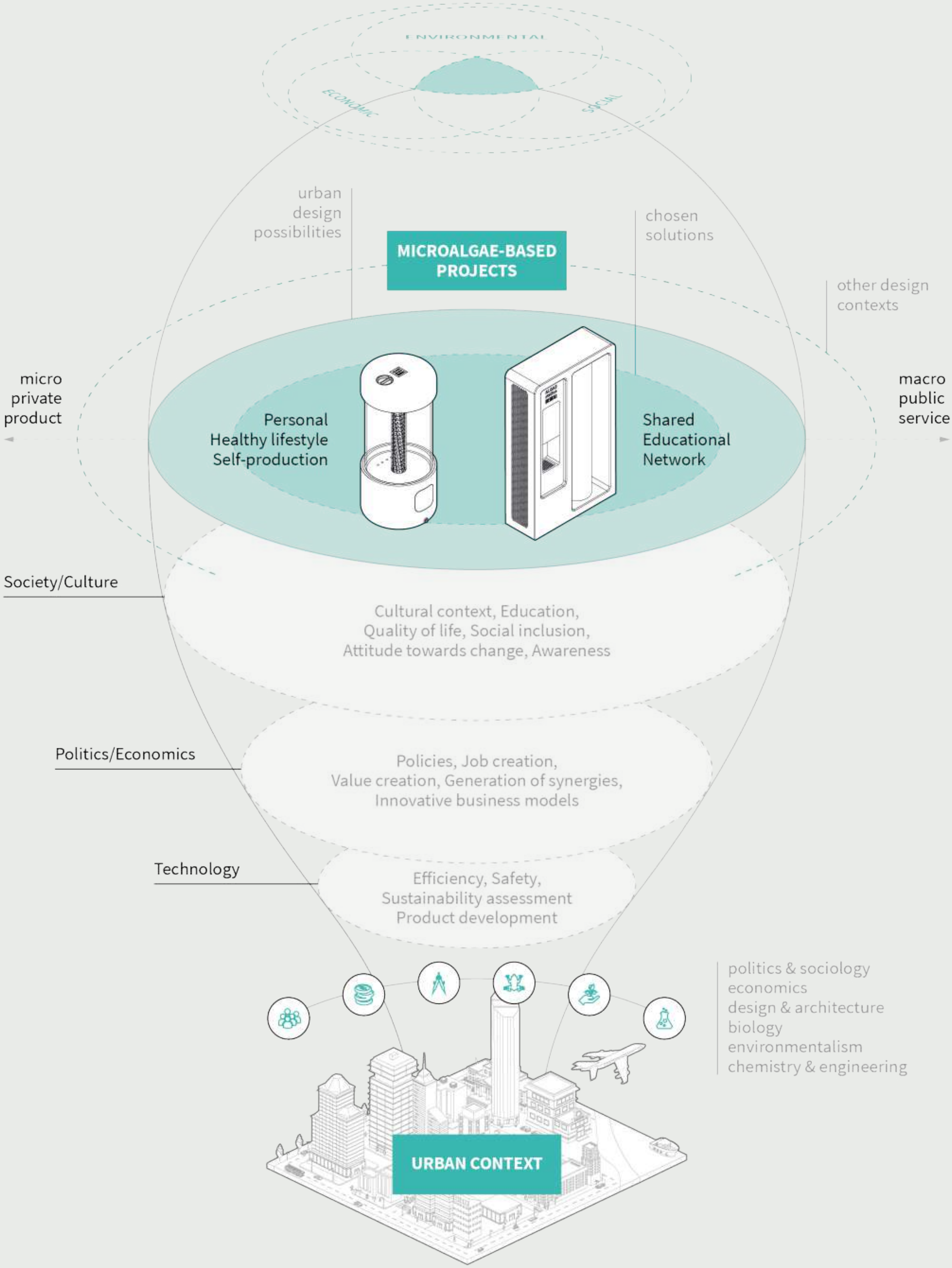
Table 9.2. The suggestions for the design of products or small-scale urban installations that involve the use of microalgae.

ed services, experiences, and educational aspects. Given the lack of knowledge on the topic possessed by an audience of non-expert users, it is good to provide them with general notions for a better understanding. Increased awareness would encourage the adoption of microalgae, which is still limited. Collaboration with other professionals is strongly recommended to fill disciplinary gaps. It is also important to involve citizens and local activities such as restaurants, canteens, shops, schools, and gyms. Even institutions and universities could participate in providing financial, scientific, and cultural contributions.

In addition to the environmental impact, the economic sustainability of the projects must be thoroughly checked. To do this, it is advisable to refer to models that have been proved successful and, if necessary, asking for the support of specialists to shorten payback periods. The project can be 'open', therefore modifiable, adaptable and improved by anyone, to facilitate its replicability. The physical scale of the outcome is not proportionally related to its impact: small products can radically improve the life quality of entire communities, while larger installations may require substantial economic and management efforts. To conclude, it is important to bear in mind that the final aim of the projects must not be the mere cultivation of microalgae for commercial use – as indeed already happens in huge production plants located in the countryside – but the use of these for the creation of value leading toward positive urban change for residents.

9.4 Theoretical framework

A theoretical framework is a conceptual structure that supports a particular research subject. It is significant in research because it allows readers (and authors) to imagine and understand the study in its broader context, identifying fundamental notions and conceptual relations between them. The fol-


ENVIRONMENTAL
ECONOMIC
SOCIAL
urban design possibilities
chosen solutions
MICROALGAE-BASED PROJECTS
other design contexts
micro private product
macro public service
Personal
Healthy lifestyle
Self-production
Shared
Educational
Network
Society/Culture
Cultural context, Education, Quality of life, Social inclusion, Attitude towards change, Awareness
Politics/Economics
Policies, Job creation, Value creation, Generation of synergies, Innovative business models
Technology
Efficiency, Safety, Sustainability assessment Product development
politics & sociology
economics
design & architecture
biology
environmentalism
chemistry & engineering
URBAN CONTEXT

lowing page presents the conceptual framework for the realization of microalgae-based design projects in urban contexts (Fig. 9.8). The framework summarizes the topics discussed previously in this thesis and underlines the main challenges posed by the act of designing innovative products, services, systems, and experiences involving microalgae: researchers and professionals coming from different fields can use it as a reference for developing new projects.

Figure 9.8. Theoretical framework including sustainability, socio-cultural, economic, and technological implications.

First of all, the fundamental aspect is sustainability. Innovative projects must respond to particular social, economic, and environmental needs. Projects should consider all these aspects, for being successful and impactful. As already mentioned, the use of microalgae is only one of the many possible solutions for achieving sustainability, and their use must make sense. Approaches to the project must be multidisciplinary: designers should collaborate with architects, biologists, chemists, and engineers for designing products, as well as with local politicians, sociologists, economists, and other experts in the development of complex services and systems. Working with experts with assorted backgrounds requires a longer time and different ways of collaborating, but it guarantees better results because all the different facets of the problem are taken into account.

A great project has solid foundations: therefore, designers must consider its technological, political-economic, and socio-cultural implications. It is necessary to use technology correctly – as a starting point for the project – but this is not fundamental because it can never be the only solution. Undoubtedly, the wise use of the available technology could increase, for instance, efficiency, automation, and security. From an economic point of view, it is necessary that the project brings value and creates jobs, and that its business model is sustainable over time. It is also required to respect local policies, or to collaborate with legislators to improve them – this is especially important for services that operate with a sharing economy model and in places where microalgae regulations are not yet well defined. Finally, it is necessary to act on the socio-cultural sphere to encourage citizens and users to change their behaviors, to make them aware of the benefits of the project, and to educate on a more environmental-friendly lifestyle. The latter is a very challenging task, but it is indispensable to eradicate well-established paradigms.

Following these indications, the possible urban design projects are virtually unlimited and can operate on different scales: micro-macro, private-public, product-service. Design decisions will be made to select and develop the solutions that are considered most valid, based on the project brief (e.g., Algae Grower and Algae Station). It should be kept in mind that this approach has been developed for cities, which have unique characteristics and problems, but the framework can also be adapted to diametrically different contexts, such as rural areas.

CHAPTER 10

Conclusions

Scientific research, despite its comprehensiveness and contribution to knowledge in a particular field of study, never comes to an end. It can be expanded, modified, implemented, used as a basis for further studies, and in some cases, criticized or even refuted. In the final chapter of this doctoral dissertation, an overview of the research is traced, the answers to the research questions are summed up, and the possible positive impacts of the projects outlined. The limits of this study and the directions for future research are also highlighted.

This research topic, at first glance, may seem unusual. In reality, it is a particularly popular and future-oriented niche of investigation, which will contribute – at least in a small part – to the development of the discipline of sustainable design and the next green revolution. The contribution to knowledge is minimal but significant (Fig. 10.1). Designing with microalgae today should not be just a purely aesthetic or technical solution – an old-fashioned approach used in many of the case studies analyzed. Concrete projects of this nature should be able to enhance the qualities of microalgae by bringing a substantial practical benefit for all, which is not just economic. As described in detail in chapter 5, microalgae can be used in many areas. The project in this thesis focused on a particular algal stream – *Spirulina platensis* - for human food use (Fig. 10.2), but its urban production does not exclude that it can also be utilized for other purposes (e.g., fertilizers).[1] Great importance has been given to the quality of the biomass: *Spirulina* was chosen because it is a healthy and nutritious product that is good for the health of those who consume it, and whose cultivation leads to visible environmental benefits. The economic feasibility, which guarantees the development of the project also in the medium-long term, is another aspect of fundamental importance that has been taken into consideration. Moreover, the recent COVID-19 pandemic has added a sanitary crisis to climate and socio-economic ones. It exposed the fragility and limitations of the current agricultural production systems and invited us to reflect on our development models. The world has stopped for months and, quarantined in homes, we realized that a healthy and nutritious diet is essential. It is, therefore, necessary to open up to new perspectives and respond to the crisis: rethinking a new way to feed our cities is the logical consequence of an inevitable revolution.

This thesis talks about design, but with a different perspective from traditional design: it takes into account the common goods, our life, and that of posterity. A product cannot be the sole solution to a problem. Instead, design becomes a tool to create societies that are more just and equitable. It is hoped that reading this thesis – and the additional articles published in scientific journals – will be useful to researchers and professionals in the field of design, biology, and engineering. Confidently, this work will arouse the interest of local governments, private companies, and entrepreneurs, who want to collaborate to implement real-world projects in urban environments, but not limited.

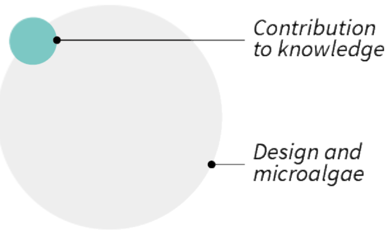


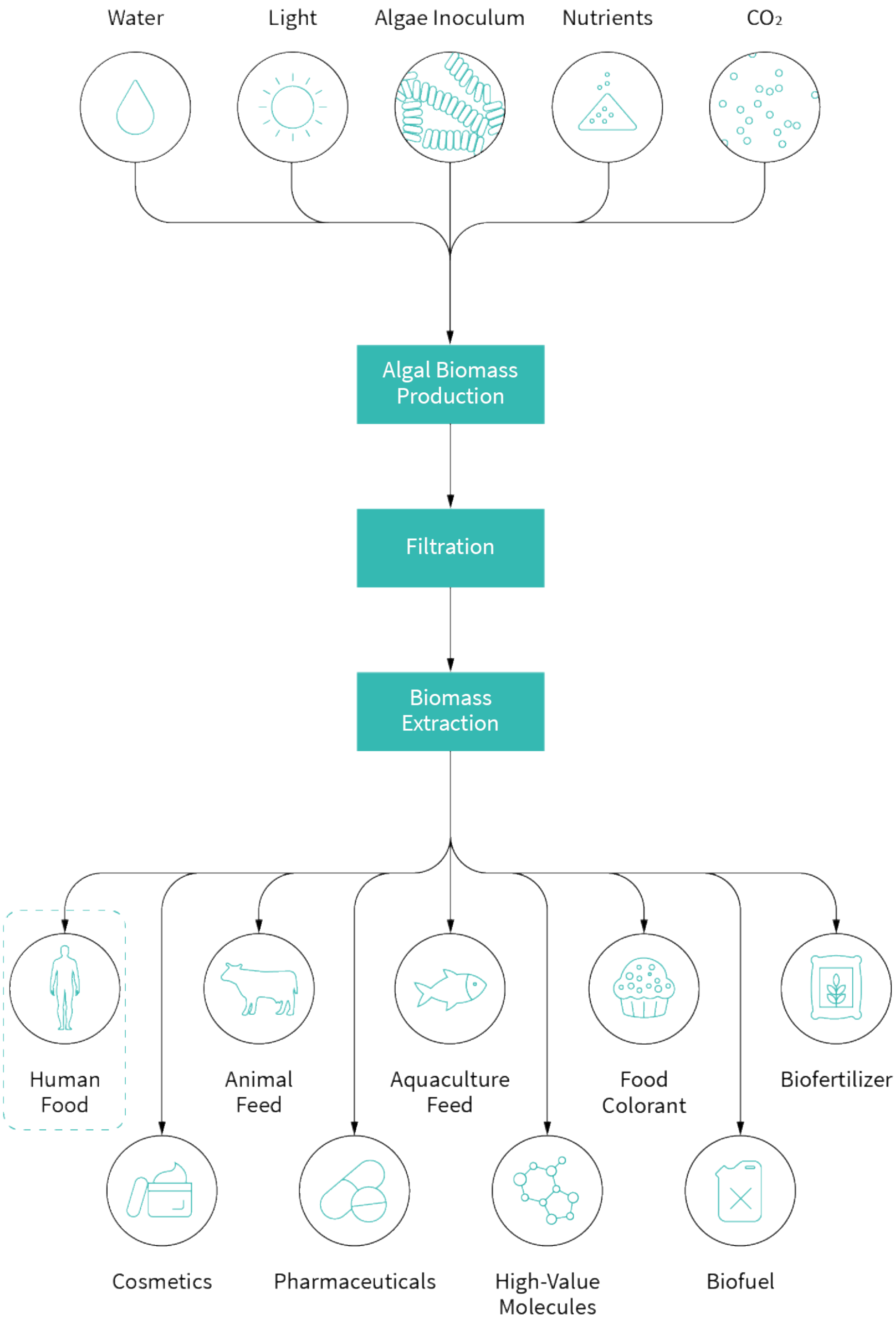
Figure 10.1. The modest but significant contribution to the knowledge of this research.

10.1 Final overview

This paragraph summarizes the doctoral dissertation, highlighting the most challenging and significant passages. The introduction to this research is considerably broad, while the design project is highly targeted. The first part of the thesis investigates diverse topics: for instance, economic, social, and environmental sustainability, and the need to adopt new development models for the decades to come. In a dedicated chaprter, the theme of food and novel foods has been discussed. It is clear that the current systems of production, distribution, supply, and consumption of food are no longer adequate, and that revolutionary strategies to guarantee food quality and quantity must be taken into consideration, mainly because of the exponential growth of the

1 Based on the literature and an extensive field and desk research, and as already highlighted in other parts of the thesis, I believe that *Spirulina* has tremendous underused potential as food. That being said, it is necessary to underline that the use of microalgae as food is only one of the many directions, and the modest design solutions presented in this dissertation are the result of personal/professional design choices and considerations.

Figure 10.2. Elements needed to grow microalgae are common. Once the biomass is extracted and transformed, it is used for several commercial and industrial applications. This research focuses on the production of *Spirulina* for human food consumption.



world population.

As for the design studies, the last few years have marked a substantial change. Designers are evolving their approach and mindset, both in the world of practice and research, embracing new methodologies and breaking down disciplinary barriers. Design for Sustainability encompasses a series of approaches with different terminologies but with similar – or same – objectives. Ecodesign, Biomimicry, Product-Service System Design for Sustainability, Systemic Design, Transition Design, are all the approaches that have been highlighted in this paper and that underline the relevance of nature-based solutions. Among all, Biodesign, a new multidisciplinary field of action that has seen the realization of projects with symbiotic relationships with nature, which also involved the use of algae and microalgae.

To limit the context, the research focused on urban environments because they are the places where most human activities are concentrated and where it is expected to see a significant increase in inhabitants. Cities are the places where our cultures have flourished and thrive; they are centers of innovation, education, and wealth, which attract talents and offer career opportunities and well-being. Most of the world's economies are located in urban regions: cities are the, therefore, the problem for sustainability, but also the key to mitigating climate change. Design is a tool for shaping present and future cities and contribute positively – and on several levels – to inclusive development.

An entire review chapter has been dedicated to microalgae. The chapter includes the taxonomy and evolution of algae, uses in history (both as food and as medicine), and technical-scientific notions necessary for a thorough understanding of the topic. The same chapter presents the global and local microalgae markets (with a study on average prices and sales channels), and alternative business models such as those of the French algaepreneurs and the rural areas in developing countries. Given the success of these models, in the design phase, they were adapted to the urban context. The second part of the thesis consists of a detailed case studies analysis, which shows the state of the art of design and microalgae and outlines the directions for future projects. This analysis has been significant and time-consuming since, to date, it is the only attempt in scientific design literature to map and categorize projects of this type. The results of the analysis were published in a scientific design journal. Finally, the design part included the development of two products and services, and above all, it allowed to trace – through theoretical research combined with a practice-based approach – new boundaries of knowledge, outlining a theoretical framework, and some guidelines for the realization of similar enduring projects.

Fig. 10.3 is a simplified mind map that helps to understand the context of this research better. In this study, 8 macro-areas of study (sustainability, food, technology, design, economics, cities, biology, and sociology) were explored, with different levels of depth. The map lists some keywords for each topic. The theme of microalgae is transversal to others and recurrent throughout the thesis: the research area covers only a small space in the vastness of knowledge. This research was undoubtedly an all-round experience, which enriched me personally and professionally and which brought out some interesting considerations, despite having limitations. The thesis tried to answer two research questions, and the following paragraph summarizes some considerations.

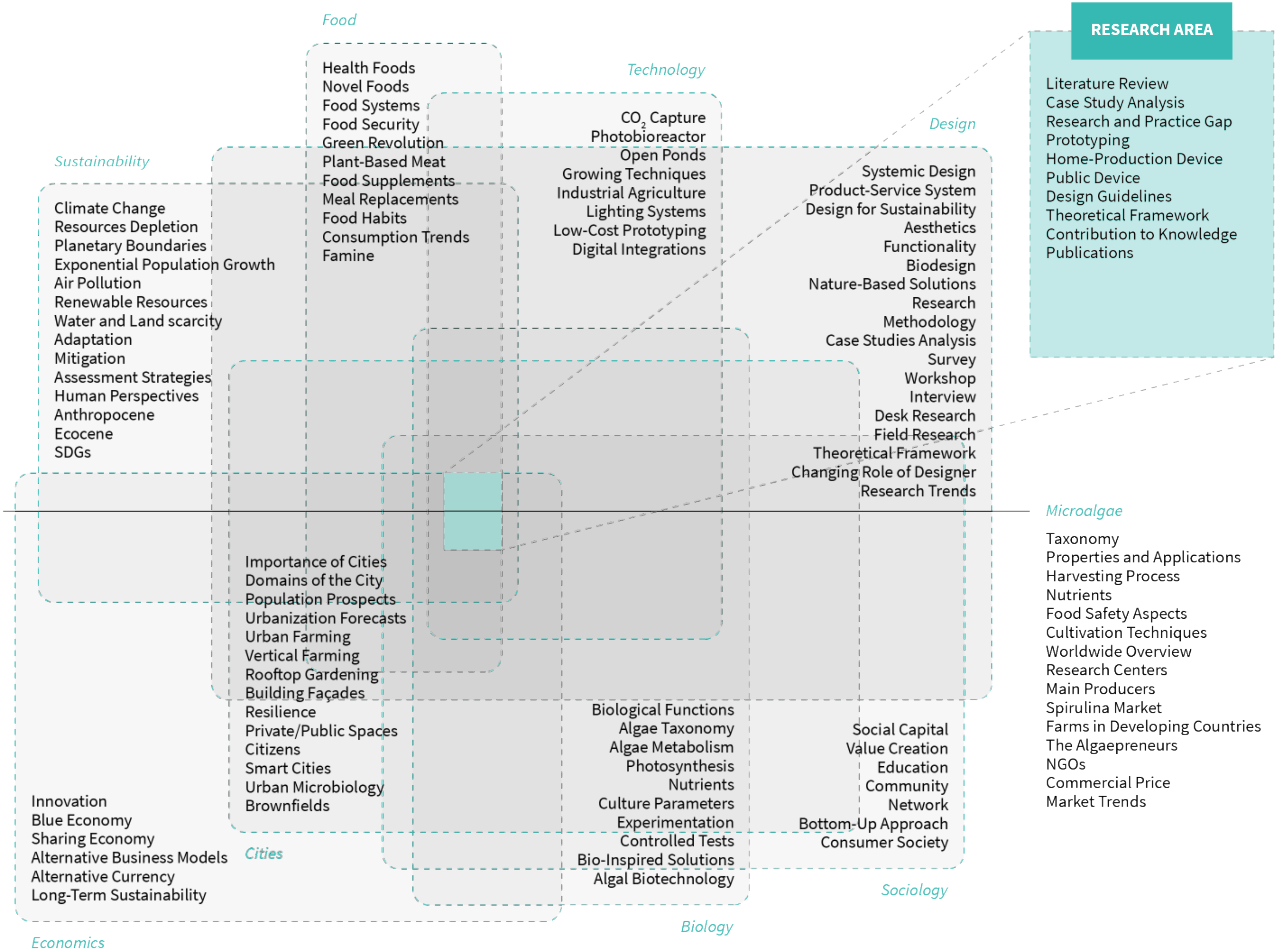
Figure 10.3 (Facing page). Simplified mind map of this research. The study covers only a little part of the vastness of knowledge.

10.2 Research answers

This doctoral research addressed two main questions: '*How can design researchers contribute to microalgal studies?*', and '*How to design products, services, and systems involving microalgae that are beneficial and sustainable for the society?*'. An attempt has been made to answer these questions exhaustively in the previous chapters, particularly in chapter 6 – Design and microalgae, and in chapter 9 – Research outcomes. The research answers are summarized below.

To answer the first research question, a rigorous literature review was needed. The study highlighted the evident lack of debate between different disciplinary profiles and the lack of structured methodologies and research in the field of design and microalgae. Designers can draw many technical and scientific notions from biology and chemistry. At the same time, they can contribute to the advancement of research on microalgal studies through active participation in multidisciplinary research groups, with no hierarchical relationships between team members: nevertheless, these collaborations are still limited. The contribution of designers, who have more transversal and generalist skills than scientists, is remarkable because they can make scientific innovations – which often remain in labs – more accessible and affordable. Design researchers are also warmly invited to publish their studies and experiments with microalgae on multidisciplinary scientific journals. This operation would strengthen the perception of design discipline that other experts have, and would arouse their interest (even today, design is often seen as a subject closely linked to art and humanities, devoid of scientific-methodological foundation).

To answer the second question, practice-based research was necessary, leading, among other results, to the design of products and services to be used in urban contexts – the Algae Grower and the Algae Station. These projects were undertaken to gain new knowledge and to demonstrate the validity of the claims by means of practice and through artifacts. For designing products, services, and systems that are sustainable and beneficial for society, many considerations must be made. These factors are summarized in the previous chapter in a few guidelines (Table 9.2), and in a theoretical framework (Fig. 9.5). First of all, designers must study general notions of phycology and master them. It is recommended to 'get the hands dirty' with experiments, hands-on, and empirical endeavors. Environmental, economic, and social sustainability is the basis for the success of these projects. Ideally, project strategies should come from different disciplines: design and architecture, politics and sociology, economics, biology, environmentalism, chemistry, and engineering. Technological aspects, such as efficiency and safety, are essential. However, even more important are the economic and socio-cultural aspects, including the creation of new business models, as well as the cultural context and attitude towards behavior change. The design possibilities are virtually unlimited.



Food
Health Foods
Novel Foods
Food Systems
Food Security
Green Revolution
Plant-Based Meat
Food Supplements
Meal Replacements
Food Habits
Consumption Trends
Famine
Technology
CO_2 Capture
Photobioreactor
Open Ponds
Growing Techniques
Industrial Agriculture
Lighting Systems
Low-Cost Prototyping
Digital Integrations
Design
Systemic Design
Product-Service System
Design for Sustainability
Aesthetics
Functionality
Biodesign
Nature-Based Solutions
Research
Methodology
Case Studies Analysis
Survey
Workshop
Interview
Desk Research
Field Research
Theoretical Framework
Changing Role of Designer
Research Trends
RESEARCH AREA
Literature Review
Case Study Analysis
Research and Practice Gap
Prototyping
Home-Production Device
Public Device
Design Guidelines
Theoretical Framework
Contribution to Knowledge
Publications
Sustainability
Climate Change
Resources Depletion
Planetary Boundaries
Exponential Population Growth
Air Pollution
Renewable Resources
Water and Land scarcity
Adaptation
Mitigation
Assessment Strategies
Human Perspectives
Anthropocene
Ecocene
SDGs
Microalgae
Taxonomy
Properties and Applications
Harvesting Process
Nutrients
Food Safety Aspects
Cultivation Techniques
Worldwide Overview
Research Centers
Main Producers
Spirulina Market
Farms in Developing Countries
The Algaepreneurs
NGOs
Commercial Price
Market Trends
Importance of Cities
Domains of the City
Population Prospects
Urbanization Forecasts
Urban Farming
Vertical Farming
Rooftop Gardening
Building Façades
Resilience
Private/Public Spaces
Citizens
Smart Cities
Urban Microbiology
Brownfields
Cities
Biological Functions
Algae Taxonomy
Algae Metabolism
Photosynthesis
Nutrients
Culture Parameters
Experimentation
Controlled Tests
Bio-Inspired Solutions
Algal Biotechnology
Biology
Social Capital
Value Creation
Education
Community
Network
Bottom-Up Approach
Consumer Society
Sociology
Innovation
Blue Economy
Sharing Economy
Alternative Business Models
Alternative Currency
Long-Term Sustainability
Economics

The projects made in this research also revealed that to achieve good results, cooperation with many stakeholders is necessary, especially for the creation of services and systems. Designers can connect professionals with the most different skills – engineers, biologists, and chefs, as happened in the course of the research – as well as entrepreneurs, citizens, policymakers, and other business partners, as hypothesized (Fig. 10.4). The educational value of these projects has to be tangible.

Concerning the limitations of the study, the answers to the research questions are exhaustive. An attempt was made to analyze the research context from several points of view and with a critical approach. Expert advice, especially from informal face-to-face meetings with engineers and biologists, served to broaden knowledge and reach these conclusions.

10.3 Urban open systems

As already mentioned in the previous chapters, this thesis does not present a traditional systemic design project. Two representative product and service design projects have been developed with an in-depth systemic approach, which activates a behavioral innovation process whose aim is to boost the characteristic features of the product, by adapting it to the territorial qualities, and educate, protect, and promote a widespread, shared environmental culture (Bistagnino, 2016).

The production of microalgae in cities opens up many possibilities and scenarios that were once inconceivable. *"Growing food in cities and urban areas may become critical as fuel costs rise, making transported food increasingly expensive. On a small land area, a community could meet a portion of its food requirements from microalgae, freeing cropland for community recreation or reforestation"* (Henrikson, 2013, p. 11). Urban open systems – to use the definition of Meadows (2008) – are sets of interconnected elements and with a common purpose, which can act on different scales, albeit with many similarities (e.g., public and private) and with cascading benefits on several levels. The final objectives are the decentralization and democratization of microalgal production and the projects' affordability and replicability.

With reference to the city levels identified by Harrison and Donnelly (2011) and described in paragraph 4.3, systemic services for the cultivation of microalgae in urban contexts would act on the natural environment by reducing the use of land for agricultural use; on resources by ensuring a new food supply system; on services by allowing the creation of new businesses (also supporting the healthcare system in the long run); on infrastructures by creating new aggregation points; and finally on social systems by giving life to a new culture of nutrition and sustainable living, which could ultimately persuade policymakers to introduce progressive laws and regulations.

As for public use systems, the Algae Station perfectly embodies the char-

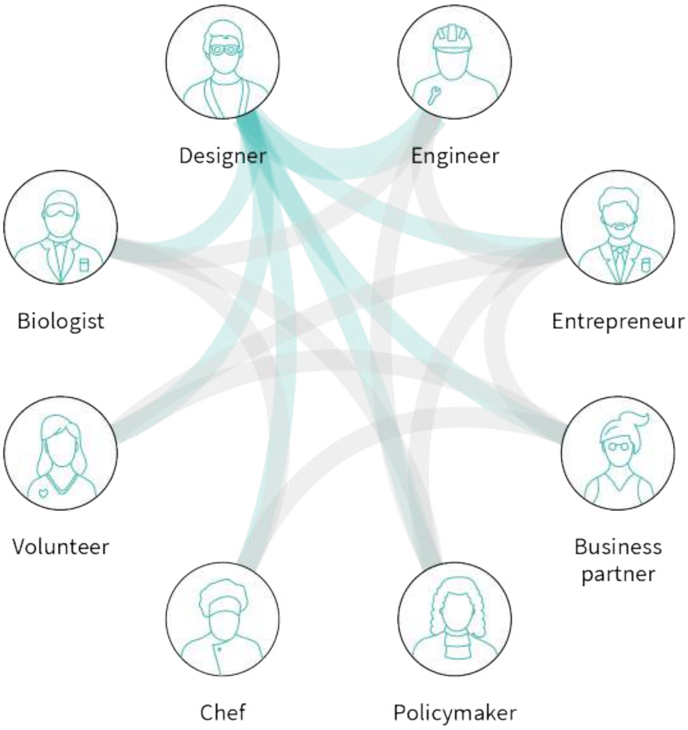


Figure 10.4. Successful projects require the involvement of many stakeholders. Designers can act as mediators with their transversal knowledge.

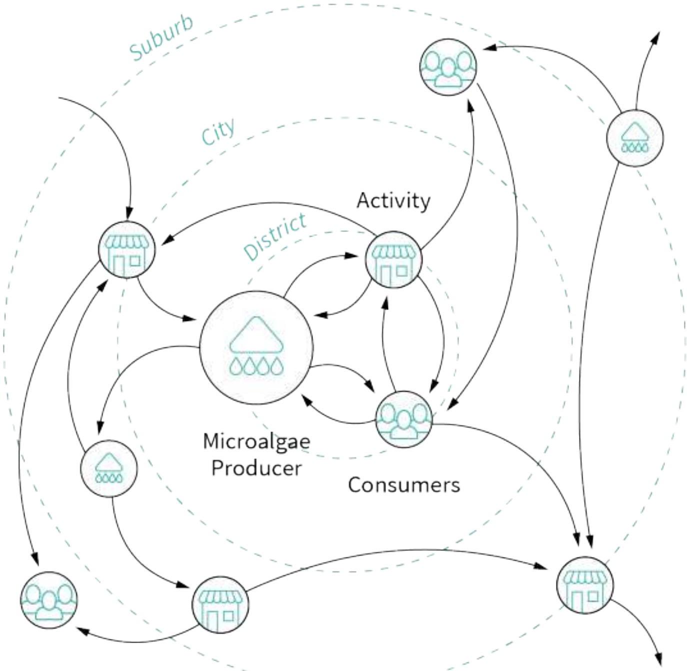


Figure 10.5. A hypothetical urban open macrosystem of microalgae producers, connected activities, and people. The output of one activity can be the input for another (e.g., nutrients).

acteristics that an urban open system should have, but obviously, it is not the only solution. Offices, schools, residential compounds, as well as hotels, restaurants, supermarkets, stations, airports, and abandoned areas, could become perfect places for the production of microalgae. The solutions adopted in these places could be simple and pay less attention to the form – as already happens in the microalgae farms in developing countries. The intention is to

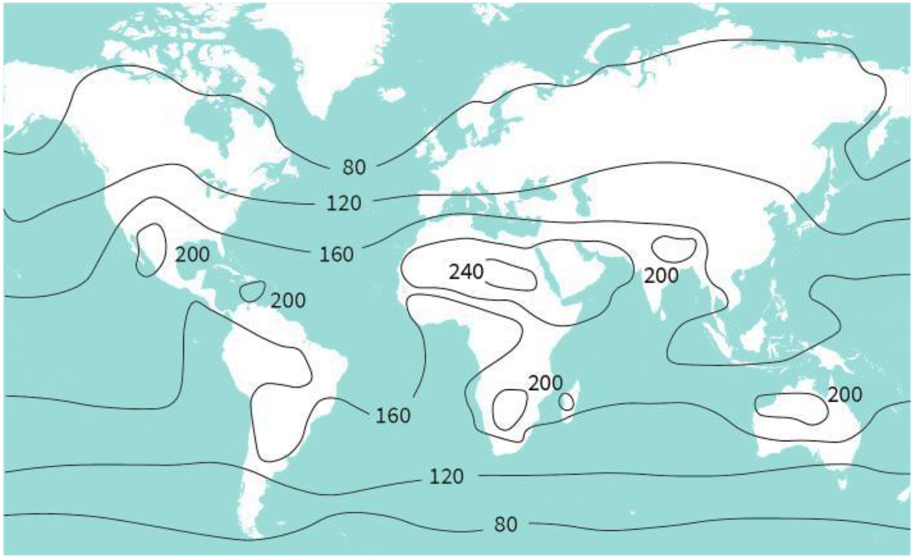


Figure 10.6. World map of algae biomass productivity (tonnes/ha/year) at 5% photosynthetic efficiency considering an energy content of 20 MJ/kg dry biomass. Adapted from "Photobiology of microalgae mass cultures: understanding the tools for the next green revolution", by M. Tredici, 2010, *Biofuels*, *1*(1), p. 154. Copyright 2010 by M. Tredici.

lower production and maintenance costs as much as possible. For example, in a supermarket (or on its flat rooftop), large quantities of fresh biomass could be produced and sold in returnable jars, or mixed with other gastronomy products. Having many customers, the supermarket could afford lower *Spirulina* sales prices, thus becoming a remarkable production, distribution, and local education hub, also activating collaborations with neighboring commercial activities, using their inputs and providing useful outputs. More open systems will form a sustainable and resilient urban macrosystem (Fig. 10.5). In Turin, like in Beijing, Dubai, New York, Sydney, or Mexico City, projects for the cultivation of microalgae in outdoor urban spaces are technically feasible, with some considerations. Their realization depends only on local stakeholders' willingness to get involved. If not determined by other technical factors, the algae biomass productivity varies according to latitude and type of climate, with higher productivity in some of the hottest areas of the world (Fig. 10.6).

As for domestic use devices, these would also be an integral part of a decentralized urban system for the production of microalgae. The problem of healthy and local food production in cities is extremely topical, especially in the light of the recent global health emergency, or possible future pandemics. Taking care of an urban garden is not for everyone because it is hard work that requires knowledge. Cultivating *Spirulina* – with semi-automatic devices – is instead much easier. By combining multi-level perspectives and practice approaches, urban producers-consumers will favor the transition toward more sustainable and plant-based eating, while regenerating communities and deploy concrete initiatives of education and communication.

10.4 Positive impacts of the projects

This doctoral research intends to advance the theory in design and microalgae while contributing to real-world problems with concrete projects. As anticipated in chapter 2.1 – Sustainability and design, the work presented addresses some of the UN Sustainable Development Goals and particularly relates to goals no. 2 (Zero hunger) and 12 (Responsible consumption and production) (Fig.10.7). The impact of this research is, therefore, highly significant. This section describes the positive tangible and potential impacts of the projects developed in the thesis. The direct environmental and economic benefits are considered, as well as the indirect repercussions with social value. First of all, it is necessary to clarify that growing microalgae directly mitigate carbon dioxide through photosynthesis – the amount of CO_2 removed is directly proportional to the amount of biomass produced – and enable climate change mitigation by leveraging a paradigm shift in food habits of many consumers.

Figure 10.7. The design research addresses a few UN SDGs, but its impact is mainly related to goals no. 2 and 12.

Quantifying – or at least estimating – the direct and indirect effects of these projects on an entire city is possible but would require very accurate assumptions and mathematical calculations typical of system dynamics studies (and the help of one or more experts in these fields is needed). However, it is easier to obtain an approximation, for example, of the economic savings that the production of microalgae at home could guarantee. A typical Italian family spends on average about € 115.00 per week for the purchase of food (including alcohol) (Istat, 2019): considering an omnivorous diet, the cost of meat, fish, eggs and dairy products – sources of protein – is a consistent part of the bill (around 40%). By regularly consuming *Spirulina* and using it in many recipes, the purchase of meat and derivates would be reduced, and possibly completely dropped in favor of a vegetarian/vegan lifestyle. It is clear that meat consumption is not being demonized since, for many people, it remains essential in a balanced and traditional diet (Pollan, 2006). The overconsumption of meat and animal derivatives, which are often nutritionally deficient, is instead exposed. The introduction of microalgae in the diet is only one of the many determining factors for lowering meat consumption. This would lead to an increase in the average production prices of meat: intensive livestock, whose business model focuses on the high number of sales to ensure advantageous prices, would probably not be any more competitive on the market, thus favoring more ethical and sustainable farming practices. The lowering of *Spirulina* prices, through the use of new technologies and production methods, is another fundamental factor for this transition. *Spirulina* consumption is a small drop in the sea of change, which, however, leads to positive environmental and economic macro-effects, and is a new approach to health with scientifically-proven benefits, both in the short and long term.

As for devices for public use in the city, and in a circular economy perspective, it would be possible to use alternative nutrients – such as the lye already adopted by French Spiruliniers. Once the production cycles have started and are at full capacity, then it is necessary to add nutrients only in a small part, since the microalgae reproduce independently. The production would follow strict hygiene protocols, which would be an extra guarantee for customers. Since *Spirulina* is cultivated for food use, the biomass produced could also be used as a fertilizer with other food waste for urban and peri-urban gardens (E. Comino, personal communication, May 13, 2020). Ultimately, and as already mentioned other times in the text, implementing projects on this scale would create jobs, add value to the final product, activate new synergies on the territory, and have tremendous educational value. The self-production of these devices from an open-source perspective and thanks to low-cost technologies (e.g., 3D printing) can allow projects to replicated and adapted even in the most remote and inaccessible corners of the world. However, the impact of these projects (product-service systems made of Algae Growers and Algae Stations, for instance) will not be the same everywhere. It will vary depending on different geographical areas/macro-areas. Below the advantages that could be obtained in selected regions are summarized. For convenience, the United Nations geoscheme system, which divides countries according to the M49 coding classification[2], has been used. Still, it is clear that each specific territory has unique characteristics and, therefore, could benefit from these projects differently.

- **Africa:** Microalgae farms have proved to be excellent solutions to tackle malnutrition problems in Africa (Henrikson, 2013). In rural areas where the water is not clean – but cities as well – closed production systems are perfect for limiting water contamination. Today, most African countries are experiencing a time of significant demographic and economic development and will grow exponentially in the years to come. However, social inequalities will be present. The Algae Grower and the Algae Station, reproduced at a low cost following the open-source instructions for self-production, could represent the perfect solution to democratize the production of nutritious, healthy, and sustainable food for feeding malnourished people.
- **America:** In the United States, decentralized production of fresh and organic *Spirulina* would be an optimal solution to counteract the widespread phenomenon of food deserts, large urban (or even rural) areas with limited access to affordable, fresh, and nutritious food (Story, Kaphingst, Robinson-O'Brien, & Glanz, 2008). A change in the Standard American diet would lead to a potential reduction in the consumption of red meat and packaged foods. This is a substantial contribution to health (e.g., obesity) and environmental systems. In South America, people would rediscover forgotten culinary and productive traditions while guaranteeing greater food security to a growing population.

2 Oceania follows a trend similar to the United States and Europe, with due consideration. More info at https://unstats.un.org/unsd/methodology/m49/

- **Asia:** The Asian diet already includes many algae- and microalgae-based recipes. Urban food production in large Asian metropolises is crucial due to the exponential population growth and the relocation of food production areas, which are destroyed to build new roads and buildings. The production of microalgae in the city could also cope, at least partly, with systemic problems in China, which is home to 20% of the world population but which has only 7% of arable land (Cui & Shoemaker, 2018).
- **Europe:** Northern European countries – for instance, England, The Netherlands, and Sweden – seem to be inclined to introduce algae in their diets, as they are already consuming them regularly. In countries like Italy, France, and Spain – more conservative and with a well-established food culture – it is more difficult to change eating habits. Urban devices (private or public) for microalgae production could be the vector for greater diffusion of this novel organic superfood. The educational value is crucial because it teaches microalgae's properties to many people who still don't know about them, leading to a desirable change in diets and a progressive reduction in meat consumption per capita.

Generally speaking, low-cost local food production of nutritional *Spirulina* could be the most effective way to feed millions of people worldwide who are being pushed towards hunger by the coronavirus pandemic, as recently warned by Oxfam (Ahmed, 2020). It is precisely in this challenging historical moment that we must act with targeted and practical solutions, and this design research has a portentous perfect timing.

10.5 Limits of the study

This study has been rather articulated: the thesis work summarizes it and frames it at best. The contribution to knowledge is remarkable. However, there are some limitations. The first chapters of the literature review and research contexts – related to design, sustainability, cities, and microalgae – are introductory to answering the research questions. It is clear that the issues addressed could be further deepened to make those chapters even more exhaustive. However, it was decided to limit the length of the text to avoid unnecessary literature redundancy.

As for the completeness of design and microalgae literature analyzed in chapter 6, the statistics are based only on the Scopus database, a book, and two conference proceedings. Although these publications and the data collected are very significant for this research field, they are not all-inclusive. There are other conference papers, journal articles, and newspaper editorials – albeit in a small number – dealing with these issues. Most of these have been mentioned throughout the text. The methodology applied to analyze microalgae case studies in urban contexts (paragraph 7.2.1) has already been used in previous studies. The methodology is qualitative and not quantitative. This may be considered as a limit too.

The design outcomes – the Algae Grower and the Algae Station – also have limitations, which have been described in paragraphs 8.5.9 and 8.6.7. These limits are mainly technical and operational and primarily dictated by the time and budget available for research. Furthermore, it was initially planned to show the devices (working prototype and scale model) during one or more thematic events, to obtain further feedback from potentially interested stakeholders: citizens, entrepreneurs, business owners, real-estate managers for the public device; target users, families, and companies for the production and marketing for the home device. Due to the impossibility of organizing these events, it has not been possible to collect other data, and further validate the results.

Talking about the Algae Grower tests, these were not carried out in a laboratory with professional instruments, but at home in a real-world case scenario. Although this set up is not a problem, it would perhaps be appropriate to repeat and compare the tests with scientific rigor, possibly supported by an expert biologist or engineer. The instruments (or the procedures) for the control and safety of the biomass for food use will undoubtedly be investigated later. Furthermore, the replicability and scalability of the proposed projects should be thoroughly examined, as well as the social effects on a community in the short-medium run. The Algae Station is, however, still in a concept phase and with obvious limitations. Most of the tests have only been hypothesized.

To conclude, a final risk of this research is that it could remain tied to the design discipline and not arouse experts from other fields. For now, however, online channels for research dissemination are delivering positive results and targeting the right audience.

10.6 Directions for future research

The next steps of this research are mainly three: improve the product prototypes (possibly by patenting their system and/or by making them available for free in creative commons); refine and improve the guidelines and the theoretical framework; continue to research and classify an ever-increasing number of case studies. Surely in a few years, there will be more projects to analyze. This study could hopefully highlight an advancement in practice and a change in the approach. Later on, a series of workshops could be organized to teach attendees how to build the Algae Grower and/or the Algae Station. The basic models can be improved, modified, simplified, and updated based on the needs of the participants (e.g., sizes). The products could be adapted not only for use in the city but also, for example, for rural areas. The organization of thematic events – which improve over time and discuss scientific, economic, and cultural topics – would allow the creation of a network of people aware of the many properties of microalgae and the potential of these projects. Therefore, it will be possible to achieve a greater user pool toward sustainability.[3]

This doctoral dissertation is also the basis for future research in several branches of knowledge. The limits of the study are opportunities for their advancement. Future research must aspire at concrete real-world applications in support of citizens and disadvantaged communities. Future research in the field of design and microalgae must be multidisciplinary and embrace sustainability, usability, functionality, aesthetics, ethics, education, usefulness, and contextuality, but not limited (Fig. 10.8). These researches may be practical experiments and should also have scientific value for the academic community.

In the light of climate change – which will bring water sea levels rising and soil erosion – the limits of agricultural land, and the exponential growth of world population, research on similar topics will not only be study opportunities but necessities. Microalgae could genuinely be the carrier of a new green revolution, which will not only disrupt the fields of chemistry and technology but will be related to behavior change while consolidating new food traditions and consumptions. Future research in the field of design must also aim to train capable and aware professionals and researchers – with a systemic vision – able to design services and systems for the common good and not only eye-catching devices intended for mass production and profit. This research should also underline the transversal role of design in a period of transition and innovation.

3 These workshops could be organized with the support of the university and local Fab Labs. The workshops are expected to be attended by passionate makers, already accustomed to manual labor. All the components could be included in a ready-to-use kit provided to users at a reasonable price. At the moment, I am in contact with Fabrizio Alessio – a member of the board of directors of Fab Lab Torino (http://fablabtorino.org) – who believes that the project is interesting and that at least one event could be organized in Turin. Due to COVID-19, there are still limitations on the number of participants, and online ways to interact in these workshops should be taken into account. The first event could be recorded and then replicated elsewhere, such as Fab Labs in different cities and countries.

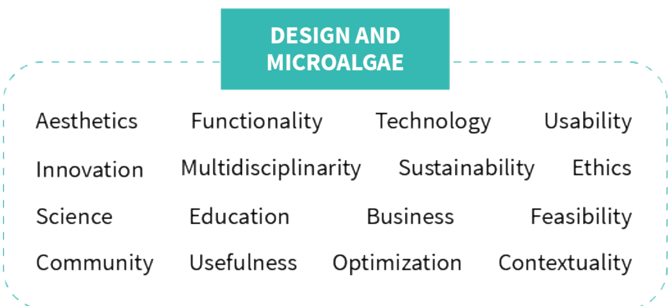


Figure 10.8. Values and topics that future research in the field of design and microalgae should embrace.

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Appendix

A chat with Lee Yi-Wen

Lee Yi-Wen is a Plant Forward Whole Foods Chef Educator, a noted member of 'The Chef's Manifesto' initiative by the Sustainable Development Goal 2 (Zero Hunger) Advocacy Hub – a network with the mission to help deliver good food for all – and a key initiator for many global food education programs. She is a world citizen with 17 years of fashion marketing experience in New York and China, who started a transition to whole foods education in 2012. At the moment, she is based in Shanghai. She is also a co-founder of The Plant Forward LLAB with the mission to educate, collaborate, and initiate real actions and positive changes using food as a social lubricant for sustainable human health and planetary well-being system.

Yi-Wen replied to 'Food for the future – Survey' in October 2019 and got in touch with me through WeChat. Almost one year later, we managed to reconnect with each other. The following is the extract of a WeChat call that occurred on 12 September 2020: the text is not a word-by-word transcription of the conversation; nevertheless, the contents have not been altered. It is an informal, semi-structured interview entitled 'The future of food: Algae, tradition, and health' to gain deeper insights into Yi-Wen's philosophy. Lee Yi-Wen (LYW), Maurizio Vrenna (MV).

MV: Hello, Yi-Wen! First of all, thanks a lot for your time this morning! I had the chance to read about your projects and collaborations with several international institutions: I am fascinated by your dedication to food and sustainability. I am looking forward to learning something new today. Tell me something about yourself. Why this passion?

LYW: I stumbled across a restaurant called 'M Café' in Los Angeles opened by the private chef of Gwyneth Paltrow, the Hollywood actress. During the fashion days, we were used to going to trendy restaurants and celebrity shows, but I did not understand the connection between food, health, and the environment. I went to eat, and I said: "Wow, everyone looks so healthy!". The colors of the food were beautiful, and after lunch, I felt energized. Not tired, you didn't feel like having an afternoon nap. So, I bought a few books thinking that I would learn how to cook, and I returned to Shanghai. But of course, when you are working and don't understand the principles and the philosophy deeply, the results are not great. Then, I decided to attend a one-week course called 'Way to health' at the Kushi Institute of Natural Healing close to Boston, Massachusetts. We were 18 people, and I was the only jet-lagged person flying from China. There was a 13-years old girl with digestive issues, a lady with pancreatic cancer, a guy with a brain tumor, a girl with breast cancer, and two nurses who were sick of doctors prescribing medications to their patients and were into holistic medicine. I though myself: "What am I doing here? I just like food; I like to eat!". Anyway, it was an exciting week because we learned a lot about the root causes of diseases, which are pretty much linked to diets, and the dangers of the SAD – Standard American Diet, rich in meat but lacking vegetables. This experience was eye-opening for me because I already wanted to leave the fashion industry. After 17 years, I was sick of that toxic and materialistic world and its detrimental impact on the environment. And I made the shift. Food was the perfect category that has not been really touched upon, even today. Food is a thriving industry that needs more people to promote and educate to better lifestyles, toward a sustainable change. I think that the recent pandemic has awakened consumers on the importance of healthy diets and to cook their own food (even if, according to some studies made by the Eat Foundation, the purchase of frozen food increased during lockdowns!). Anyway, I made this shift when I was 40 years old, and this was smooth. I got a calling, and I dropped everything! I traveled to India, Thailand, and Bali to study raw food: it was financially challenging! Nevertheless, I am very grateful for this change because I want to do something meaningful in my life!

MV: That's a cool story, thanks for sharing your experience! We are now in a very particular moment: climate change, population growth, urbanization, and a global pandemic are just some of the many challenges we face. People are shifting their diets too. Even if the portion of vegan and vegetarian consumers is still relatively low – especially in the most developed countries –

this number is increasing. The change is not only a matter of habits but has ethical and environmental reasons. What do you think we will be eating in the next decades?

LYW: From my point of view, plant-based meat and plant-based foods are the hottest topics now. There's so much investment, and I think this is great because at least investors have the money to promote the connection between food and the environment. Nevertheless, I still think we need to go back to our traditions and choose to eat whole foods because this will finally heal our Earth. Lab-made food doesn't, and it limits chefs' creativity by substituting minced pork or burgers. So, it is great that this industry is thriving because it is also a solution for people who want to shift to more plant-based eating. But to me, this is just a treat, because it is not whole food, it is engineered! Your body may not understand what it is. Plant-based meat is a great solution, especially in the United States, but I still believe that putting plants at the center of our diets and supporting local farmers is the key. With a world population reaching 10 billion, we need to disrupt the food system through micro-regional hubs and cooperatives, in Western countries and especially in China.

MV: Tradition and taste are probably among the most critical aspects of food culture. How to embrace new flavors and ingredients while preserving centuries-old traditions?

LYW: That's a great question! We need to make the shift, but food has to be tasty! Chefs have mastered so many cooking techniques to create the umami flavor and boost tastes: grilling and glazing are just some of them. Also, seaweeds, mushrooms, and fresh herbs are excellent to improve the umami flavor. There are plenty of ways to make food taste delicious. That's why when I travel, I love to take cooking classes. A couple of years ago, I went to Thailand to attend a five-days vegan cooking class. For instance, did you know that you can combine two different soy sauces to recreate that same fishy flavor of the traditional fish sauce? I also learned from a Peruvian chef in Sweden when I joined The Chef's Manifesto, to save onion skin, grill it, blend it, and create vegan-style bonito flakes. There are so many things to play with, but so much food is wasted because of standardization and costs. Most of the regular people, and even some chefs, do not have feelings toward food. They don't visit farms; they don't have empathy with the products. They just want to make plates look beautiful.

MV: I know that you have been using algae in your tasty recipes. How did you discover this ingredient?

LYW: Actually, through the study of macrobiotics. Seaweed is used a lot in macrobiotic cuisine. It is rich in flavor and is nutrient-dense. Besides, algae produce oxygen for the aquatic environment and us. You can cook them by just using natural ingredients. I love a dish that consists of layering sauté onions, shredded carrots, and then adding some wakame, seasonings, and soy sauce. It allows the vegetables to release their flavor, without the need to stir-fry.

MV: In your opinion, what are the most relevant properties of algae? Have you ever cooperated with doctors and nutritionists?

LYW: Algae have plenty of functional nutrients. What I learned is their capacity to remove radiations and to purify the body from heavy metals. When using algae, it's always a triple win: for the planet, for our bodies, and our taste experience! Regarding the collaboration with doctors and nutritionists, yes, I taught at an integrated medicine clinic. I collaborated with two functional medicine doctors and naturopaths: they were talking about hormonal imbalance, digestive issues, chronic diseases, while I was teaching functional ingredients and how to prepare anti-inflammatory recipes and healthy dishes.

MV: Have you ever used *Spirulina* in your culinary experimentations? If so, how?

LYW: Many people assume *Spirulina* in capsules, but I love to sprinkle it over millet, with some extra nuts and seeds. That makes it beautifully green and nutritious! Also, I collaborated with chef David Laris to create a salad dressing with *Spirulina*.

MV: Considering the exponential population growth, researchers argue that algae, including *Spirulina*, could be the key to feeding the world. What do you think about it?

LYW: At the moment, *Spirulina* is not a fundamental ingredient of our diets. But I think that this microalga has potential. It's an excellent food because of its protein content and is also very easy to digest. People in poor rural areas could eat it because they may not have access to other foods. Again, everything goes back to education because people have no idea what they want. First of all, you need to educate them on what's a nutritionally-balanced diet, secondly, tell them what is missing, and make it taste delicious! You'll have to develop new recipes with local people because everybody's taste is different. That's why I position myself as a chef educator, to inspire more chefs to understand the importance of their role and bridge the gap from farm to table by supporting more sustainable food systems.

MV: Eastern cuisine is much different from the Western one, as well as the perception of the ingredients. What do we need to do to facilitate the transition toward a more sustainable lifestyle? How to introduce algae and microalgae in our daily meals?

LYW: Algae, for instance, *Spirulina*, have quite a strong flavor. That's why people take capsules. The taste needs to be balanced, and particular attention has to be paid to the color. If we want people to say: "Oh, today I need to eat some algae!" we need to teach them the properties of this novel food. Not only home cooks but chefs as well so they can incorporate algae in their menu design. Besides, I think that the device you designed – the Algae Grower – could help many people. The ocean is so polluted with microplastics and mercury, and the home-production of food in closed systems is the future. See the rise of hydroponics technology, for example.

MV: In markets and supermarkets, algae-based products are not that easy to be found. For instance, many people are used to growing basil, rosemary, and other spices at home in Italy. Do you think that by cultivating algae and microalgae locally (at home or in urban spaces), we may change our perception of these ingredients?

LYW: Yes, definitely! You know, I also have a balcony and love to grow rosemary and other spices. I think producing microalgae at home is brilliant because fresh herbs don't have as much protein content. But, actually, I have never thought about it. You are ahead of your time!

MV: One last question: How could a chef and a designer collaborate, in your opinion, to create a device for the cultivation of *Spirulina*? What should be the characteristics of this device?

LYW: I believe in collaboration and co-creation: collecting energies can bring much more impact. Some years ago, I worked with Philips, and I helped them put together a group of wellness practitioners to test a product. Working with designers is crucial because you guys can make beautiful and functional products. And kitchens need that! So, a Spirulina-harvesting device should be user-friendly, functional, compact, and significantly minimize waste. Over the years, I've learned that many people order fresh vegetables from the farm, but have no idea how to cook them or make them taste delicious. For this reason, the device should come with a sort of recipe book. That's the missing bridge. But nowadays, people are lazy and don't want to read, so short videos online are much better – imagine social media like Xiaohongshu (小红书).

MV: Thanks, Yi-Wen, for your time today. It was great talking with you and learning so many new things! I hope we will have the chance to cooperate in the future.

A conversation with Ehsanul Karim

Ehsanul Karim is the former General Manager of EnerGaia Co, Ltd. in Bangladesh. Ehsanul and I had the chance to get to know each other in 2011, while attending classes at KTH Royal Institute of Technology in Stockholm, Sweden. The following is the extract of a Skype call that occurred on 24 September 2019: the text is not a word-by-word transcription of the conversation; nevertheless, the contents have not been altered. It is an informal, semi-structured interview to gain deeper insights into EnerGaia's project. Ehsanul Karim (EK), Maurizio Vrenna (MV).

MV: Hi, Ehsanul! First of all, thanks for your availability! Do you mind telling me something more about yourself? What is your background, and what are you doing now? When was the first time you have heard about microalgae?

EK: Hi, Maurizio, it is nice to hear from you! I have been studying mathematical modeling and simulations in the field of computational and applied mathematics. After living in Sweden for around six years, I moved back to my hometown Dhaka, Bangladesh. Since June 2019, I am running my own company and consultancy firm, Karim & Winstanley Pvt Ltd. I am a *Spirulina* producer, researcher, and a technology provider, depending on the client needs. The first time I heard about the *Spirulina* business was a bit before starting my adventure with EnerGaia. I have done so much research, and I now became an expert in the design of *Spirulina* production systems. I provide consultancy for companies that are interested in these systems. Many of my clients are in the US.

MV: The world is facing several challenges today: air pollution, scarcity of resources, and exponential population growth are just a few of them. Do you think that producing microalgae could be a way to feed people and reduce CO_2 levels?

EK: Yes, definitely. Microalgae do photosynthesis to grow, a natural way to convert carbon dioxide into oxygen. *Spirulina* is used for many applications, including fish feed, poultry feed, human feed, and even food for astronauts. You just need to be sure that the biomass you grow is contaminant-free. Avoid contamination is, indeed, a difficult task. I believe that more and more companies will be producing *Spirulina*, also considering the demographic growth.

MV: When did you start working for EnerGaia, and what was your role? Is EnerGaia an NGO?

EK: EnerGaia is a no-profit organization. EnerGaia's work in Bangladesh has been done entirely under my direction. I have been the country director since the foundation of the branch, and I contributed a lot to EnerGaia's development. When we started in 2017, I found out that *Spirulina* production was already present in Bangladesh for a couple of decades, but the final product was costly to buy because the production technology was not efficient enough.

MV: I read that EnerGaia started operating in 2009. They established a first *Spirulina* farm on the rooftop of a luxury hotel in Bangkok. How were you managing the company in Dhaka? What was your business model, and how did it differ from the one adopted in Thailand?

EK: EnerGaia's work in Bangladesh is different from EnerGaia in Thailand, Singapore, and Indonesia. In these countries, they are more focused on urban cultures, eventually on rooftops. In Bangladesh, we give importance to community-based work in the countryside, creating sources of sustainable income while utilizing locally-available resources and non-fertile lands. We valorize waste, and our approach is entirely different from the one of the other countries. For instance, we have been trying to find cheap nutrients that could be used at the rural level, rather than purchasing ready-made NPK. We realized that it is possible to provide nutrients not only with salts or fertilizers but even with plant-based products. As input, we decided to use rotten tomatoes that are rich in phenols: tomatoes are also commonly available in our region.

To reduce costs significantly, we use urea rather than potassium nitrate or sodium nitrate, which are very expensive nutrients. The production costs went down significantly, showing that this is an efficient model that can be replicated in many other rural areas.

MV: Dhaka is one of the largest metropolitan areas in South Asia, a modern city and the country's center of industrial, commercial, cultural, and political activities. As in many other big cities, the gap between rich and poor people is widening. How were you cooperating with disadvantaged communities?

EK: The goal of EnerGaia Bangladesh is to create new employment possibilities, and we struggle especially to empower jobless women. We provided our technology to people living in rural areas, on the outskirts of Dhaka, and placed around twenty barrel-bioreactors in a 140 m^2 yard. The families take care of *Spirulina* cultures. We buy most of the production from them, and we also give back some dried biomass after processing, for their consumption. We believe that this is a win-win solution, with an ethical business model.

MV: Ehsanul, do you mind telling me something more about the low-cost technology system you are using?

EK: Sure, I am proud of our patented solution: we have been successfully using it both in Thailand and Bangladesh. First, some basics. Microalgae need water, nutrients, and light to grow in an alkaline environment. *Spirulina*, for instance, thrives at pH 9-11. Very few organisms can survive at that level of pH, but the culture can be contaminated with other microalgae: we don't want these alien species. For this reason, we built our photobioreactors to facilitate cleaning and growth, while guaranteeing a high quality of the final product. Regular photobioreactors are made of glass and are super-expensive. Even though productivity is very high, only a few companies, especially in higher-income countries, can afford this technology. We came up with an economical solution that has right sunlight limitation and penetration, that is strong enough, and does not break if exposed to UV over some time. We use specific plastic bags, made of a combination of HDPE, LDPE, and UV protection chemicals. They are pretty cheap: each bag costs only 1,00 $. To hold them, we place the bags inside a handmade wire mesh structure. The harvesting process is simplified by connecting all the bioreactors and using simple laws of physics. We blow air from one side, which gives enough pressure to transfer water from one bioreactor to another. The system runs continuously, and, at some point, the fully-grown *Spirulina* gets trapped in a net. When the product is harvested, it is 90-95% water and 5-10% biomass, so you need to centrifuge the water out. We then use a dehydrator that takes about 10-12 hours at 60-65 °C to get rid of the moisture content. The biomass becomes then a chip that you can grind and make it into a powder. That is how the production cycle works overall. We are now considering to produce *Spirulina* even at night, to increase yields. To do so, we identified the right light spectrum for artificial lighting.

MV: According to some studies, producing one kg of dried algal biomass can absorb up to 1.83 kg CO_2. Did you somehow ever assessed the levels of carbon dioxide subtracted? Have you considered harvesting *Spirulina* indoor?

EK: We never made a proper study on the quantity of carbon dioxide subtracted. Right now, we prefer using sodium bicarbonate instead of carbon dioxide from the air, because the technology for the latter is not efficient yet, and very expensive. We use air filters when we pump air in the barrels, to minimize airborne contamination risks. Besides, to reduce the production costs, we prefer using sunlight rather than artificial lighting systems, so we mainly harvest *Spirulina* in outdoor environments.

MV: Is EnerGaia branding the products? Which channels are you mainly using for selling the biomass? Do you sell it mostly in Bangladesh or you also export it?

EK: We sell *Spirulina* both for human and animal consumption, in different forms. We cultivate *Arthrospira Platensis* because it is a stream with more proteins and less lipid content. The quality of our product is rather high, and it does not smell bad because we check its parameters very carefully. In Bangladesh, we are not branding our products, since we mainly sell to business customers. In Bangkok, for instance, we make Spirulina-enriched pasta, and at Novotel, we use it for healthy drinks, cocktails, and smoothies. We are also making noodles. In Bangladesh, we are trying to introduce *Spirulina* in local recipes: our main staple foods are rice and curry, so we are trying adding *Spirulina* to them. Unfortunately, some people are not attracted to this very bright green color. So we introduced *Spirulina* in the green curry (Palak paneer), which is made with spinach and is already green. In rural areas, we also combined *Spirulina* with lentils and beans. We export our products abroad. If used for the fish and poultry feed industry, we sell it at around 10,00 to 15,00 $ per kg. For pharmaceutical use, 35,00 to 45,00 $ per kg (B2B price). Some buyers in Europe and the US are also willing to pay up to 80,00 $ per kg. Currently, we do not extract phycocyanin – the only naturally blue food color – because the process is expensive. Nevertheless, we are conducting some research on it.

MV: In my country, Italy, microalgae are not very well known. They are mostly consumed by sportspeople or vegetarians/vegans as a food supplement. Apart from producing and selling *Spirulina*, were you (or your collaborators) organizing educational events or lessons with experts on the topic?

EK: As I said before, we use to work with two large universities. Therefore there are many opportunities to learn and share. We train families in rural areas to take care of *Spirulina* cultivation: I attended and moderated these events many times. Also, the students had the chance to make several field trips at the production sites in the countryside.

MV: Were you also collaborating with third-party companies or institutions like universities and other NGOs? Did you activate partnerships or joint projects at local and international levels?

EK: Yes, we collaborate with several international NGOs from the UK, USA, and even Italy. Our clients are from all over the world. In Bangladesh, there is a lot going on! We have been working on exciting solutions with microbiologists, biotechnologists, and students. I did this by partnering with two major agricultural universities: one is Bangladesh Agricultural University in Mymensingh, and Sher-e-Bangla Agriculture University in Dhaka. So I did our setup in two locations in collaborations with them, and students did much research regarding nutrient management, productivity, harvesting, input production, quality production processes like drying, grinding, etc.

MV: One last question. Currently, microalgae can be used for biofuels, biofertilizers, cosmetics, wastewater treatments, animal and fish feed, human food consumption. New promising research may be disruptive. How would you envision the future in 20-30 years from now? Do you believe that *Spirulina* and other microalgae will be common in our diets? Do you think we will see bigger, delocalized production facilities or smaller and connected farms like EnerGaia?

EK: I'm not a seer, but the *Spirulina* market is booming. The worldwide demand for microalgae is increasing, which is a sign that people are slowly changing their eating habits. EnerGaia's business model is successful because it dramatically lowers production costs and obtains a high-quality product. Families can also manage smaller plants.

MV: Ehsanul, you raised some very interesting points. I think that EnerGaia's business model represents a virtuous example that should be taken as a reference by others. Thanks for your precious time today, Ehsanul!

Food for the future – Online Survey

Hi! Thanks for participating in this survey. You are taking part in a joint research study from Tsinghua University, China and Politecnico di Torino, Italy. It will need no more than 7 minutes! The global population is exponentially growing and it is estimated that by 2050 the Earth will be inhabited by 2.4 billion people more. Considering the finiteness of our lands, scientists, researchers, and entrepreneurs are exploring novel fields in sustainable food production and design. The research aims at gaining insights into current eating habits, to delineate future contexts for food production and sustainable systems in our cities.
The data collected are anonymous and solely used for academic purpose. Please reply according to your current eating habits. If you want to be updated on the future results of the survey, you can leave your contacts at the end of the survey. Enjoy!

1. **Are you a male or a female?** ☐ Male ☐ Female

2. **How old are you?** ☐ 0-17 ☐ 18-22 ☐ 23-30 ☐ 31-40 ☐ 41-50 ☐ 51-60 ☐ 61+

3. **Where are you from?** ☐ China ☐ Other Country Please specify ______

4. **Which city do you live in?** ☐ Beijing ☐ Shanghai ☐ Shenzhen ☐ Other city Please specify ______

5. **What is your education?** ☐ High-school or lower ☐ Bachelor ☐ Master ☐ Ph.D.

6. **What is your current occupation?**

☐ Student ☐ Employee ☐ Freelancer ☐ Retired ☐ Other Please specify ______

7. **Which of these better describe yourself and your relationship with food? (Up to 2 answers)**

☐ **A vegetarian/vegan**
I do not eat meat or other animal derivatives

☐ **A meat enthusiast**
I love to eat meat

☐ **A healthy food lover**
I am very attentive to my diet and always look for organic and healthy food

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- [ ] **A food amateur**
  No matter what it is, I just love to eat any kind of food!
- [ ] **A wannabe (or expert) chef**
  I like to cook and I know where to buy my ingredients
- [ ] **A social media master**
  I always take pictures of food and share it on social media
- [ ] **Other** Please specify ______________________

8. How do you usually eat? (Up to 2 answers)

- [ ] I cook at home
- [ ] I eat at a fast-food (McDonald's, etc.)
- [ ] I use a home delivery service
- [ ] I buy some convenience food
- [ ] I eat at the restaurant
- [ ] I purchase ready-made snacks and drinks from vending machines

9. Where do you buy your groceries? (Up to 2 answers)

- [ ] Supermarket
- [ ] Vending machines
- [ ] Wet market
- [ ] Street vendors
- [ ] Small shops
- [ ] Online

10. What is 'healthy food' in your opinion? (Up to 2 answers)

- [ ] **Food rich in proteins**
  E.g., beef meat and beans
- [ ] **Low fat and low carbs recipes**
  E.g., oatmeals and lettuce
- [ ] **Something with health benefits**
  E.g., vitamin pills, protein powder, cod liver oil
- [ ] **Sustainably-produced products**
  E.g., organic vegetables, antibiotic-free farm-raised animals
- [ ] **Other** Please specify ______________________

11. When it comes to food, what are the most important things you take into account? (Rate on a scale from score 1 to 5 in which 1=not important; 5=most important)

Quality	1	2	3	4	5

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Price	1	2	3	4	5
Taste	1	2	3	4	5
Local production	1	2	3	4	5
Sustainability	1	2	3	4	5
Nutritional values	1	2	3	4	5
Freshness	1	2	3	4	5
Brand	1	2	3	4	5

12. According to your definition of 'healthy food', are you satisfied with your diet?

- ☐ Yes, my diet is excellent
- ☐ No, my diet is not good
- ☐ My diet is fine
- ☐ My diet is really bad, I have to change!

13. Have you ever heard about microalgae and Spirulina? ☐ Yes ☐ No

14. What do you think microalgae and Spirulina can be used for?

Please describe

____

15. Have you ever eat Spirulina in any form? ☐ Yes ☐ No

Microalgae are single-celled organisms that mainly live in water. They are different from seaweed essentially because of their small dimension. They have a long evolutionary path and produce a lot of oxygen, necessary for the life of all animal species on Earth. Some of them, like *Spirulina*, have been used for food and as a medicine for several centuries. *Spirulina* is a superfood: it has a high protein content, anti-cancer properties and protects from diseases and infections. A handful of *Spirulina* has more proteins than a steak, without the need of a lot of water for its production, and thus a very low environmental impact. *Spirulina* is great for everyone, in particular athletes, children, and elderly people.

16. In the future we may change our eating habits. Among these foods, which ones would you be willing to eat? (1 or more answers)

☐ **Insects**
Certain insects are considered a delicacy. Due to their high protein content, they may be integrated into familiar products such as flours and snacks.

- [ ] **Microalgae**
  Spirulina can either be eaten fresh or dry by adding it to drinks and staple foods.
- [ ] **Lab-grown synthetic meat**
  Lab-grown meat may be better for the environment and improve on several health aspects of conventional meat.
- [ ] **Lab-grown fruits and vegetables**
  Soil-less hydroponics cultures can use less water and control the nutrients.
- [ ] **Meal replacements**
  A meal replacement is a drink, bar, or soup intended as a substitute for a solid meal, usually with controlled quantities and nutrients.
- [ ] **None of them**

Spirulina is usually found in powder and is characterized by a blue-green color. It has a delicate sea-taste similar to the one of seaweed, with a slightly sulfuric edge. These characteristics may change according to where and how it grows. Some people love it, some people hate it. Certainly, *Spirulina* can be used in several tasty recipes and mixed with a lot of ingredients.

17. Based on your previous knowledge and on the description above, which of these drinks with Spirulina would you like to try? (1 or more answers)

- [ ] ***Spirulina* non-alcoholic drink**
  Bubble Tea, smoothies, juices, milkshakes, etc.
- [ ] ***Spirulina* alcoholic drink**
  E.g., beer with added *Spirulina*
- [ ] ***Spirulina* functional drink**
  Energy/healthy drink

18. And which of these foods with added Spirulina? (1 or more answers)

- [ ] **Spirulina pasta**
- [ ] **Spirulina hamburger**
- [ ] **Spirulina hot dog**
- [ ] **Spirulina chips**
- [ ] **Spirulina cheese**
- [ ] **Spirulina chocolate**
- [ ] **Spirulina croissant**
- [ ] **Spirulina ice-cream**
- [ ] **Spirulina seasoning**

19. Which of these factors do you think could be a barrier to the adoption of Spirulina? (1 or more answers)

- [ ] **Taste**
- [ ] **Appearance**
- [ ] **Color**
- [ ] **Smell**
- [ ] **Cultural background**

Page 4 of 6

☐ Other Please specify ________

20. Would you love to participate in a tasting event, in which you will be able to eat some of these foods and drinks?

☐ Yes ☐ No ☐ Maybe

Nowadays designers and engineers are creating futuristic and smart kitchen appliances for any need (rice cookers, coffee makers, cold press extractors, home farming devices, etc.). Even if microalgae are usually harvested in larger-scale plants, some people are trying to cultivate *Spirulina* at home! *Spirulina* is actually becoming more and more popular: many shops are selling it, together with starting kits for the cultivation. By harvesting *Spirulina*, you can make money, start your own business, purify the air of your home (microalgae have a high photosynthetic activity, much higher than plants!), while always having a source of superfood ready to consume.

21. Have you tried to grow your own vegetables? ☐ Yes ☐ No

22. Are you willing to harvest Spirulina at home? ☐ Yes ☐ No ☐ Maybe

23. Why?

Please describe ________

24. Do you think your residential community (compound, school campus, etc.) may be interested? A device for the production of Spirulina may engage neighbors in common activities, produce income, and purify the air of common spaces.

☐ Yes ☐ No ☐ Maybe

25. Why?

Please describe ________

26. Please order by importance the characteristics that, in your opinion, a Spirulina home-production device should have:

☐ Aesthetically pleasant ☐ Functional ☐ Safe ☐ Economic ☐ Easy to use

☐ Highly productive ☐ Fashionable and cool ☐ Integrated with furniture

Page 5 of 6

27. What do you think about Spirulina? Do you want to tell your opinion about this research? Is something missing? (Open answer)

Please describe

Thanks a lot for your time today! The survey is now concluded. Your answers were really important and you contributed to the development of future urban farming equipments, shaping the future of food! If you want to be posted on the outcomes, you can leave your contacts.

28. Your contacts for future updates:

- ☐ **Name** Not compulsory
- ☐ **WeChat** Not compulsory
- ☐ **E-mail** Not compulsory

* The full bilingual survey (English and Chinese), with pictures and animations is available at: https://www.wjx.cn/jq/46678562.aspx

Food for the future – Workshop Survey

THU, Beijing | 3 November 2019

Part 1 – Tasting time

1. What is your name? Please specify ______

2. Group number Please specify ______

3. Are you a male or a female? ☐ Male ☐ Female

4. How old are you? ☐ 18-22 ☐ 23-30 ☐ 31-40

5. Where are you from? ☐ China ☐ Other Country Please specify ______

6. What is your education? ☐ High-school or lower ☐ Bachelor ☐ Master ☐ Ph.D.

7. What is your profession/expertise? Please specify ______

8. Which of these better describe yourself and your relationship with food? (Up to 2 answers)

☐ A vegetarian/vegan
I do not eat meat or other animal derivatives

☐ A meat enthusiast
I love to eat meat

☐ A healthy food lover
I am very attentive to my diet and always look for organic and healthy food

☐ A food amateur
No matter what it is, I just love to eat any kind of food!

☐ A wannabe (or expert) chef
I like to cook and I know where to buy my ingredients

☐ A social media master
I always take pictures of food and share it on social media

☐ Other Please specify ______

9. Have you ever heard about microalgae and Spirulina? ☐ Yes ☐ No

10. Have you ever eat Spirulina in any form? ☐ Yes ☐ No

Page 1 of 5

11. Which of these factors do you think could be a barrier to the adoption of Spirulina? (1 or more answers)

- [ ] Taste
- [ ] Appearance
- [ ] Color
- [ ] Smell
- [ ] Cultural background
- [ ] Other Please specify ________

You will now taste some unconventional recipes. Take your time to enjoy the food. For each of them, we kindly ask you to give a score from 1 to 5 (1=very bad; 5=very good). These include the visual aspect, the smell, and the taste. You are invited to share your opinion with the other invitees. Do not hesitate to ask us any question!

12. Recipe n. 1 – Spirulina lemonade (1=very bad; 5=very good)

How does the drink look like?	1	2	3	4	5
How does the drink smell like?	1	2	3	4	5
How does the drink taste like?	1	2	3	4	5
How would you rate it overall?	1	2	3	4	5

13. General comments and feedback

Please describe ________________________________

14. Recipe n. 2 – Spirulina crackers (1=very bad; 5=very good)

How does the drink look like?	1	2	3	4	5
How does the drink smell like?	1	2	3	4	5
How does the drink taste like?	1	2	3	4	5
How would you rate it overall?	1	2	3	4	5

15. General comments and feedback

Please describe ________________________________

16. **Recipe n. 3 – Spirulina chocolate cookies (1=very bad; 5=very good)**

How does the drink look like?	1	2	3	4	5
How does the drink smell like?	1	2	3	4	5
How does the drink taste like?	1	2	3	4	5
How would you rate it overall?	1	2	3	4	5

17. **General comments and feedback**

Please describe

Did you love these recipes? They are really easy to cook, with great nutritional values, and the ingredients are cheap and easy to find! We actually still have a couple of questions for you...

18. **Are you willing to...**

- Prepare these recipes at home
- Eat them again in a restaurant
- Do both of the above
- I do not like microalgae

19. **Tell us your opinion about novel foods and microalgae**

Please describe

Part 2 – Growing time

20. **Are you willing to harvest Spirulina at home?** Yes No Maybe

21. **Why?**

Please describe

22. **Do you think your residential community (compound, school campus, etc.) may be interested? A device for the production of Spirulina may engage neighbors in common activities, produce income, and purify the air of common spaces.**

Yes No Maybe

Page 3 of 5

23. Why?

Please describe

Part 2 – Design time

24. Please order by importance the characteristics that, in your opinion, a Spirulina home-production device should have:

- [ ] Aesthetically pleasant
- [ ] Functional
- [ ] Safe
- [ ] Economical
- [ ] Easy to use
- [ ] Highly productive
- [ ] Fashionable and cool
- [ ] Integrated with furniture

25. A mood board is a tool used by designers to help them get a good idea of what their users are looking for. Do you find them suitable for a Spirulina production device? Please rate them on a scale 1 to 5. (1=I do not think it is suitable at all; 5=I think it is perfect)

Mood Board n. 1 (Neat, Modern, Simple)	1	2	3	4	5
Mood Board n. 2 (Technological, Digital, Futuristic)	1	2	3	4	5
Mood Board n. 3 (Familiar, Analog, Warm)	1	2	3	4	5

26. Think about a Spirulina production device, and keep in mind what you did during the growing part. On a scale 1 to 5, how much would you love these operations to be automated? (1=Totally manual operation; 5=Fully automated operation)

1. Inoculum	1	2	3	4	5
2. Nutrients	1	2	3	4	5
3. Stirring	1	2	3	4	5
4. Control	1	2	3	4	5
5. Harvest	1	2	3	4	5

27. We hope you learned something interesting today! Based on the presentation, what would you love to know more about Spirulina? (1=I don't want to know; 5=I want to know a lot)

Page 4 of 5

Environmental sustainability of its production	1	2	3	4	5
Health benefits and nutritional values	1	2	3	4	5
Innovative features of the growing devices	1	2	3	4	5
Technical product/device aspects	1	2	3	4	5
Biology/Chemistry notions	1	2	3	4	5
New recipes and instructions for cooking	1	2	3	4	5

* The single parts of the survey, with pictures and bilingual (English and Chinese) are available at: https://www.wjx.cn/m/48904780.aspx (Part 1 – Tasting time), https://www.wjx.cn/m/48905117.aspx (Part 2 – Growing time), and https://www.wjx.cn/m/48903392.aspx (Part 3 – Design time).

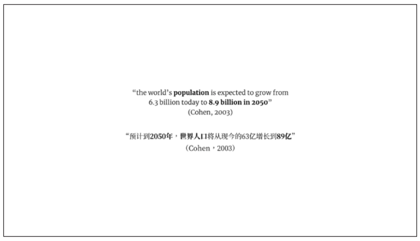
Page 5 of 5

Slide 1. Food for the future – Workshop.

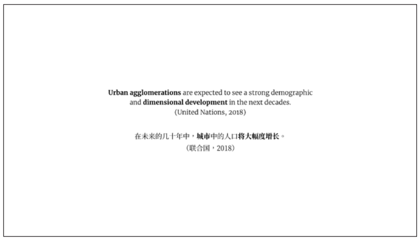
Slide 2. Introduction to the workshop by Prof. Liu Xin.

Slide 3. Research project from Politecnico di Torino and Tsinghua University.

Slide 4. Introduction of moderators: Maurizio Vrenna and Sun Yu-Chi.



Slide 5. Expected population in 2050.

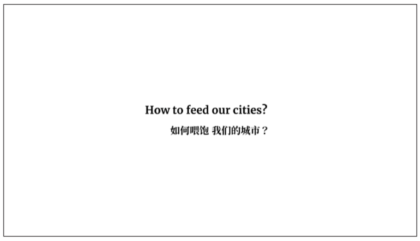


Slide 6. Rise of urban agglomerations.

Slide 7. Problems in cities: air pollution.

Slide 8. Problems in cities: social differences.

Slide 9. Problems in cities: urbanization.



Slide 10. How to feed our cities?

Slide 11. How to feed the world?

Slide 12. Novel foods: vertical hydroponics farming.

Slide 13. Novel foods: lab-grown meat.

Slide 14. Novel foods: insects.

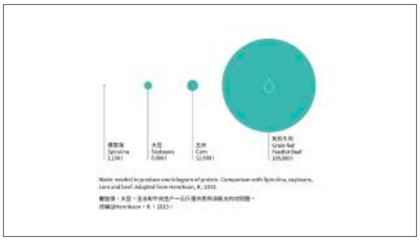
Slide 15. Novel foods: microalgae.

Slide 16. Differences between algae and microalgae.

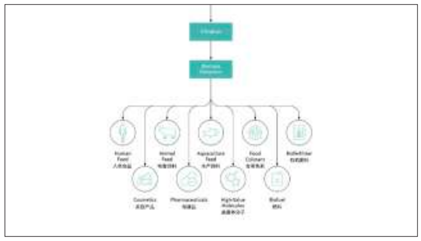
Slide 17. Definition of microalgae.

Slide 18. Uses in history.

Slide 19. Microalgae-based foods and recipes.



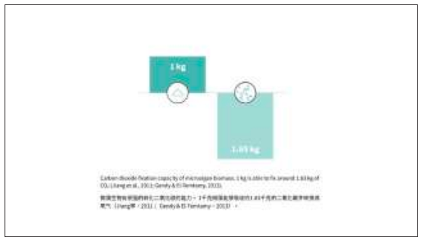
Slide 20. Water needed to produce 1 kg of proteins.



Slide 21. Multiple commercial and industrial uses of microalgae.

Slide 22. Spirulina-based cosmetics.

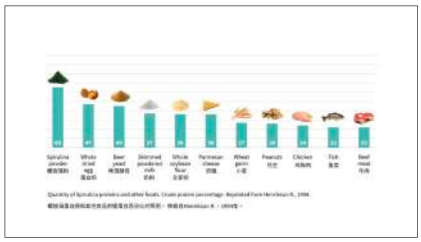
Slide 23. Spirulina-based cattle feed.



Slide 24. Carbon dioxide fixation capacity of microalgae biomass.

Slide 25. Part 1 – Tasting time.

Slide 26. *Spirulina* nutrients compared to other foods.



Slide 27. Quantity of *Spirulina* proteins compared to other foods.

Slide 28. Health benefits of *Spirulina*.

Slide 29. Uses at home.

Slide 30. Da Giuliano bakery in Chaoyang district, Beijing.

Slide 31. Participants were asked to evaluate the recipes.

Slide 32. Online evaluation/enquiry form.

Slide 33. Recipe 1 – *Spirulina* lemonade.

Slide 34. Recipe 2 – *Spirulina* crackers.

Slide 35. Recipe 3 – *Spirulina* chocolate cookies.

Slide 36. Part 2 – Growing time.

Slide 37. *Spirulina* growing kit distributed to each group.

Slide 38. Growing time – Phase 1: Inoculum.

Slide 39. Growing time – Phase 2: Nutrients.

Slide 40. Growing time – Phase 3: Stirring.

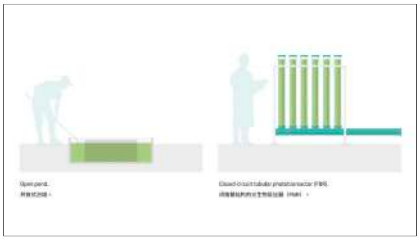
Slide 41. Growing time – Phase 4: Control.

Slide 42. Growing time – Phase 5: Harvest.

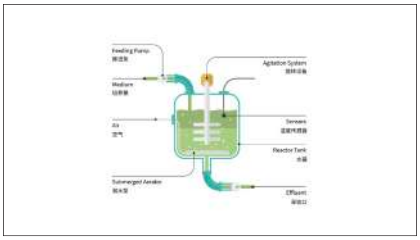
Slide 43. Brief video about Phase 5.

Slide 44. Online evaluation/enquiry form.

Slide 45. Part 3 – Design time.



Slide 46. Open ponds and photo-bioreactors: a comparison.



Slide 47. Main functions of a photo-bioreactor.

Slide 48. Ecoduna. World's biggest photo-bioreactor facility.

Slide 49. Case study: Culture Urbaine.

Slide 50. Case study: Algae Dome.

Slide 51. Case study: BioUrban 2.0.

Slide 52. Case study: Living Things.

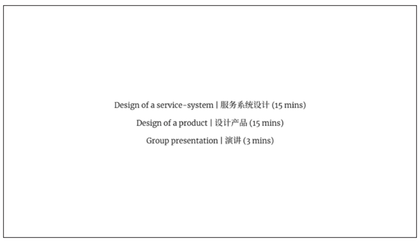
Slide 53. Case study: Farma.

Slide 54. Case study: Spirugrow.

Slide 55. Previous online survey results: main problems for users.

Slide 56. Online evaluation/enquiry form.

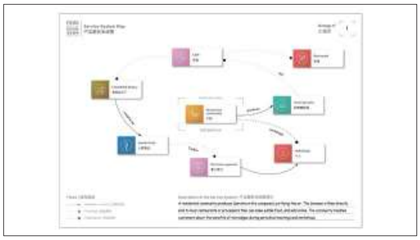
Slide 57. Mood boards.



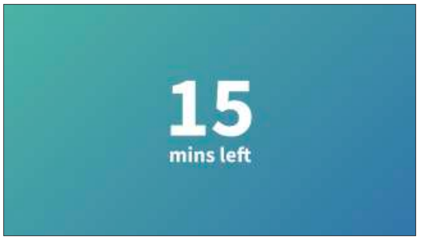
Slide 58. Introduction to group work.

Slide 59. What is Product-Service System Design.

Slide 60. The cards utilized by the groups to envision their PSS.



Slide 61. Example of PSS.



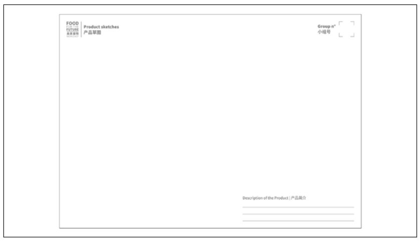
Slide 62. Time left.

Slide 63. Time's up!

Slide 64. Case study: WaterLilly 3.17.

Slide 65. Concept: Filene's Eco Pods.

Slide 66. Concept: Hydrogenase algae-farm.

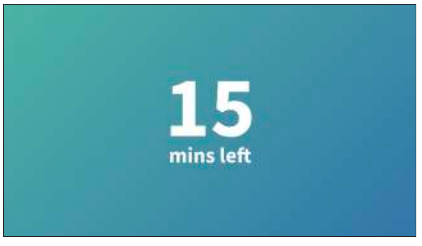


Slide 67. Product sketches template.

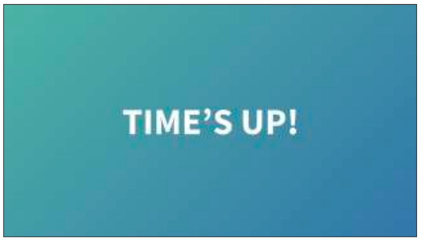
Slide 68. Microalgae and product design: various suggestions.

Slide 69. Microalgae and product design: various suggestions.

Slide 70. Microalgae and building façades: various suggestions.



Slide 71. Time left.



Slide 72. Time's up!

Slide 73. Group work presentations.

Slide 74. Thanks.

Slide 75. Contacts.

Category 1. Production place

Home
家里

Residential community
小区

School
学校

University
大学

Office
办公室

Restaurant
饭馆

Bar/Café
酒吧/咖啡厅

Public space
公共空间

Other
其他

Category 2. Primary product

Fresh Spirulina
新鲜螺旋藻

Dry Spirulina
干燥螺旋藻

Category 3. Processor

Food/drink factory
食品加工厂

Restaurant
饭店

Pharmaceutical company
制药厂

Community
生活社区

Bar/Café
酒吧/咖啡厅

Home
家里

Other
其他

Category 4. Processed product

Human food
人类食品

Animal feed
动物饲料

Drinks
饮料

Pharmaceuticals
保健品

Cosmetics
美容产品

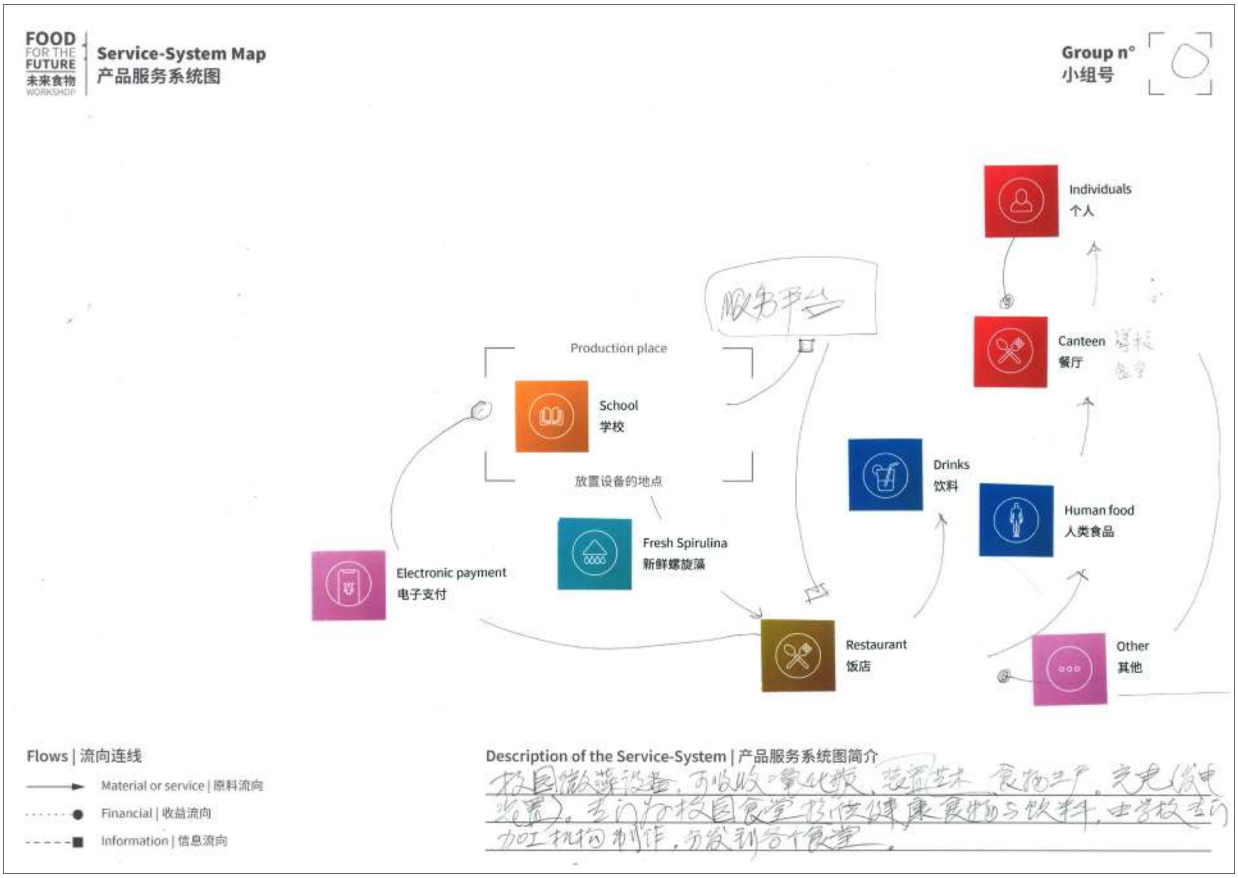
Biofertilizers
肥料

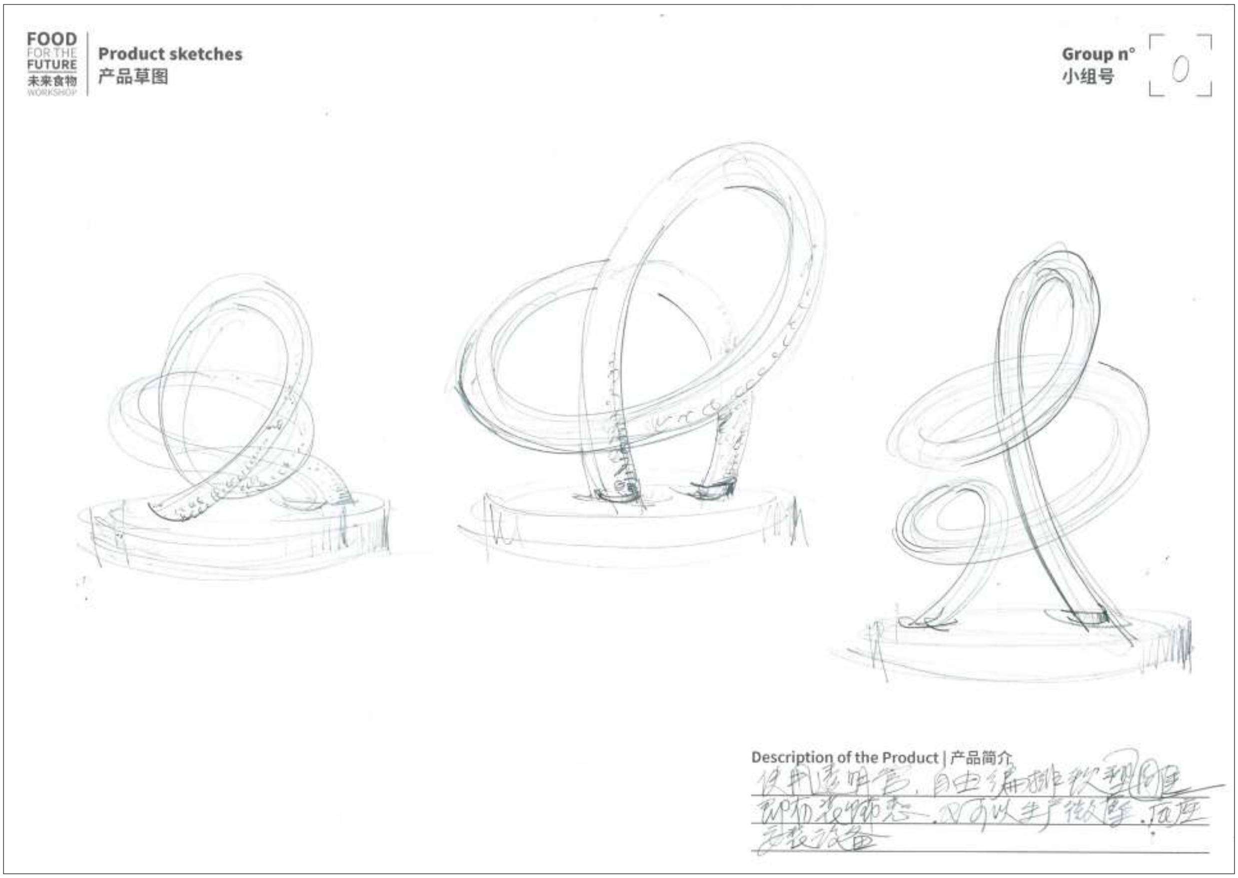
Category 5. Payment methods

- Electronic payment 电子支付
- Cash 现金
- In-kind contribution 实物交换
- Redeem code/ Voucher 礼品码/代币
- Other 其他

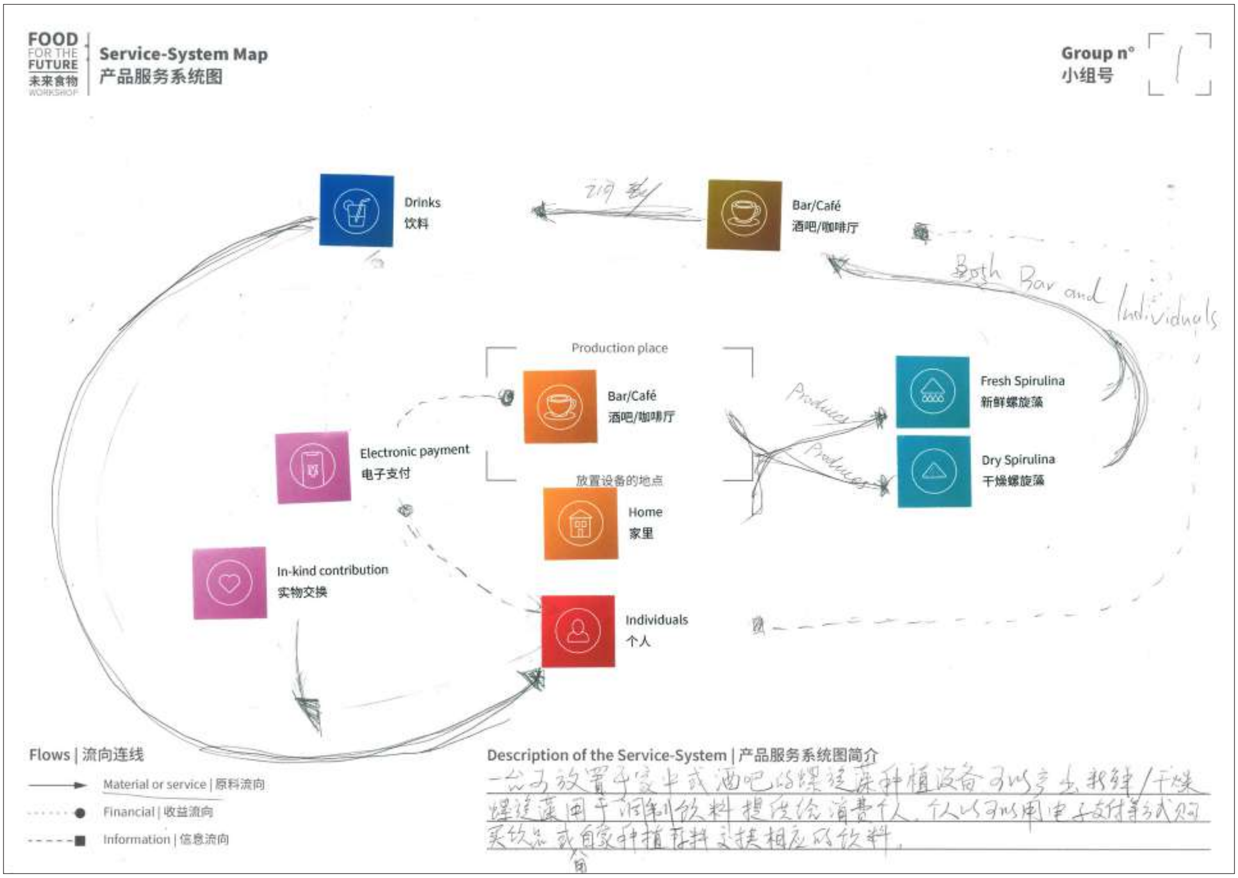
Category 6. Final customer

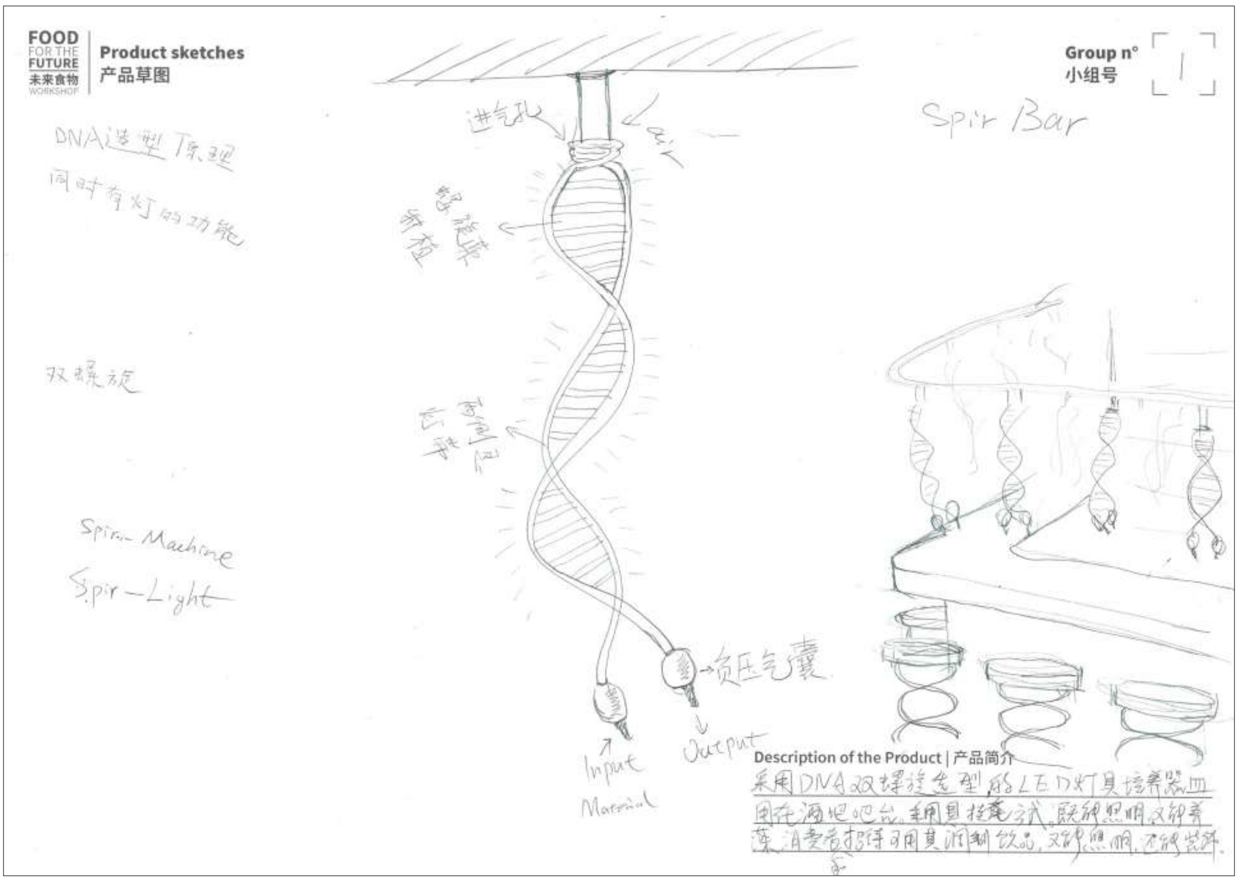
- Individuals 个人
- Local entrepreneur 本地企业
- Community 社区
- Public bodies 公共机构
- Hospital 医院
- Canteen 餐厅
- Gym 健身房
- Local market 本地市场
- Supermarket 超市
- Restaurant 饭馆
- Pharmacy 药店
- Small shops 小商店
- Other 其他



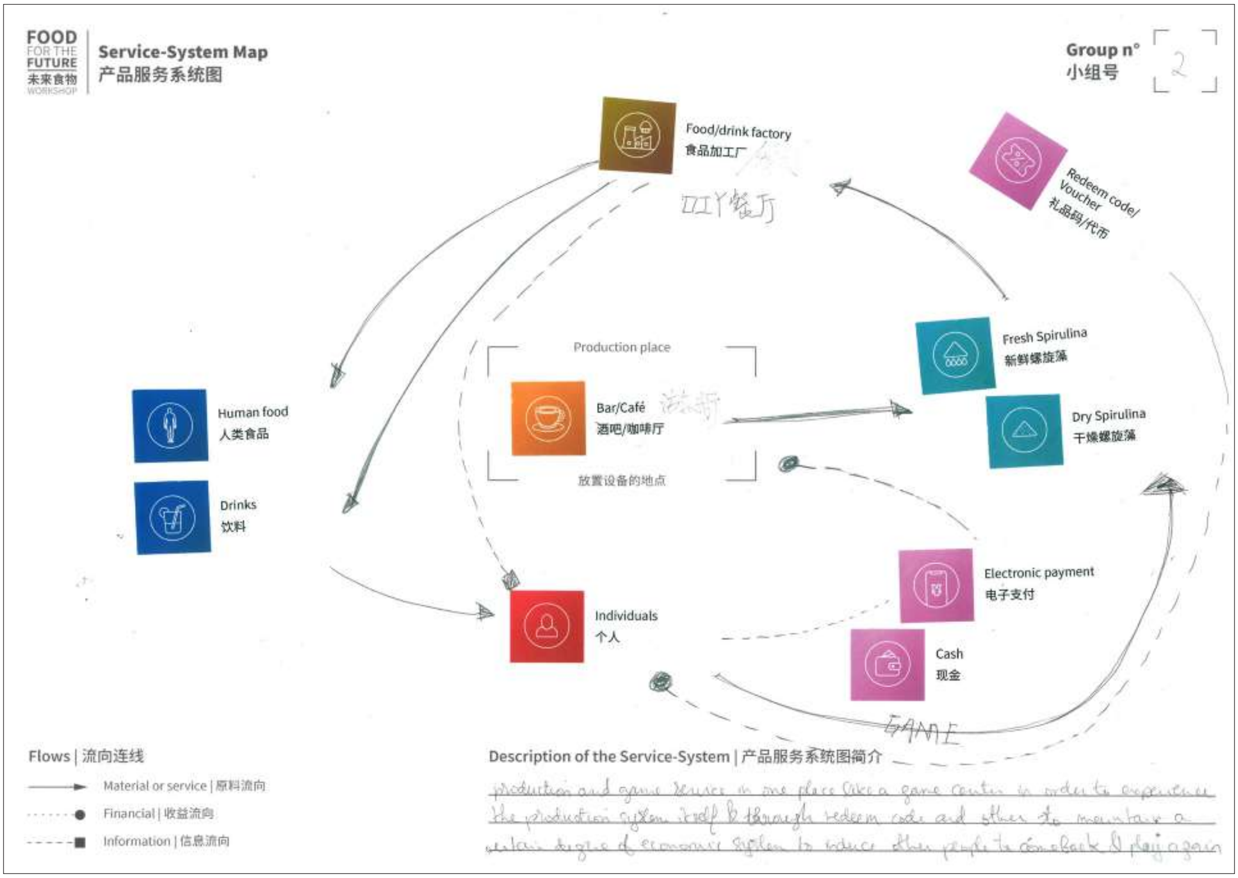


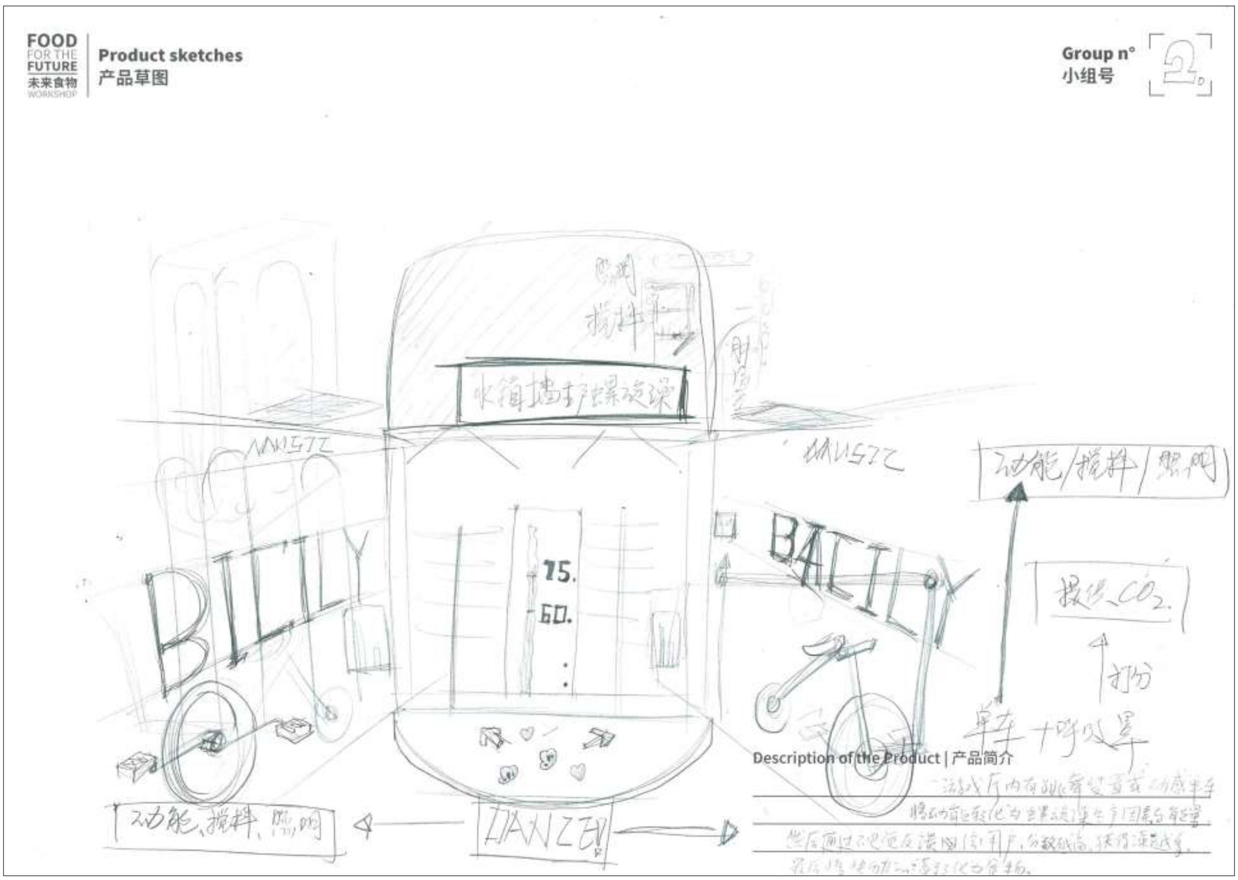
Group n. 0 (刘新, 钟芳): *Product-Service System Map and Product sketch.*



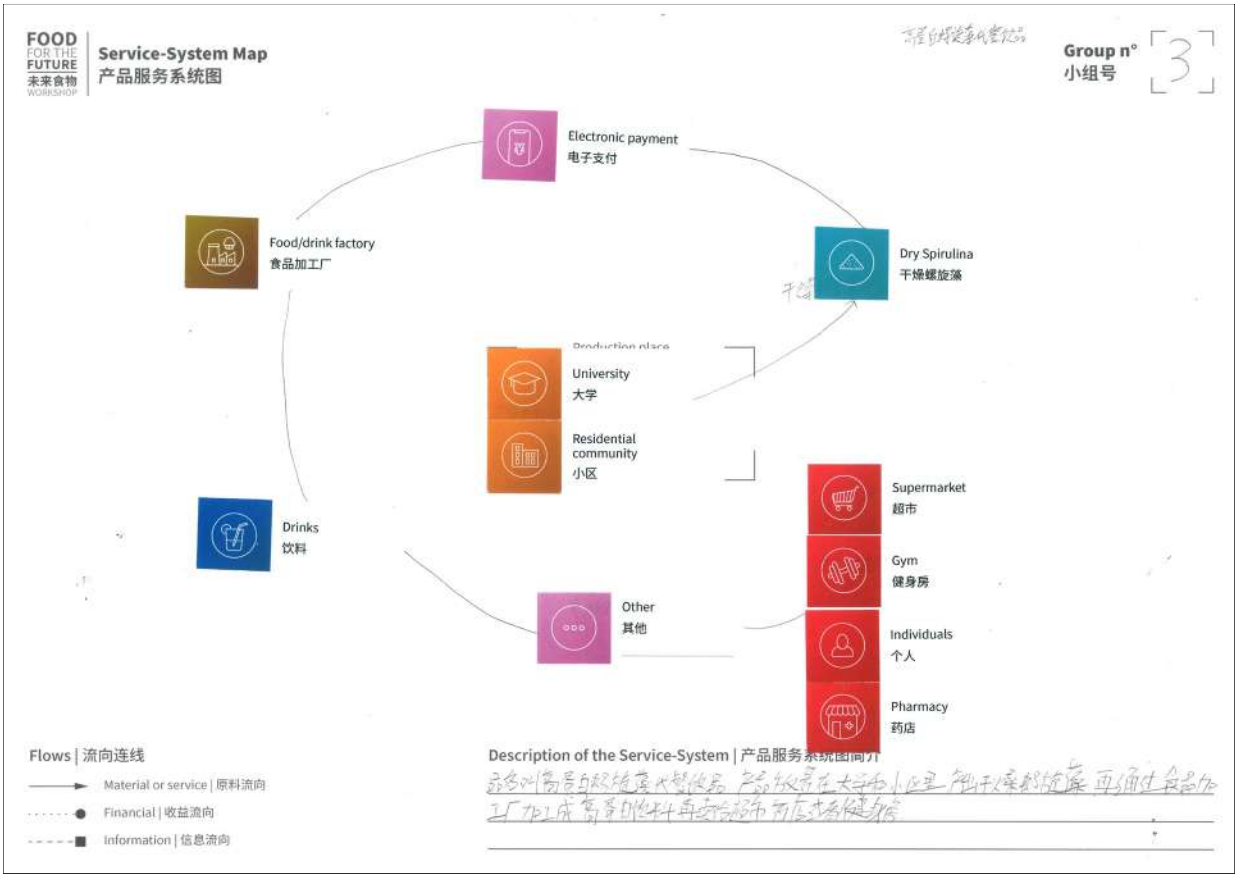


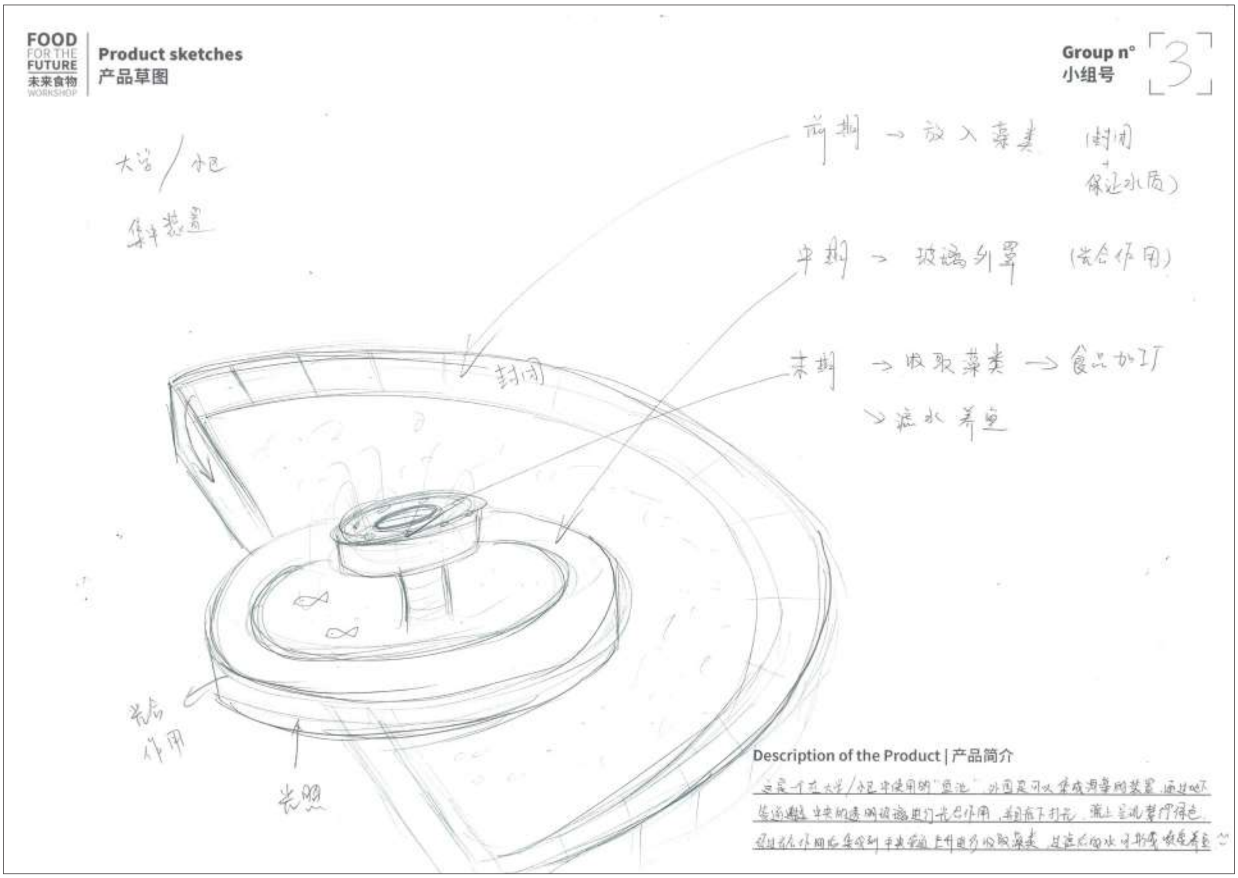
Group n. 1 (宋佳珈, 王渤森, Daniel Gockler): *Product-Service System Map and Product sketch.*



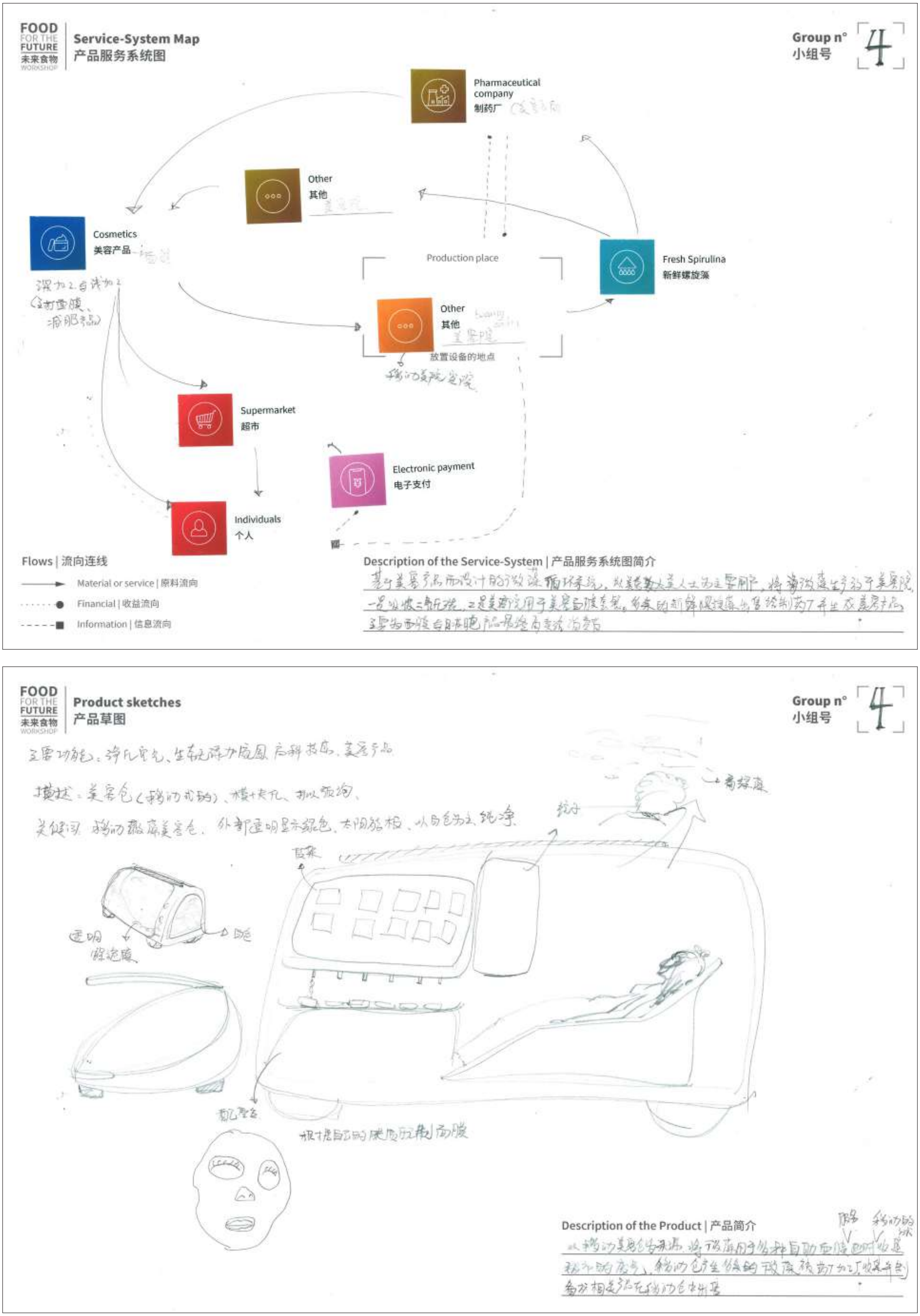


Group n. 2 (洪力飒, 黎书, 梁茹茹): *Product-Service System Map and Product sketch.*

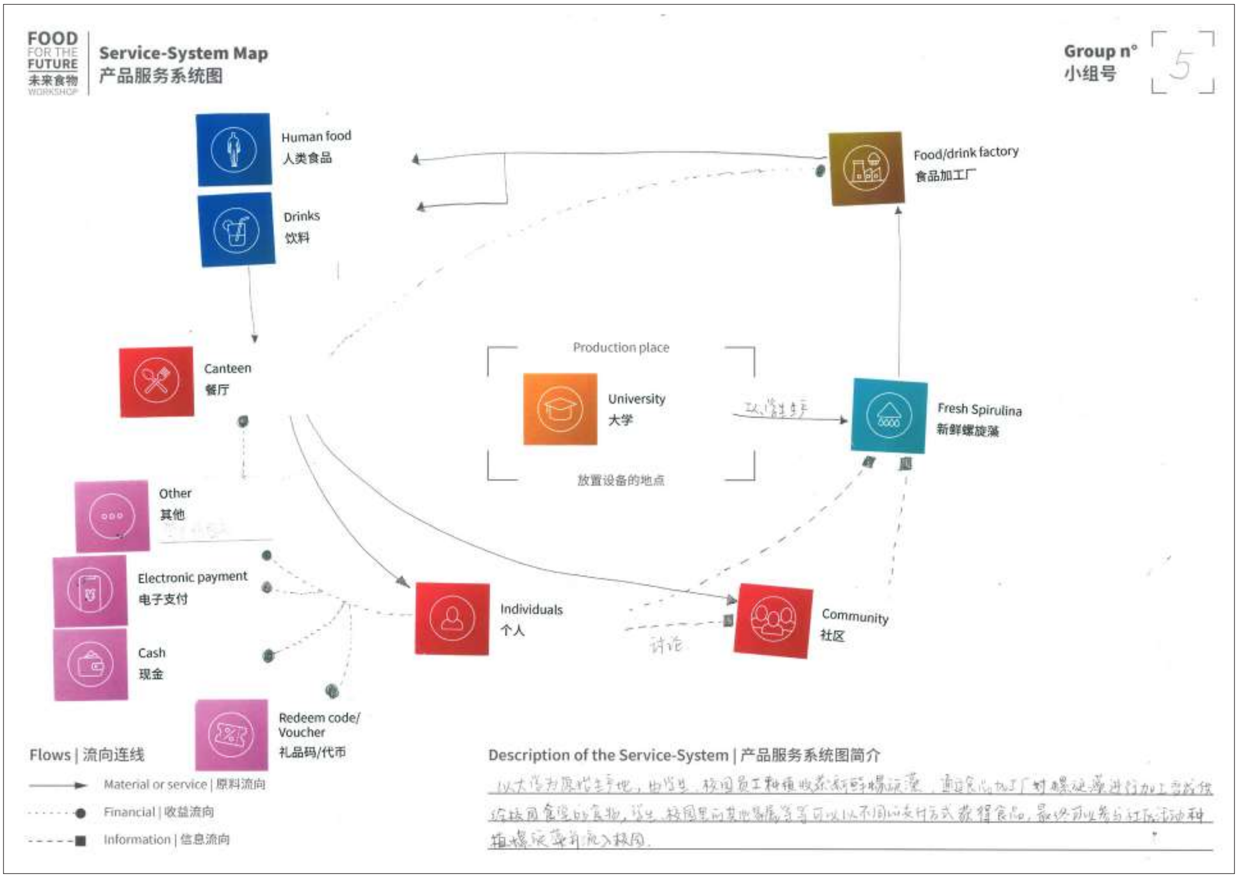


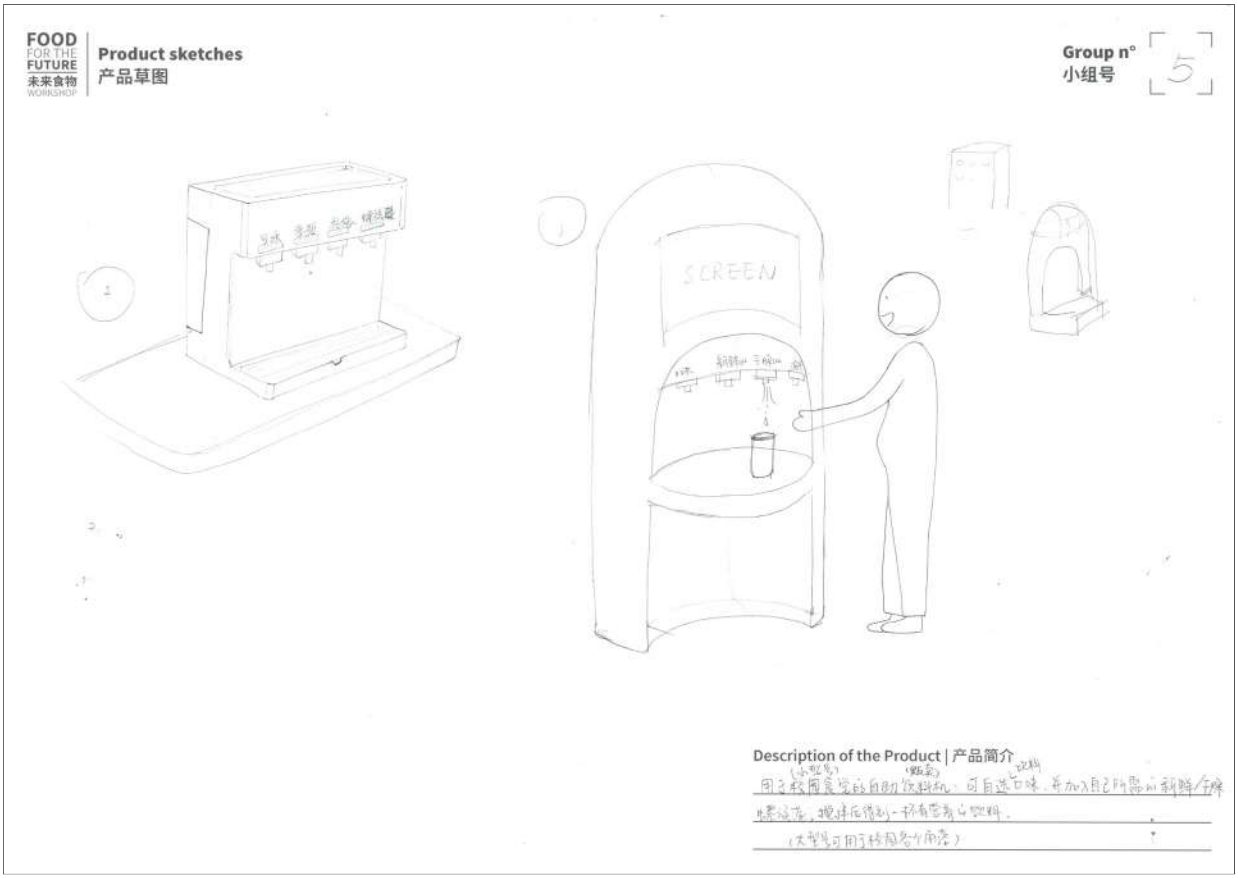


Group n. 3 (苌彬, 邬梓桐, 李天): *Product-Service System Map and Product sketch.*

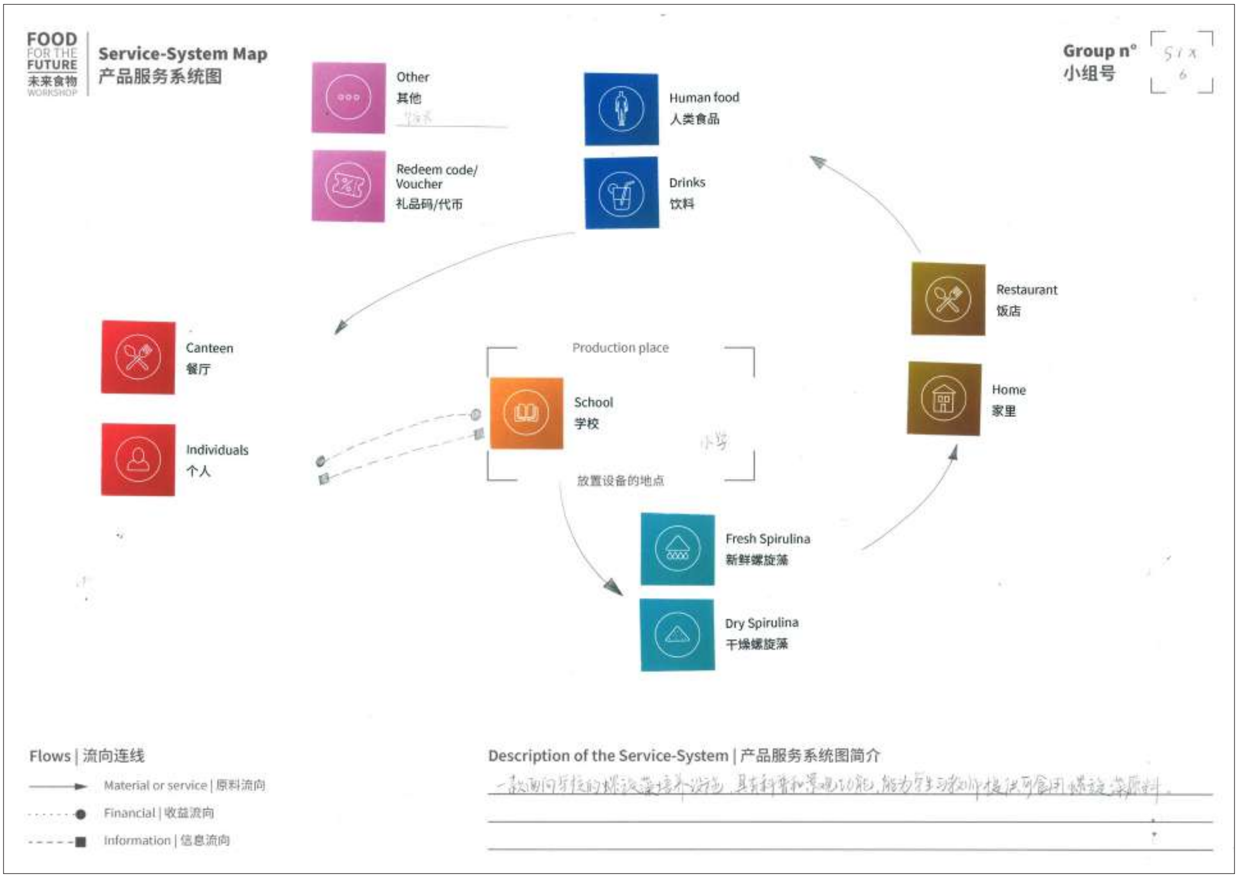


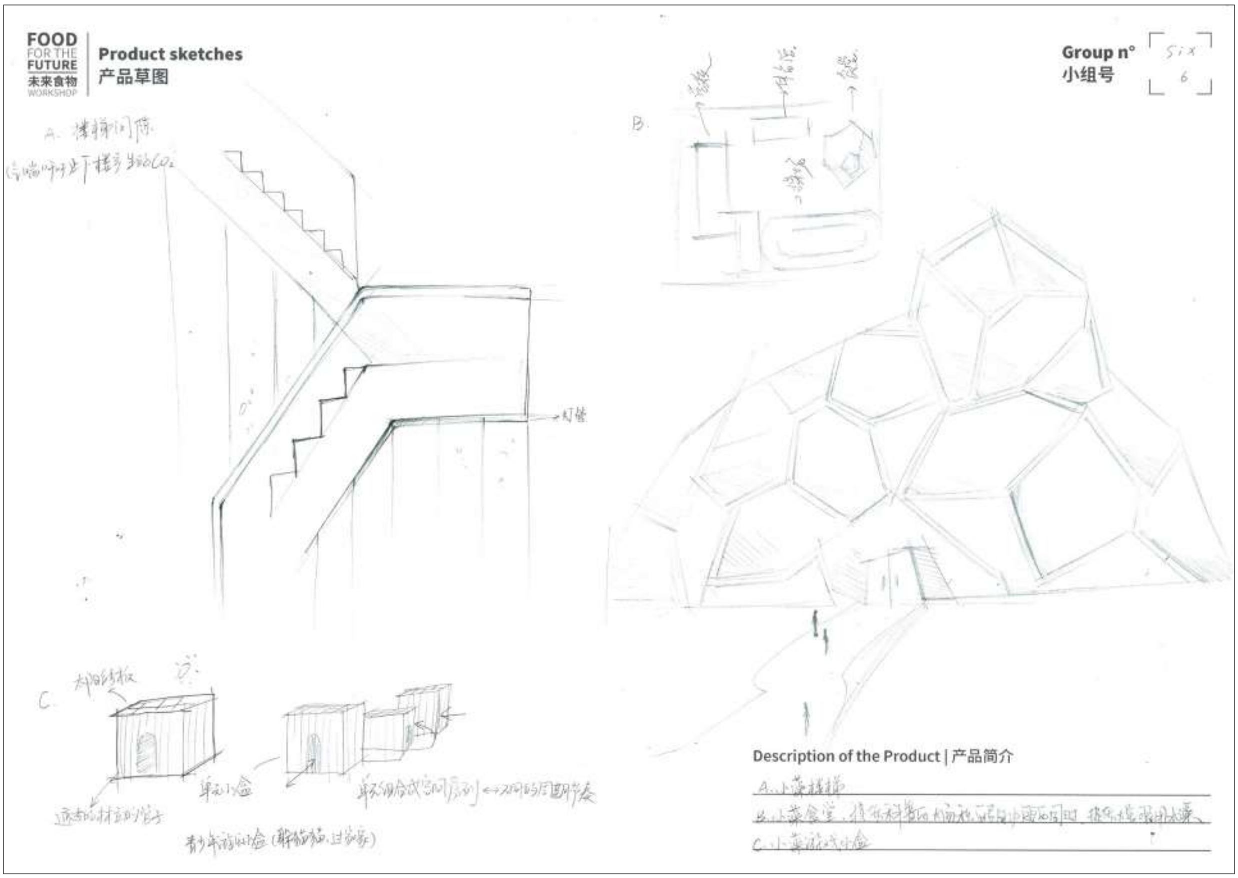
Group n. 4 (黄孙杰, 王金钰, 花生豆): *Product-Service System Map and Product sketch.*



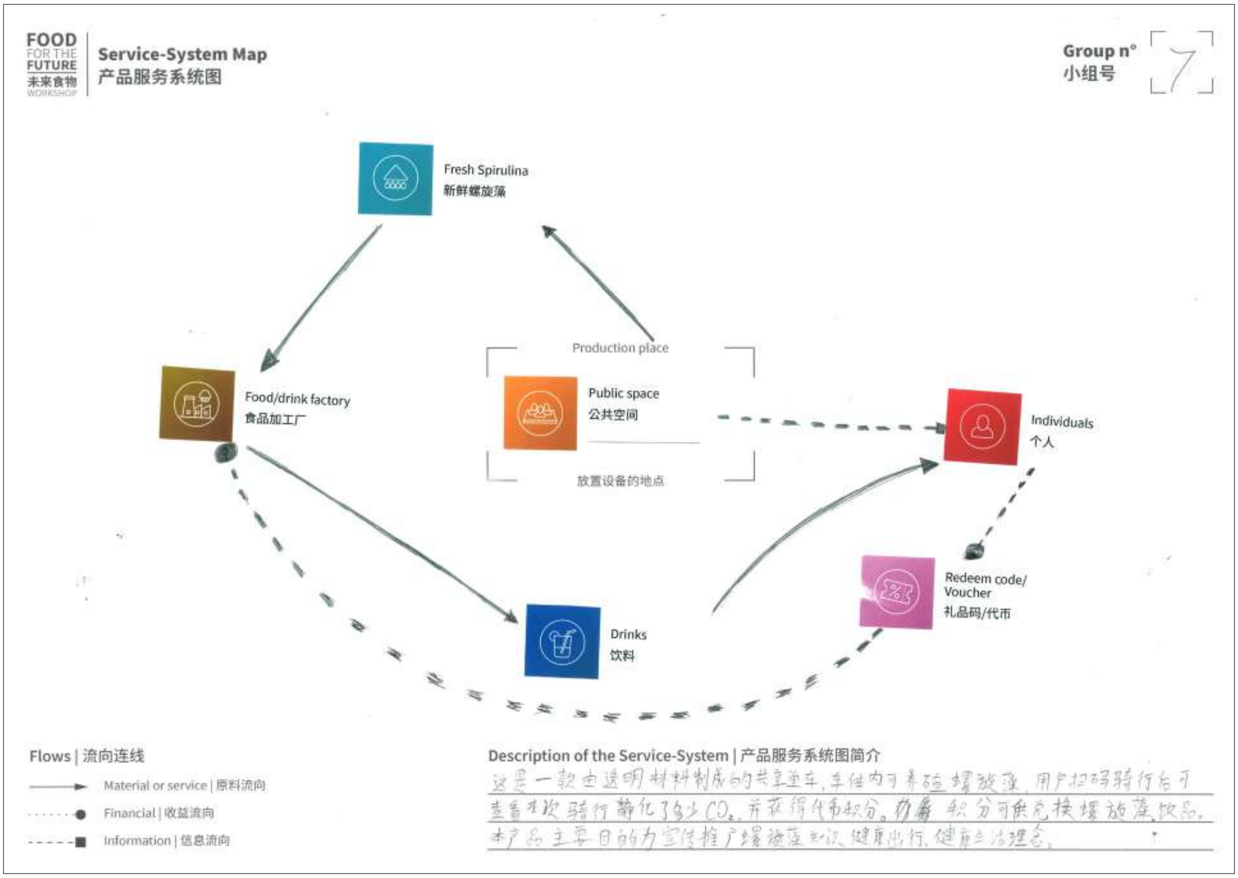


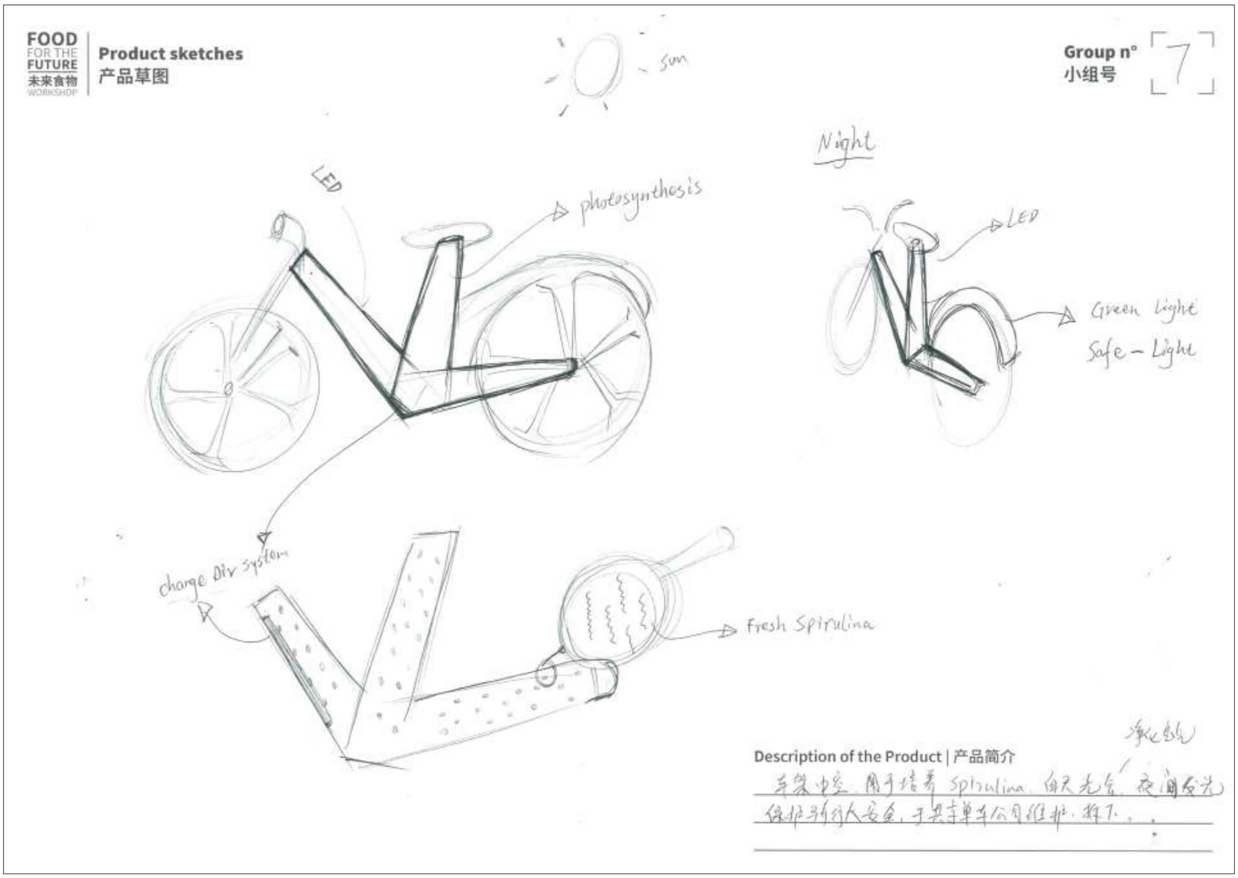
Group n. 5 (廖卓颖, 陈瑶, 康婧): *Product-Service System Map and Product sketch.*



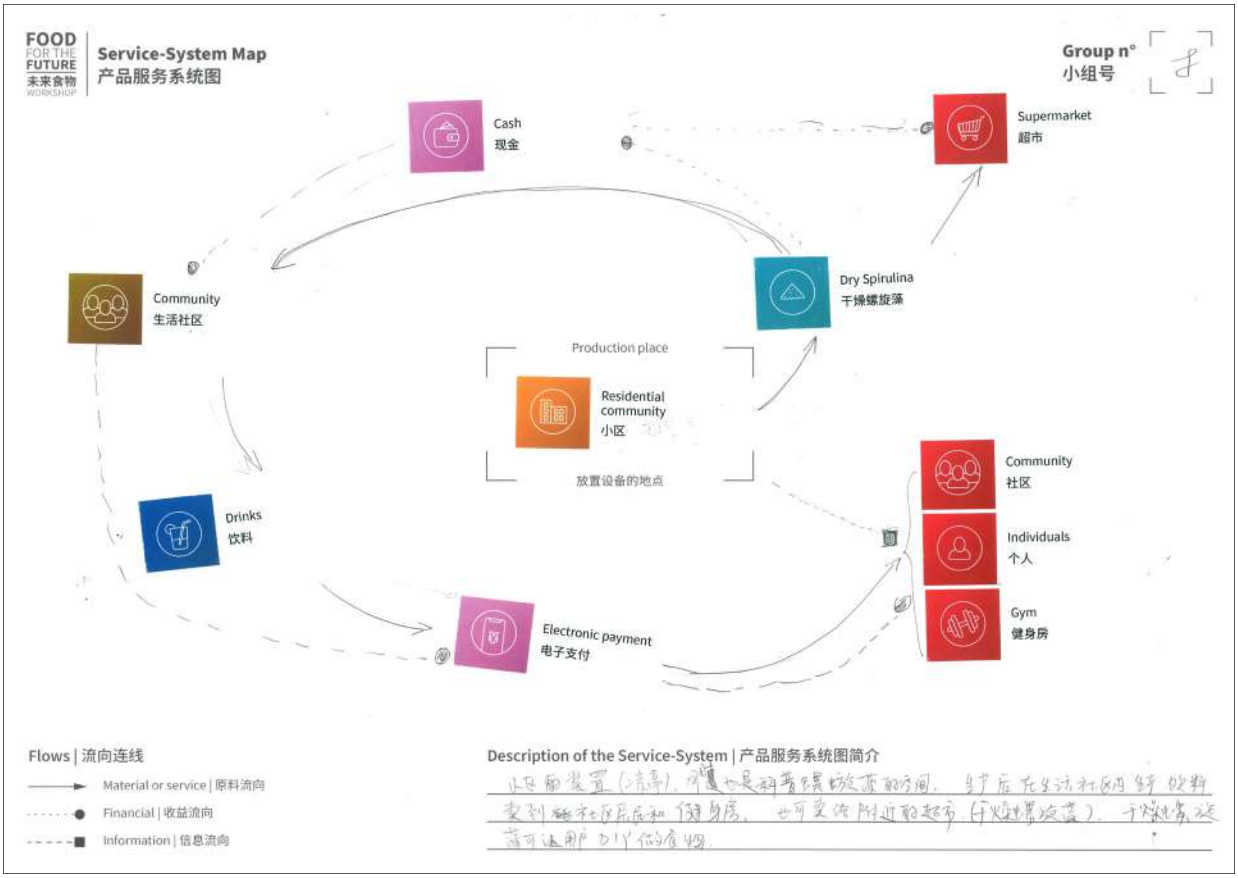


Group n. 6 (田润泽, 陈祉璇, 高歌): *Product-Service System Map and Product sketch.*





Group n. 7 (李博功, 张雨生, 贺小易): *Product-Service System Map and Product sketch.*



Group n. 8 (白俊慧, 韦家柳, 严泽腾): *Product-Service System Map and Product sketch.*

The Algae Grower. Details of the drawer track slider.

Details of the extractable drawer and the magnetic buckle mechanism.

The connections on the inner part of the lower main body, with the front button and the power connector.

Anti-slip silicone gasket.

Water check valves.

The elements utilized in the high-fidelity prototype.

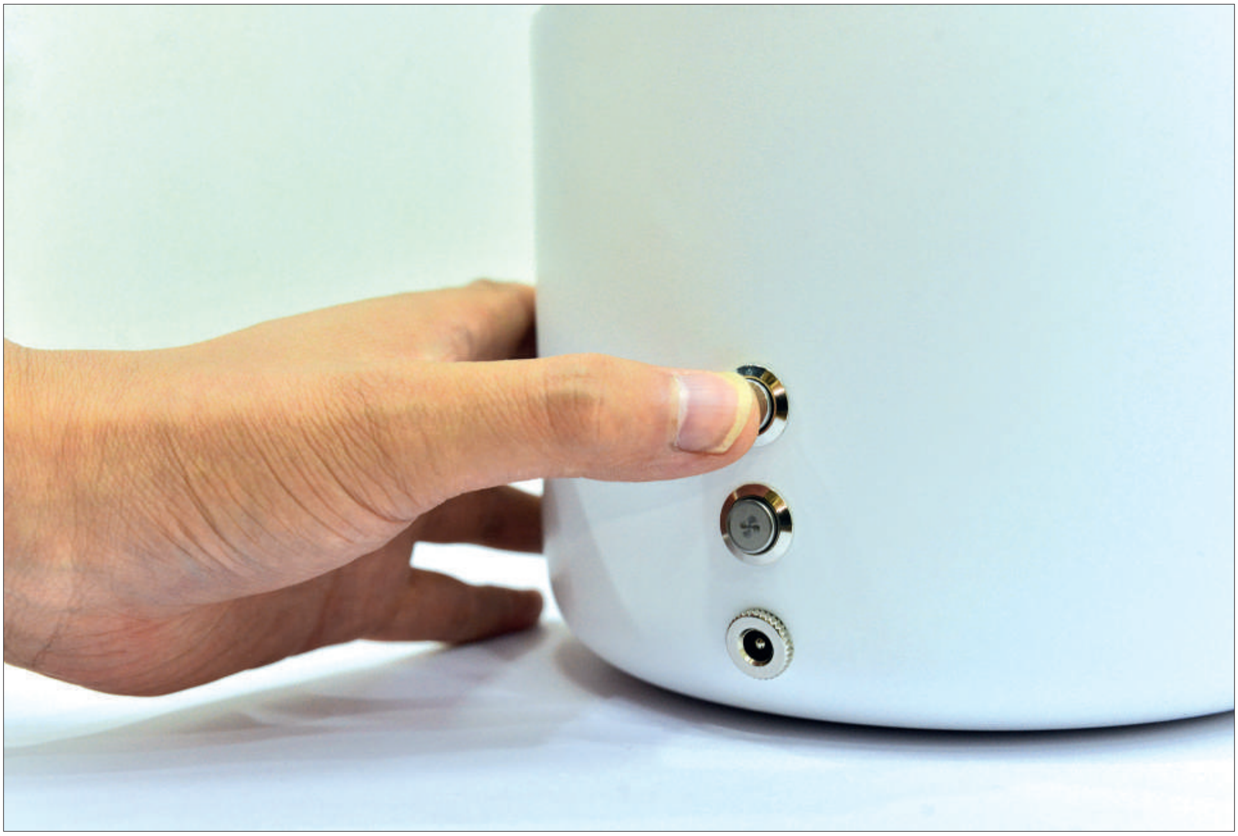
The Algae Grower. Spirulina culture illuminated by LED light. Copyright 2020 by Li Tian.

The Algae Grower. Device off (no lighting and bubbling).

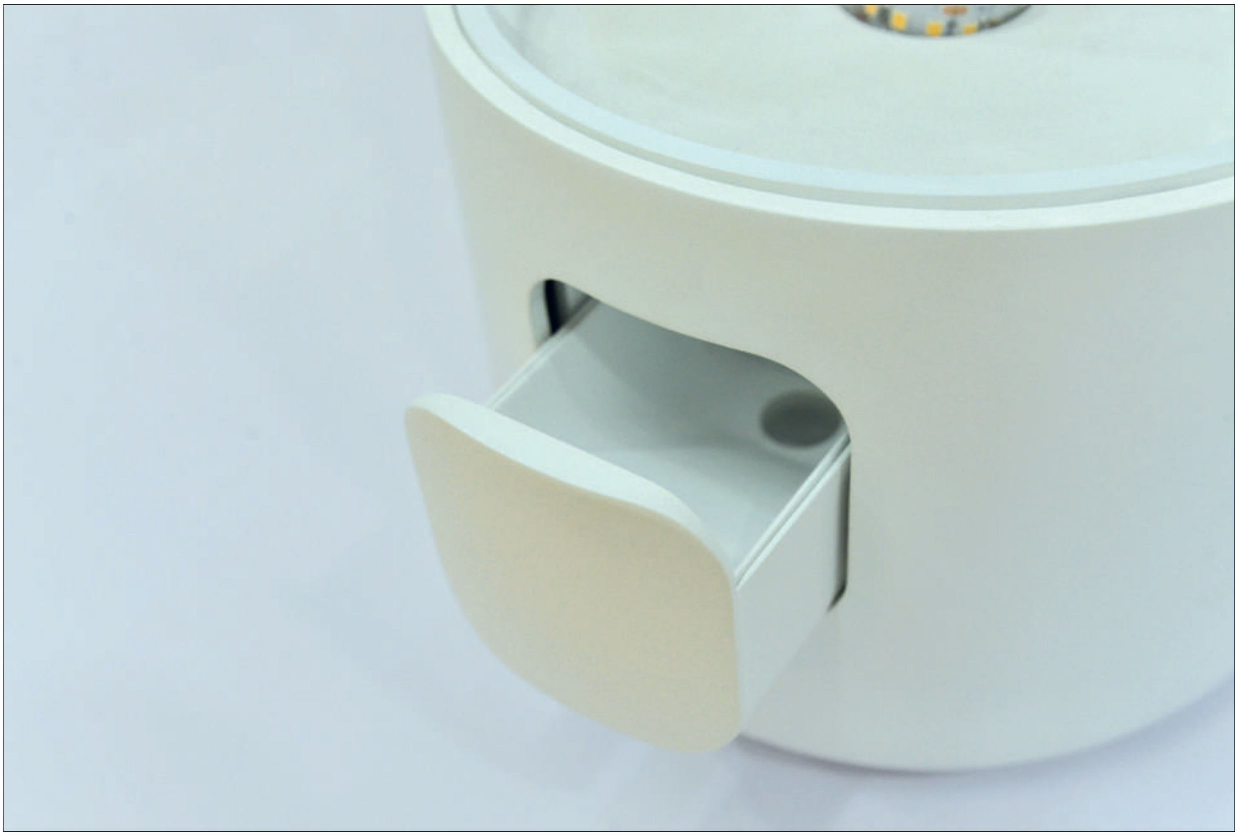
Easy-to-open top lid. The handle is ergonomic.

Detail of the opened top lid and the silkscreened logo.

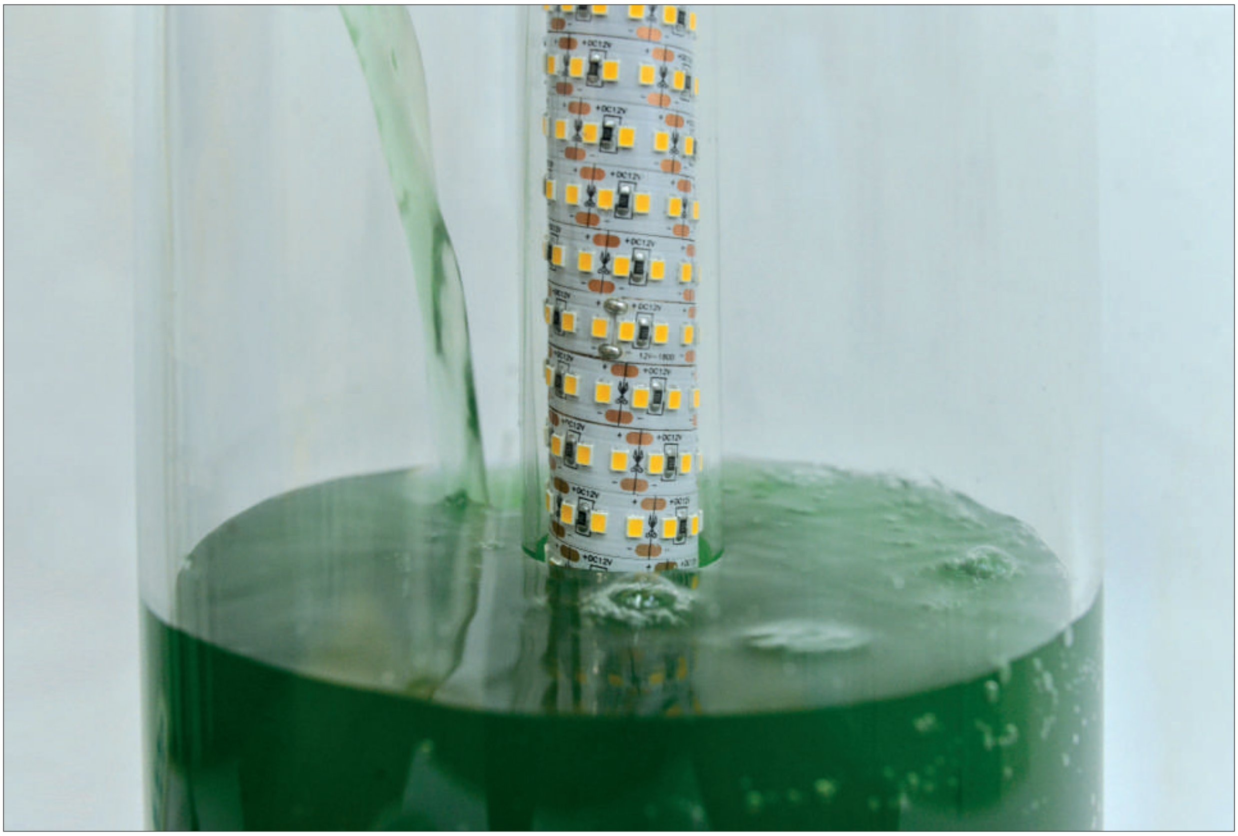
Detail of the front of the device: closed drawer and Spirulina harvesting button.



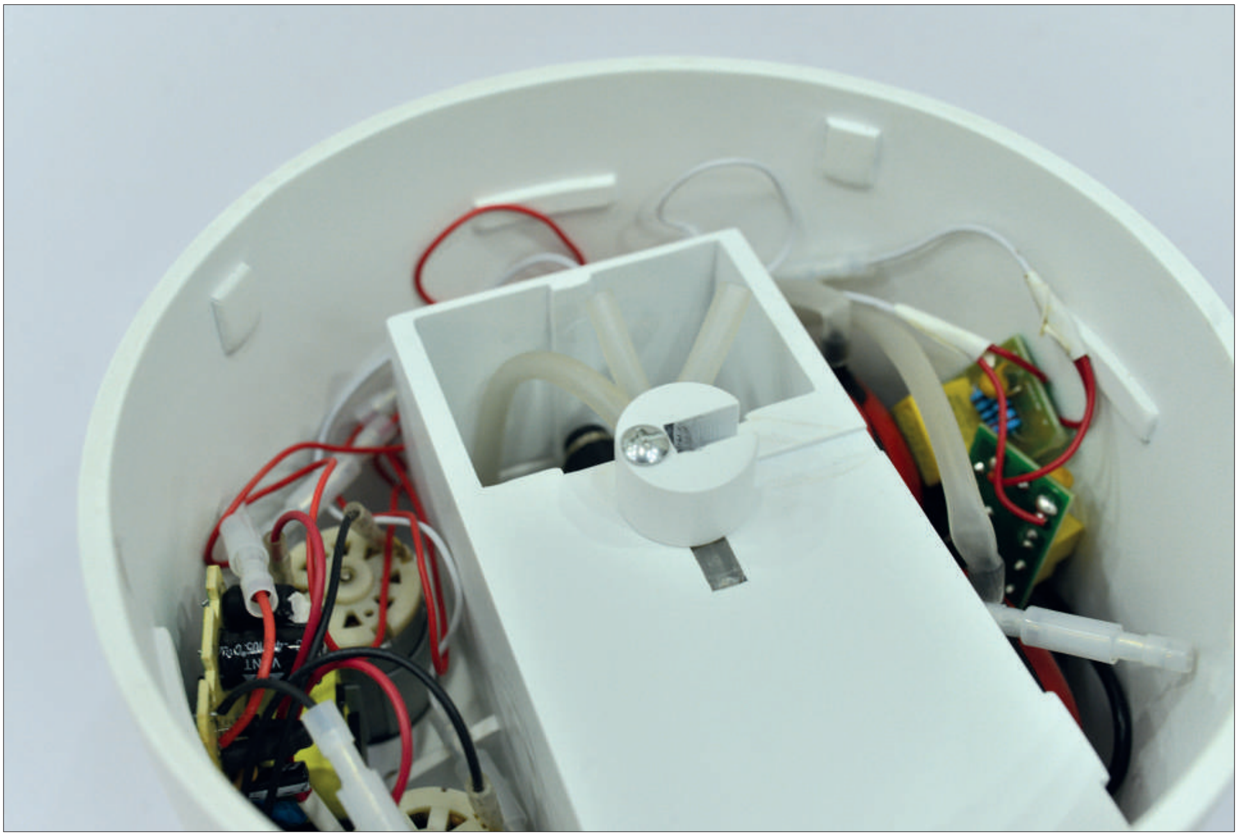
Buttons on the back of the device and power plug socket connector. Icons are laser-engraved on the buttons.



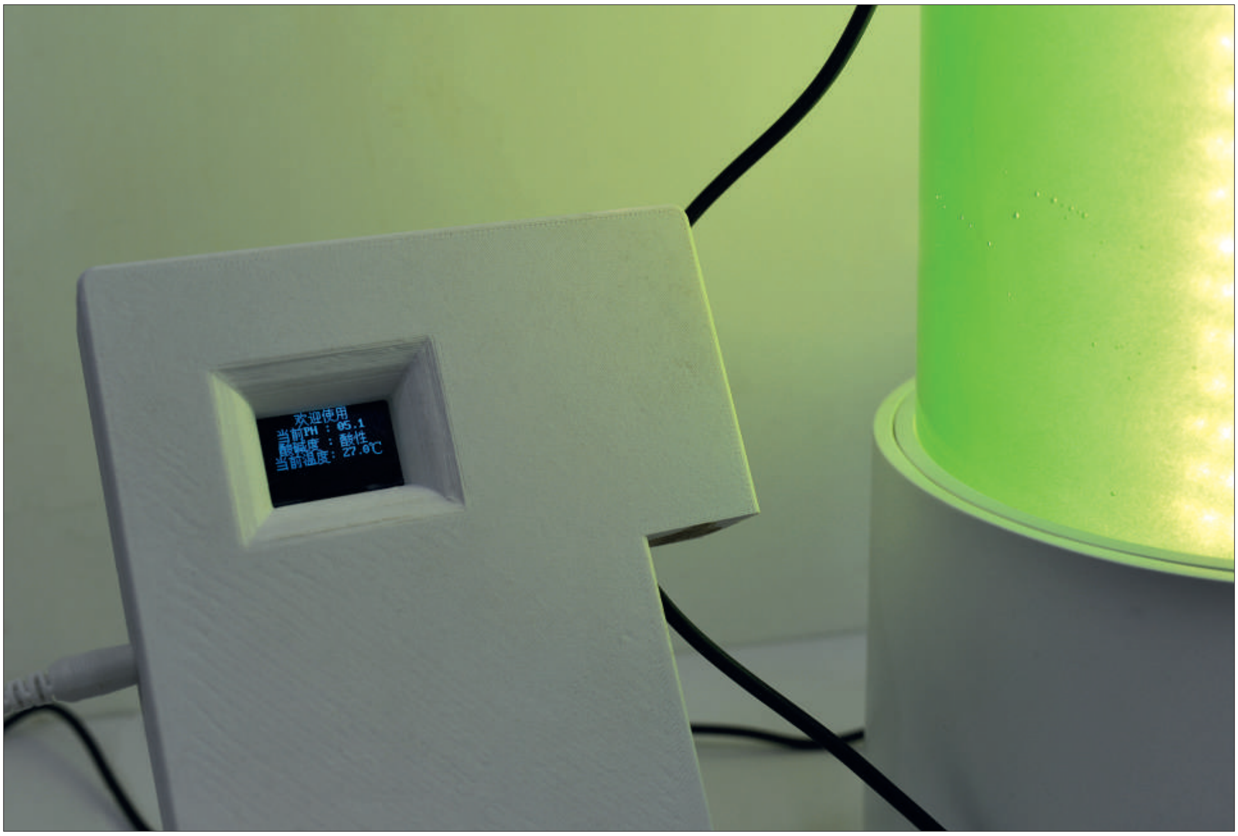
Front drawer. The inner part is removable to facilitate the change of the harvesting net if broken.



Detail of the central LED lighting system while the tank is filled with alive Spirulina inoculum.



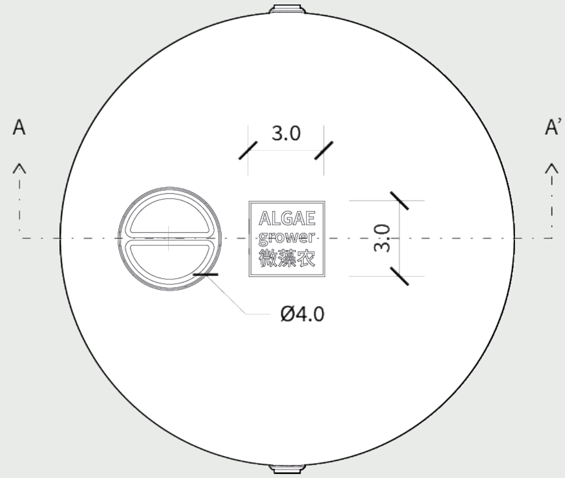
Internal components, air and water pipes, and various cabling.



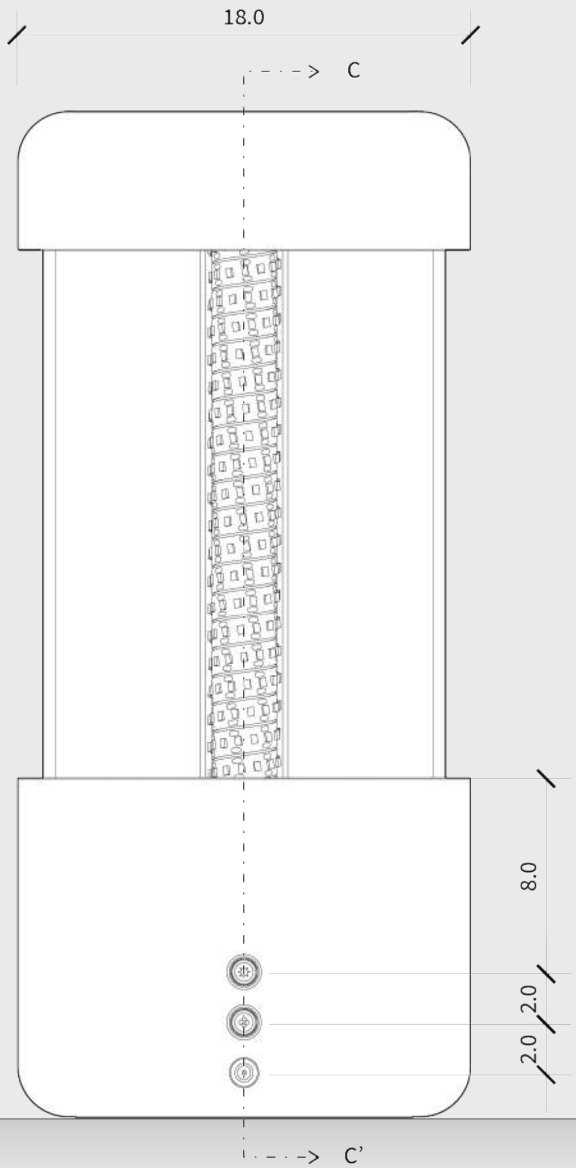
External pH and temperature sensors, measuring culture parameters.

The Algae Grower

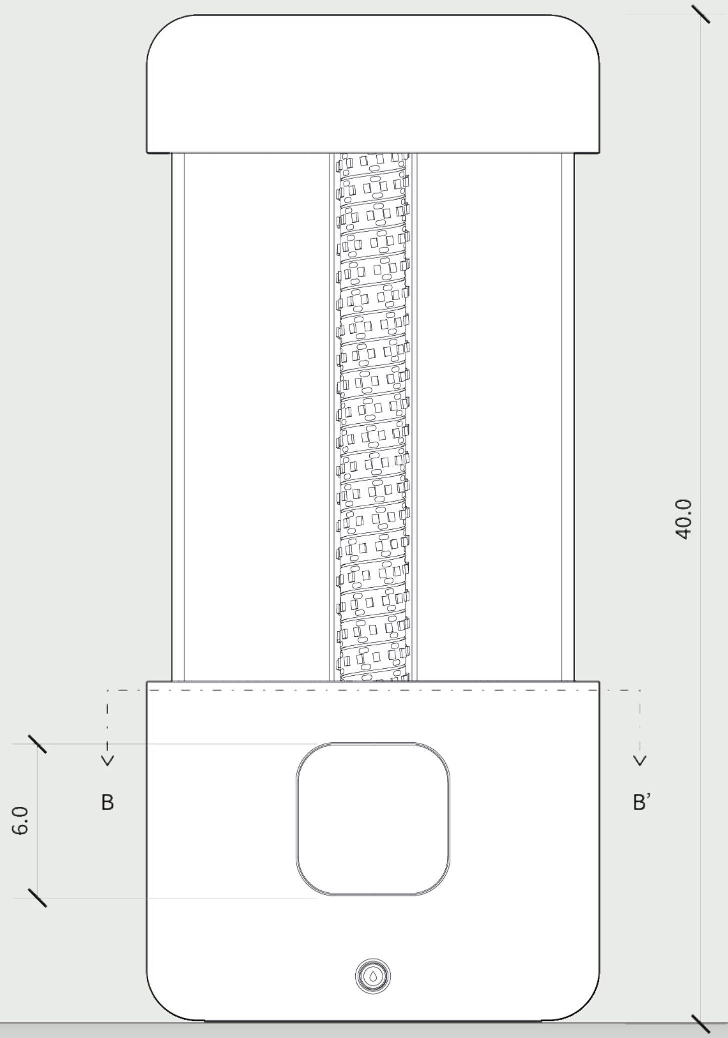
SCALE 1:3
Quotes in cm



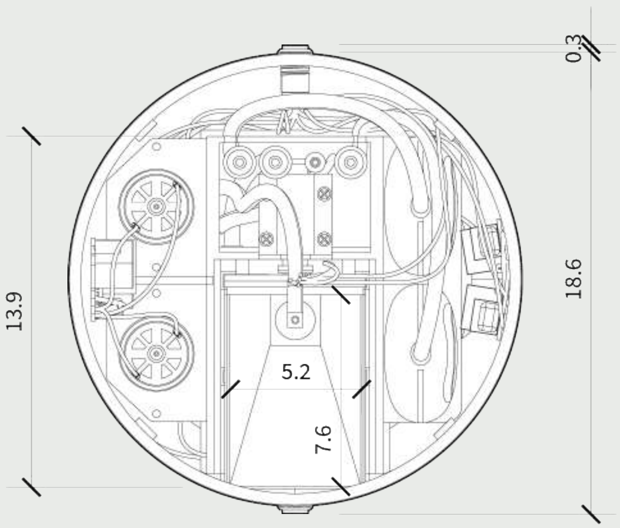
TOP VIEW



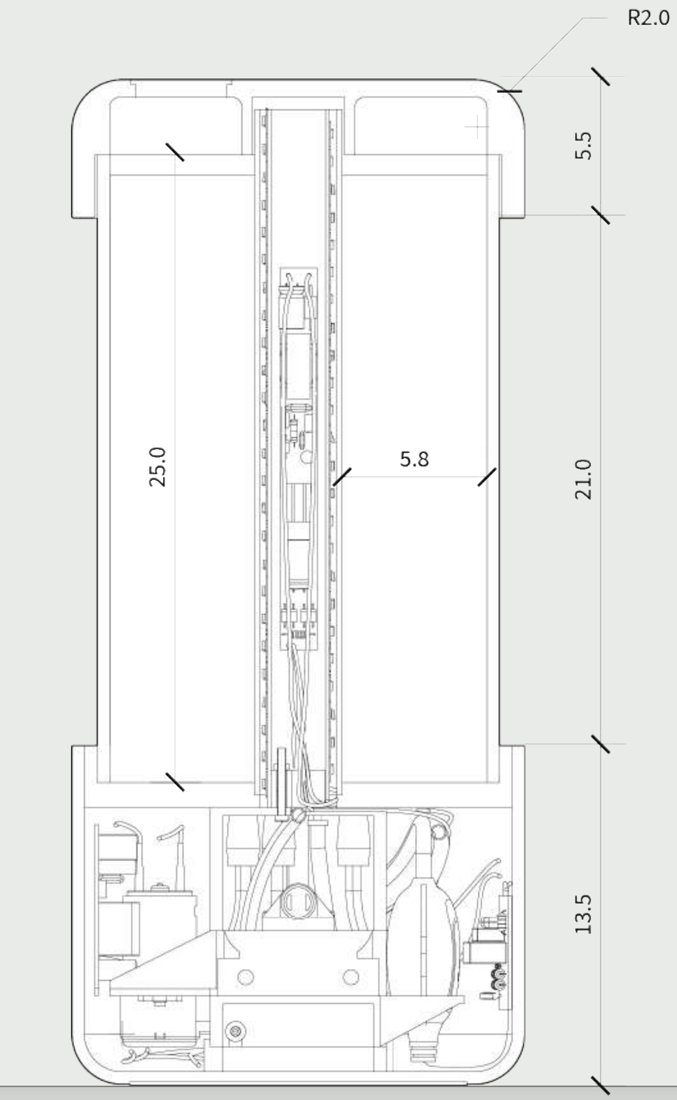
BACK VIEW



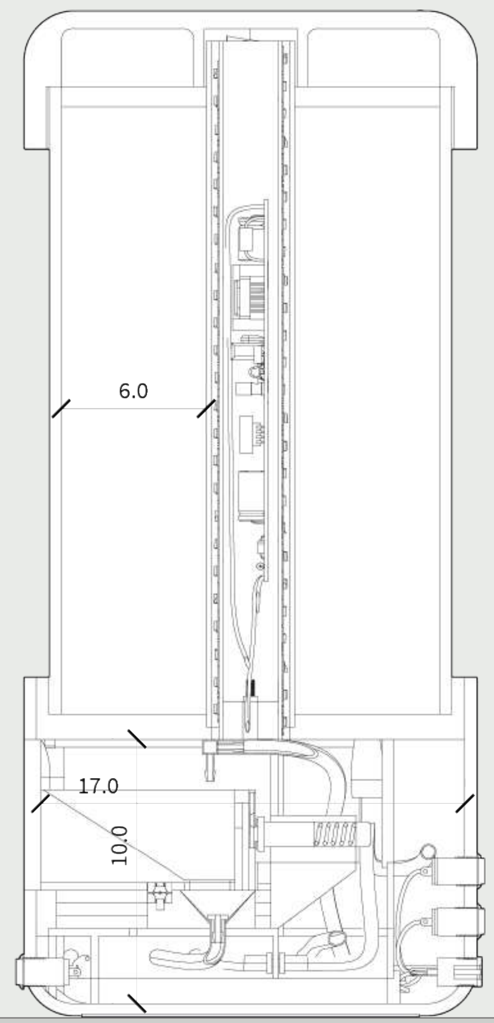
FRONT VIEW



SECTION B-B'



SECTION A-A'



SECTION C-C'

The Algae Grower – User validation test (Open questions)

1. Gender: ☐ Male ☐ Female

2. Age: ☐ <18 ☐ 18-35 ☐ >35

3. Current occupation: ☐ Student ☐ Employee ☐ Other Please specify

4. Does the prototype do what it is supposed to do?

Please describe

5. Do you think that the product's design matches its purpose?

Please describe

6. How do you feel about the product?

Please describe

7. What is the first thing you did when you interacted with the device? How did you do it?

Please describe

8. Were you confused at some point?

Please describe

9. If you have this product at home, do you think you will use it regularly?

Please describe

10. What would you change about it? Why?

Please describe

11. Would you recommend this product to a friend?

Please describe

12. Please describe this product using your own words.

Please describe

13. Other considerations:

Please describe

14. Notes from the moderator:

Please describe

Q&A with Wikifactory

The following is the extract of a Skype call that occurred on 14 July 2020 between Nicolò Gnecchi, Wikifactory Community & Partnerships Lead, and me. Nicolò connected with me to push and support agritech projects on their platform, asking questions related to the Algae Grower context, and why I decided to make the instructions available in open source. Sentences may have been paraphrased in a few occasions. The full story is available on Wikifactory website.[1] Wikifactory (WF), Maurizio Vrenna (MV).

WF: What was the lightbulb moment that made you realize we need a device to grow microalgae at home?

MV: The Algae Grower is just a small outcome of my broader research in sustainable design. Aside from an academic, I'm also a designer and a maker. I believe that designers today have the great responsibility to understand why they are designing products, and who is going to use them. Designers also have to address sustainability issues. By sustainable, I mean economically, environmentally, and socially. Design nowadays means not only the production

1 Gnecchi, N. [niko11]. (2020, July 16). Q&A with Maurizio Vrenna, creator of the Algae Grower [Blog post]. Retrieved from https://wikifactory.com/+wikifactory/stories/qa-with-maurizio-vrenna-creator-of-the-algae-grower

of products but also the related services and systems in which these products operate.

WF: Why should designers be concerned about food security?

MV: By studying the current exponential growth in urbanization and global population, I realized that the ongoing efforts in changing food systems are probably not enough. We need radical behavioral change to feed more people with an ever-diminishing arable land. There are plenty of scientific papers on the benefits of microalgae in biology, microbiology, and medicine, but aside from a few experimentations, no academic research from the point of view of design. My study attempts to fill this gap by mapping what's going on in the field of microalgae and design and also through this project explore methodologies that innovates and explores new uses of *Spirulina*. The Algae Grower is not an idea that I had overnight, but the result of an in-depth literature review and methodological research. In this sense, it's more than just a photobioreactor; which is the technical name of a device that utilizes light and heat to grow microalgae. It's an attempt to answer the question: *"How can designers create products, services, and systems involving microalgae that are beneficial and sustainable for the society?"*. I realized that the Algae Grower is only one of the many possible design solutions. It's my personal and professional interpretation of a Spirulina-harvesting device to be used in present and future cities.

WF: Tell me more about this device? How does it work?

MV: The Algae Grower has a 4-liter tank. This is filled with drinkable water. Fresh *Spirulina* inoculum can be bought from labs, or it can be shared among the growers' network. That's how we create a community of active users: a system of makers that self-fabricate the hardware (for example, with 3D printers) and a community of enthusiasts that share *Spirulina* harvests, and suggestions on how to take care of the culture. Inside the tank, *Spirulina* is always moving thanks to an air pump. When you see that the culture turns into a dark green color (it will take around a week), this means that it is ready to be harvested. You can also use a particular tool called 'Secchi stick' to measure the optical density of the water. Then, you press a button that activates another pump to suck the water and the biomass out. A net traps the biomass in a drawer, and the remaining nutrient-rich water goes back into the culture. You can extract the drawer and take a spoon of fresh *Spirulina*: put it directly in your yogurt, pasta dough, or bread, and make your tasty recipes! It's that easy!

WF: Green yogurt huh? So *Spirulina* is good for you?

MV: *Spirulina* is nothing new, and you can buy it in powder or pill form in many pharmacies. But now thanks to this device you can also cultivate it at home. *Spirulina* is a superfood and a rich source of vitamins (Vitamin E, Vitamin B12), minerals (calcium, magnesium, phosphorus, sodium, potassium, and iron). It contains 60-70% of high-quality proteins, as well as carbohydrates, lipids, and essential amino acids.

WF: Why only a 4-liter tank?

MV: I've seen other similar projects online with bigger tanks, but I was striving for feasibility and acceptability. So, I did something really simple: I took a meter, measured the dimensions of my kitchen counter, and then that of a friend of mine. I deduced that if I made the Algae Grower any bigger, it wouldn't fit in most kitchens. The device can produce 5-6 grams of *Spirulina* each day, which is enough for one person. The daily recommended dose ranges from 1 to 8 grams, so maybe it's not enough for a whole family. If the project is Open Source, you can change the dimensions of the tank and have it bigger and taller, according to your needs. That's what Wikifactory is for. Secondly, this project is not about forcing you to eat *Spirulina* until you go green, but rather to educate people about this incredible alternative and complementary nutrient that you can grow in your own kitchen with a simple appliance. So maybe it's not for everyday consumption. Maybe twice a week, we can eat pasta with *Spirulina* instead of a steak, right? Moreover, you can also freeze the extra *Spirulina* produced and consume it later. This is a smooth transition because we'll soon need to adapt to an inevitable change in food consumption and habits.

WF: So, this project is more an experiment in microalgae awareness rather than product design?

MV: Yes, the idea is to raise awareness on microalgae within the design community (but not limited), help designers understand what microalgae are, and provide them with some guidance around the self-production of such a device. The final goal of this project is to grow a broader user base and find ways to solve real-world problems related to nutrition. Ultimately, it is also about creating a more resilient society. By uploading the instructions on Wikifactory, we can democratize the way of producing *Spirulina* at home. Is this going to be one way to feed us in the next decades? Maybe...

WF: So, will *Spirulina* become the healthy espresso of the future?

MV: Well, as far as I know, some companies are already selling the 'Unicorn Latte' with added Phycocyanin – an extract of *Spirulina* with a very bright blue color. It's a 100% natural protein boost, and it's trending on social media. I tried it once, and it's not bad!

WF: What about a commercial product? Why did you choose Open Source?

MV: One of the first thoughts was to patent this design. I did a lot of research, and patenting something is really complicated. It takes time and money, and it's something that you can exploit commercially only in certain jurisdictions. Once you have a patent, it doesn't stop the design from being easily reproduced by someone else. Then you may have other legal issues on how to defend the patent. So I and my collaborators, we decided to share the prototype as Open Source because we believe in creating a community, and in the ethical role of academia. Besides, the prototype still has some limits. For example, it doesn't include a heater because the structure is made of plastic that could melt if exposed to high temperatures. I hope to get feedback from makers all over the world on how to improve the Algae Grower. Eventually, we can organize a series of workshops and discuss it! On the other hand, I am also in touch with some factories and companies because I believe that this project is commercially viable.

WF: Has the COVID-19 crisis affected the way you think about this project?

MV: I was working on the Algae Grower in Beijing in January when the COVID-19 pandemic started and disrupted everything. The current sanitary crisis has convinced me – even more – that self-producing food at home is crucial for the future of cities. Urban gardens are definitely a growing trend. We are already seeing this in cities like New York, Shanghai, and Copenhagen. Harvesting food requires time and knowledge, and you have to get your hands dirty. So, even if you are a concerned citizen and care about self-producing your vegetables, maybe you don't have the time to dedicate to indoor farming. The Algae Grower, instead, allows you to harvest *Spirulina* in a semi-automatic way. It's effortless: you just have to fill the tank with water and *Spirulina*, turn on the bubbling and the light, and let it grow! We also know from this virus that one of the defenses is a strong immune system. This is where it makes a lot of sense of growing *Spirulina* in our homes.

WF: What do you mean by a design approach to microalgae?

MV: I believe that projects involving microalgae made by designers – rather than scientists or engineers – need to have a broader view. Scientists and biologists have a pretty vertical knowledge, and they usually strive to maximize yields. So they would look for the best lighting solution systems, or struggle to find the right parameters for light and temperature. These are fundamental issues, no doubt, but mostly technicalities. As designers, we should try to see the bigger picture. A project also needs to educate users on how to use microalgae and why. At the same time, we need to create a community of active users. Also, how do you make *Spirulina* a palatable superfood? This was part of my research, and I worked with chefs to prepare delicious recipes. Probably in 10 years, we will be talking about this again, and we will say: *"Hey, this was a small step in the right direction, and we took part in this incredible change!"*.

The Algae Grower Plus with Beatriz Castelar

Beatriz Castelar is a visiting researcher at the University of Turin, Italy. With more than 15 years of experience in research and innovation, she is currently collaborating on projects related to enhancing water use in aquaculture using multi-trophic systems. She holds a Ph.D. in botany, seaweed ecology, and aquaculture. In 2014 she founded 'd'Alga Aquicultura Urbana' in Rio de Janeiro, Brasil. d'Alga Aquicultura Urbana is a pioneering startup that produces high-quality aquatic organisms (fish and sea vegetables) for human consumption in urban and peri-urban areas.[1]

Beatriz and I got in touch the first time in late July 2020, after she read an online article about the Algae Grower and one of my publications.[2] She was interested in the possibility of replicating the project and eventually scaling it up by using multi-trophic systems. As of October 2020, and with the support from my side, she set up a preliminary version of a new integrated Spirulina-

1 More info about d'Alga Aquicultura Urbana and the team at https://dalgaaquicultura.com

2 Katsikopoulou, M. (2020, 13 July). Algae Grower home device can satisfy average adult's daily nutritional needs [Blog post]. Retrieved from https://www.designboom.com/design/algae-grower-home-device-average-adult-daily-nutritional-needs-07-13-2020/ and Peruccio, P. P., & Vrenna, M. (2019). Design and microalgae. Sustainable systems for cities. *Agathón*, *2019*(6), 218–227. doi:10.19229/2464-9309/6212019

production device. The following is the extract of a Zoom call that occurred on 6 October 2020: the text is not a word-by-word transcription of the conversation; nevertheless, the contents have not been altered. It is an informal, semi-structured interview to gain deeper insights into Beatriz's vision for this project. Beatriz Castelar (BC), Maurizio Vrenna (MV).

MV: Hi Beatriz, it's nice to talk with you today! Do you mind introducing yourself and saying something more about your expertise?

BC: Hi Maurizio, thanks for the invitation! It's a pleasure to sharing my experience (and passion) in algae production with you. I am an oceanographer with an unusual formation – a Ph.D. in botanic. In short, I'm a phycologist. When I was attending university, I was very interested in aquaculture and particularly seaweed cultivation. Since 2004, I have worked with different algae species, cultivation systems, and scales – from in vitro to extensive marine cultivations. In 2012, I worked as a researcher at the Fisheries Institute of Rio de Janeiro, where I had the opportunity to compose a multidisciplinary team. It was a turning point in my career because I developed an in-land integrated multi-trophic aquaculture (IMTA) composed of fish and seaweeds. These closed systems are exceptional for five main reasons: the effluents of one species are converted into the biomass of another; the productivity is usually much higher than traditional one-species systems; the water use is significantly reduced; there is no conflict with other activities on coastal zones; it is suitable for urban spaces, and consequently their footprint is reduced dramatically.

MV: Wow, this is great! I know you started a company in Rio de Janeiro to produce seaweed and microalgae. How is your experience with that? What is the main difficulty you have encountered?

BC: Exactly! Stimulated by the good results of those researches, I decided – together with two partners – to start a seaweed aquaculture business in Rio de Janeiro. It was a great experience, and actually, it still is! In 2016, we founded d'Alga Urban aquaculture, with the intent to produce seaweeds for food use. We did it in a very independent form, without external investors. d'Alga is an innovative start-up, not only because of the production system but also because we were the first to produce Sea lettuce (Ulva) in Brazil.[3] Besides, we were the first to make urban aquaculture in Rio (and maybe in Brazil!). We developed many new products ourselves (Salt d'Alga, and Marine Pesto), and

3 It is suggested to read Reis, R. P., Castelar, B., & Santos, A. A. Dos. (2017). Why is algaculture still incipient in Brazil? *Journal of Applied Phycology*, 29(2), 673–682. doi:10.1007/s10811-016-0890-8

in collaboration with other companies (e.g., fish and algae sausages and hamburgers, rice bread with algae, kombucha, etc.). However, being an entrepreneur is not an easy task. We faced many challenges, most of them related to financial issues. For example, in 2018, a storm destroyed part of our facility's roof: a high amount of freshwater inundated the tanks, resulting in a significant loss in both structure and genetic material. To overcome this challenge, in parallel with the reconstruction of the algae systems, we start a Salicornia production in IMTA with Tilapia (Oreochromis niloticus). Today, Salicornia is our main product, and we offer it in fresh and dried (vegSalt) versions.

MV: And then you moved to Italy... That's a long trip! Have you been working yet on something similar to d'Alga Aquicultura Urbana in Turin as well?

BC: Yes, a long trip and a remarkably exciting change! Italy has many similarities with Brazil. We both have around 8,000 km of coastline, and neither of us eats nor produces seaweeds. On the other hand, Italy is much more conservative in introducing new elements in Mediterranean cuisine, and the temperate climate is definitively a big challenge for any food production. I arrived in Italy in March 2018. Since then, I have been collaborating on a European project (AquaVal), conducted at the University of Turin. The project aims to improve trout farms' sustainability testing freshwater systems using mussels as biofilters and protein ingredient in fish feeds. In parallel, I started to communicate my 'green' ideas to different audiences, professionals, and institutions in Turin, and that's how I found your publication!

MV: Oceanographers and designers don't often make projects together. How did you find about the Algae Grower, and why do you think it is interesting?

BC: That is the point! In fact, I have never collaborated with designers before, and it sounds top innovative at all (and I love innovation!). My mother is an artist, and I grew up in her design studio. So I have a passion for aesthetically pleasant objects! When I have known about the Algae Grower, I instinctively connected it with my previous experiences in urban aquaculture. So, I asked myself: *"Why not scaling up the Algae Grower using IMTA concepts in an urban context? This way, we can produce algae sustainably, avoiding chemicals"*.

MV: Let's talk about the 'Algae Grower Plus'. I know your idea is to integrate microalgae and fish production in a sort of closed-loop system. Am I right?

BC: Exactly. One of my criticism in algae production is the consumption of chemicals – i.e., inorganic nutrients (nitrate and phosphate) for biomass production. We have enough (negative) experiences about eutrophication by terrestrial agriculture, right? And the natural sources of these chemicals are ecofriendly... On the other hand, considering that one of the big fish farming problems is water eutrophication promoted by the effluents, rich in nitrate and phosphate, why not connecting fish and algae in a smart production system? Moreover, why not doing that in an urban context – where around 70% of the world population lives – and protein production is scarce?

MV: What characteristics did you draw from the original Algae Grower? Is the term 'Plus' not only related to the size but also the features?

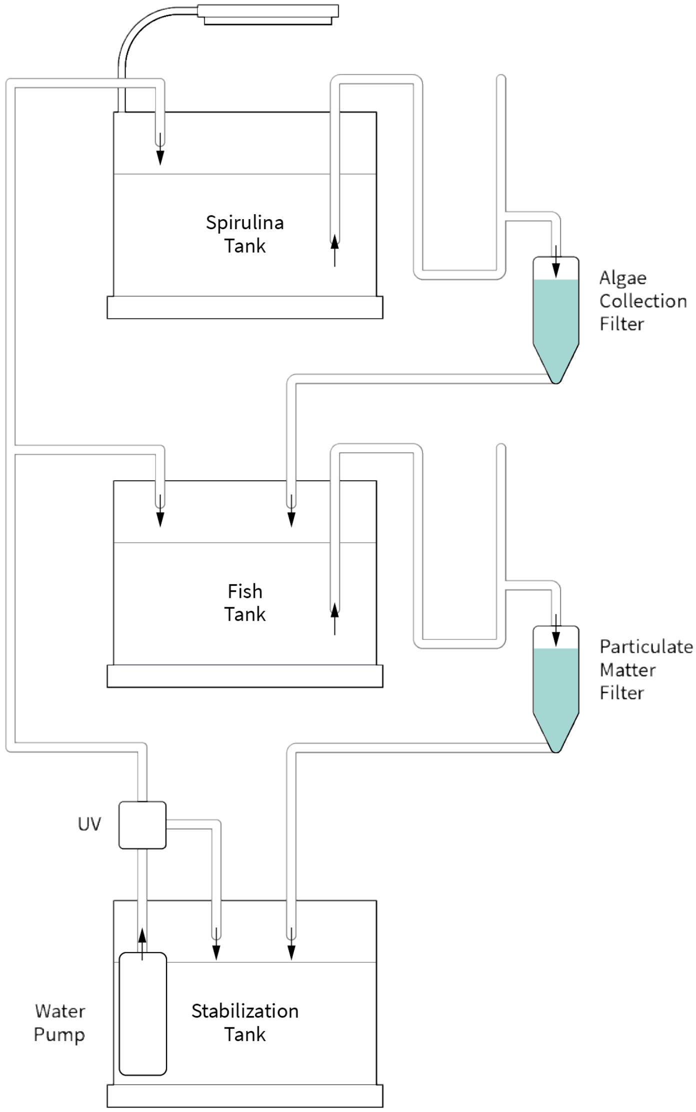
BC: The original Algae Grower inspired me to realize a home-IMTA system (I called it the 'Algae Grower Plus'). I utilized the same essential materials that you used in your first experiment (the homemade photobioreactor). In addition, I connected the *Spirulina* tank with an ornamental fish aquarium. This test is to verify if I can obtain a complete source of nutrients for the algae biomass production without using other chemical supplies. The term 'Plus' does not refer to the size but is related to this extra feature.

MV: You have been working on something already. Can you describe how this prototype functions in detail?

BC: This early prototype is composed of three containers, one for growing *Spirulina*, one for ornamental fish rearing, and the third one for water treatment, where a UV lamp act as a water purificator to avoid bacterial contaminants (Fig. A.1; Fig. A.2). The vessels are positioned on different levels – stacked over the others – and are connected using pipes. So the water from the algae tank (top) flows by gravity through a filter that retains the biomass and falls into the fish tank (middle). In turn, the water rich in nutrients by fish excreta falls into the treatment vessel with the UV lamp, and a pump propels the clean water into the algae tank, thus closing the loop!

MV: So you're now in the testing phase, correct? Any interesting results?

BC: Yes. One of the challenges to test IMTA systems on a reduced scale is to find representative fish species. I am now working with ornamental fishes (guppy, Poecilia reticulata), the most popular aquaria fish. At first, I traditionally cultivated the *Spirulina*, and then I stabilized the pH between algae and fish vessels, adding sodium bicarbonate. For four weeks, I monitored the acclimation of the species to the new condition. Now, in the second phase, I started to gradually reduce the chemical nutrients supply and increase the supply of fish effluent. In the third phase, after completely excluding the chemicals, *Spirulina* productivity will be monitored. Of course, fishes are fed. I am working with



a high-quality feed, with insect meal in its formulation. I intend to connect the Algae Grower Plus with less impactful raw-materials, and insects-based feeds have proven to be reliable alternatives.

MV: Is there something you need (or want) to improve?

BC: Yes, three key points should be improved. 1. To conduct a complete mass balance in the components for modeling a commercial scale; 2. To find/develop a cheap and efficient heater for an all-year production; 3. To have a more and functional attractive design, but this is what designers do!

MV: And what about the next steps?

BC: In the near future, I'm going to test the system on a more realistic scale.

I'll also start developing a business plan for better understanding costs and required investments.

MV: How do you envision the future of the Algae Grower Plus? An academic project or a commercially-viable product?

BC: Definitively, a commercially-viable product, with many direct and indirect social-economic gains for Turin, a city that lovely welcomed me. Besides producing green and animal proteins within the city, the Algae Grower plus can be adapted to different urban contexts – e.g., co-housings, commercial and apartment complexes, CO_2 reduction industries, public spaces for didactical ends, and so on.

MV: I hope we will find the right way to collaborate on this project together! I am happy to have met such an enterprising woman! Thanks for your precious time, Beatriz!

BC: Thank you, Maurizio! I can't realize this without your collaboration, and your design expertise is essential to complete this project!

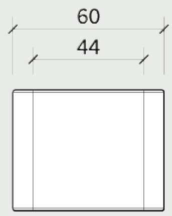
Figure A.1 (Left). The early prototype of the Algae Grower Plus. The three tanks are connected, stacked over each other, and stored in a cabinet. Reprinted courtesy of Beatriz Castelar, 2020. Copyright 2020 by Beatriz Castelar.

Figure A.2 (Right). The schema shows the water flows between the tanks of the Algae Grower Plus. Filters collect the algae biomass and the fish excreta. Adapted courtesy of Beatriz Castelar, 2020. Copyright 2020 by Beatriz Castelar.

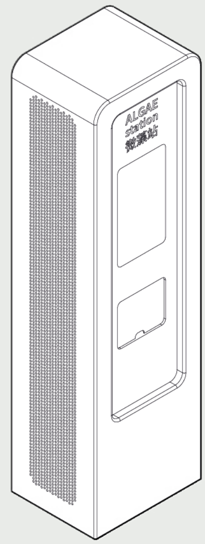
A

Dry Spirulina vending machine

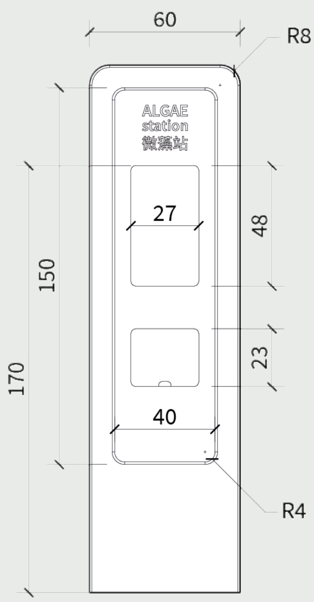
SCALE 1:33
Quotes in cm



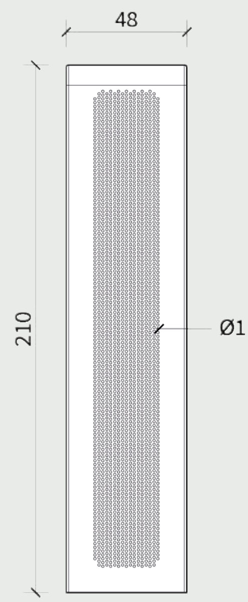
TOP VIEW



ISOMETRIC VIEW



FRONT VIEW

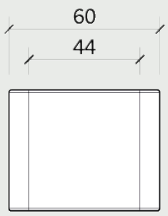


SIDE VIEW

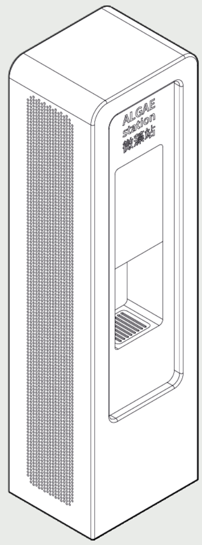
B

Fresh Spirulina vending machine

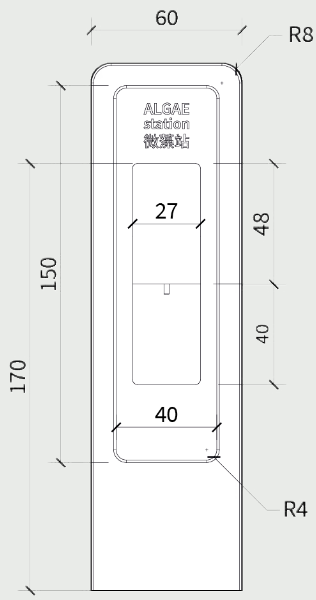
SCALE 1:33
Quotes in cm



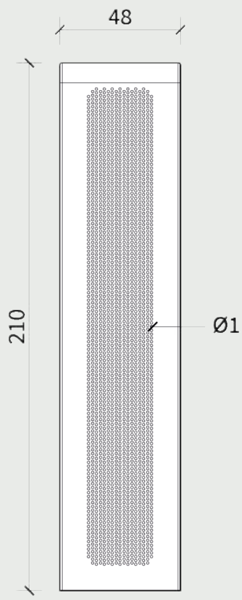
TOP VIEW



ISOMETRIC VIEW



FRONT VIEW

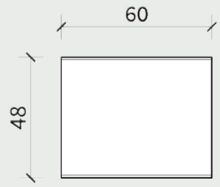


SIDE VIEW

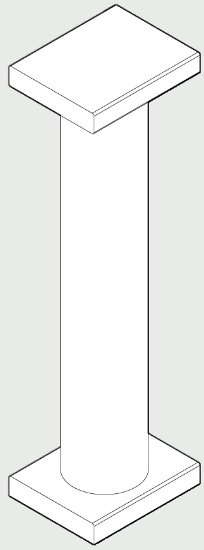
C

PBR module

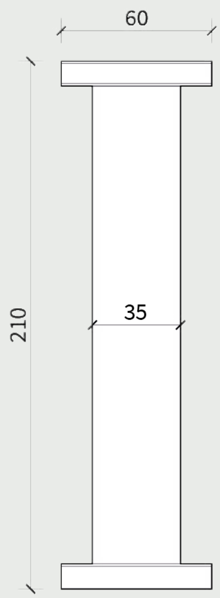
SCALE 1:33
Quotes in cm



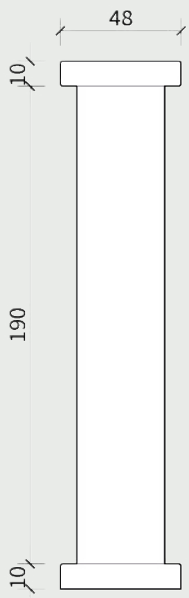
TOP VIEW



ISOMETRIC VIEW



FRONT VIEW



SIDE VIEW

The Algae Station: Scale 1:10 model of a hypothetical configuration. Front view.

The Algae Station: Scale 1:10 model of a hypothetical configuration. Back view.

Detail of the Dry Spirulina vending machine module.

Detail of the Fresh Spirulina vending machine module and side microperforations .

Detail of the roofing, where modular photovoltaic panels could be installed.

Overview of the configuration and the educational/advertising billboards.

ASSUMPTIONS

Construction costs (€)	
Structure	900
Tubular glass	600
Hydraulic system	400
Electric system	400
Pneumatic system	300
Screen	300
Photovoltaic panels	300

Monthly operating costs		
	€/liter	lite
Culture medium	0.05	150

Maintenance costs		
	Year 1	Yea
Ordinary maintenance	200	200

	Year 1												Yea
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Biomass production													
Kg	0	1	3	3	3	3	3	3	3	3	3	3	0
Price/kg	220	220	220	220	220	220	220	220	220	220	220	220	22

MONTHLY INCOME STATEMENT

	1	2	3	4	5	6	7	8	9	10	11	12	13
Revenues (*Spirulina*)	0	220	660	660	660	660	660	660	660	660	660	660	0
EBITDA	-377	-224	216	216	216	216	216	216	216	216	216	216	-37
Depreciation	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53
EBIT	-430	-277	163	163	163	163	163	163	163	163	163	163	-43

CUMULATED INCOME STATEMENT

	1	2	3	4	5	6	7	8	9	10	11	12	13
Revenues (*Spirulina*)	0	220	880	1,540	2,200	2,860	3,520	4,180	4,840	5,500	6,160	6,820	0
EBITDA	-360	-567	-334	-101	132	365	598	831	1,064	1,297	1,530	1,763	-36
Depreciation	-53	-107	-160	-213	-267	-320	-373	-427	-480	-533	-587	-640	-53
EBIT	-413	-674	-494	-314	-135	45	225	405	584	764	944	1,123	-41
Tax	0	0	0	0	0	-157	-157	-157	-157	-157	-157	-313	0
Net income	-413	-674	-494	-314	-135	-112	68	248	428	607	787	810	-41

CASH FLOW STATEMENT

	1	2	3	4	5	6	7	8	9	10	11	12	13
CF from operations	-377	-224	216	216	216	216	216	216	216	216	216	216	-37
CF from investing	-3,200	0	0	0	0	0	0	0	0	0	0	0	0
CF from financing	-4,000	0	0	0	0	0	0	0	0	0	0	0	0
Cash flow	423	-224	216	216	216	60	216	216	216	216	216	60	-37

CUMULATED CASH FLOW STATEMENT

	1	2	3	4	5	6	7	8	9	10	11	12	13
CF from operations	-377	-600	-384	-168	49	108	325	541	758	974	1,190	1,250	-37
CF from investing	-3,200	-3,200	-3,200	-3,200	-3,200	-3,200	-3,200	-3,200	-3,200	-3,200	-3,200	-3,200	0
CF from financing	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	4,000	0
Cash flow	423	200	416	632	849	908	1,125	1,341	1,558	1,774	1,990	2,050	-37
Cumulated cash	423	200	416	632	849	908	1,125	1,341	1,558	1,774	1,990	2,050	1,6

er	Harvest	Total
0	7.5	30

	€/kWh	kWh/day	€/day	Total
Electricity	0.2	6.16	1.2	37

	Gross salary	Time	Total
Labour	1,800	20%	360

ar 2	Year 3	Year 4	Year 5
0	200	200	200

Inflation (Costs)

	Year 1	Year 2	Year 3	Year 4	Year 5
Inflation	0%	0%	0%	0%	0%

Depreciation

Years	5

Tax

Italian regime	28%

Time and period

Years	5
Months per year	12
Days per month	30

Starting cash

Cash	4,000

ar 2												Year 3											
	14	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
	1	3	3	3	3	3	3	3	3	3	3	0	1	3	3	3	3	3	3	3	3	3	3
2	222	222	222	222	222	222	222	222	222	222	222	224	224	224	224	224	224	224	224	224	224	224	224
	222	666	666	666	666	666	666	666	666	666	666	0	224	672	672	672	672	672	672	672	672	672	672
77	-222	222	222	222	222	222	222	222	222	222	222	-377	-220	228	228	228	228	228	228	228	228	228	228
3	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53
30	-275	169	169	169	169	169	169	169	169	169	169	-430	-273	175	175	175	175	175	175	175	175	175	175
	222	888	1,554	2,220	2,886	3,552	4,218	4,884	5,550	6,216	6,882	0	224	896	1,568	2,240	2,912	3,584	4,256	4,928	5,600	6,272	6,944
60	-565	-326	-87	152	391	630	869	1,108	1,347	1,586	1,825	-360	-563	-318	-73	172	417	662	907	1,152	1,397	1,642	1,887
3	-107	-160	-213	-267	-320	-373	-427	-480	-533	-587	-640	-53	-107	-160	-213	-267	-320	-373	-427	-480	-533	-587	-640
13	-672	-486	-300	-115	71	257	443	628	814	1,000	1,185	-413	-670	-478	-286	-95	97	289	481	672	864	1,056	1,391
	0	0	0	0	-165	-165	-165	-165	-165	-165	-331	0	0	0	0	0	-190	-190	-190	-190	-190	-190	-380
13	-672	-486	-300	-115	-94	92	277	463	649	834	855	-413	-670	-478	-286	-95	-93	99	291	482	674	866	981
77	-222	222	222	222	222	222	222	222	222	222	222	-377	-220	228	228	228	228	228	228	228	228	228	228
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	-222	222	222	222	57	222	222	222	222	222	57	-377	-220	228	228	228	39	228	228	228	228	228	39
77	-598	-376	-154	69	126	348	571	793	1,015	1,238	1,295	-377	-596	-368	-140	89	127	356	584	812	1,041	1,269	1,308
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	-598	-376	-154	69	126	348	571	793	1,015	1,238	1,295	-377	-596	-368	-140	89	127	356	584	812	1,041	1,269	1,308
73	1,075	699	546	614	740	1,088	1,659	2,452	3,467	4,705	6,000	5,623	5,027	4,659	4,519	4,608	4,735	5,091	5,675	6,488	7,529	8,798	10,106

Year 4												Year 5											
37	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**
0	1	3	3	3	3	3	3	3	3	3	3	0	1	3	3	3	3	3	3	3	3	3	3
226	226	226	226	226	226	226	226	226	226	226	226	228	228	228	228	228	228	228	228	228	228	228	228
0	226	678	678	678	678	678	678	678	678	678	678	0	228	684	684	684	684	684	684	684	684	684	684
-377	-218	234	234	234	234	234	234	234	234	234	234	-377	-216	240	240	240	240	240	240	240	240	240	240
-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53	-53
-430	-271	181	181	181	181	181	181	181	181	181	181	-430	-269	187	187	187	187	187	187	187	187	187	187
0	226	904	1,582	2,260	2,938	3,616	4,294	4,972	5,650	6,328	7,006	0	228	912	1,596	2,280	2,964	3,648	4,332	5,016	5,700	6,384	7,068
-360	-561	-310	-59	192	443	694	945	1,196	1,447	1,698	1,949	-360	-559	-302	-45	212	469	726	983	1,240	1,497	1,754	2,011
-53	-107	-160	-213	-267	-320	-373	-427	-480	-533	-587	-640	-53	-107	-160	-213	-267	-320	-373	-427	-480	-533	-587	-640
-413	-668	-470	-272	-75	123	321	519	716	914	1,112	1,309	-413	-666	-462	-258	-55	149	353	557	760	964	1,168	1,371
0	0	0	0	0	-183	-183	-183	-183	-183	-183	-365	0	0	0	0	0	-191	-191	-191	-191	-191	-191	-383
-413	-668	-470	-272	-75	-59	138	336	534	731	929	944	-413	-666	-462	-258	-55	-42	162	365	569	773	976	989
-377	-218	234	234	234	234	234	234	234	234	234	234	-377	-216	240	240	240	240	240	240	240	240	240	240
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-377	-218	234	234	234	52	234	234	234	234	234	52	-377	-216	240	240	240	49	240	240	240	240	240	49
-377	-594	-360	-126	109	343	578	812	1,046	1,281	1,515	1,749	-377	-592	-352	-112	129	369	610	850	1,090	1,331	1,571	1,811
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
-377	-594	-360	-126	109	161	395	629	864	1,098	1,332	1,384	-377	-592	-352	-112	129	178	418	659	899	1,139	1,380	1,429
9,729	9,135	8,775	8,649	8,758	8,919	9,313	9,943	10,806	11,904	13,237	14,621	14,244	13,652	13,300	13,189	13,317	13,495	13,913	14,572	15,471	16,610	17,990	19,419

PROJECT ANALYSIS

	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
Revenues		6,820	6,882	6,994	7,006	7,068
Operating costs		-5,257	-5,257	-5,257	-5,257	-5,257
Annual cash flow from operations	-4,000	1,250	1,295	1,308	1,384	1,429

Net present value	15%
Present value of annual cash flow	1,645
Net present value	428
Internal rate of return	19%
Payback period (years)	**3.11**