LAYERS OF RESILIENCE

EMPOWERING ECOLOGICAL DYNAMICS TO STRENGTHEN THE BUILT ENVIRONMENT

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ABSTRACT

In a context increasingly altered by the climate and biodiversity crises, the theoretical discourse and practices which shape the built environment have shifted in the past 50 years towards sustainable architecture, branching out on various concepts, such as adaptability, material life cycle assessment, circularity, urban mining and the digitization of the construction process. However, these strategies focus primarily on minimizing the environmental impact of the construction industry and thus, on mitigating climate change, while they miss addressing the inevitable impacts of a changing climate on architecture itself. If buildings are to be viewed as material repositories (Rau & Oberhuber, 2022), it becomes crucial to consider not only their material flows, but their material longevity and resilience as well. By perceiving weathering not solely as a destructive process, but as one of material exchange that encompasses both destructive and constructive elements, this research paper aims to identify what kind of constructive processes take place when materials are weathering, as well as what design strategies can facilitate these mechanisms. These phenomena lead to the bioprotection of the built environment and take the shape of physical bioprotection or biomineralization. Moreover, they can be achieved by making use of both natural and engineered ecological dynamics which take place on the outermost layer of a building. The analysis leads to a better understanding of material resilience and aims to contribute to a longer lifespan of the built environment in a changing climate.

KEYWORDS: *weathering, material decay, bioprotection, bioreceptivity, biomineralization, ecological dynamics*

I. INTRODUCTION

1.1. Problem statement

"The whole idea of architecture is permanence. (…) It is an illusion." (Brand, 1994, p.16-17)

Contrary to the popular opinion that buildings are static once their construction phase has ceased, the built environment has proved over time that it is one of the most dynamic man-made entities, particularly due to human, technological and climatic factors. (Brand, 1994) The latter is the fundamental cause of the weathering and decay of the built environment, well acknowledged phenomena which occur due to temperature variations, wind, solar radiation, moisture and humidity.

The relationship between the built environment and climate, particularly with climate change, is defined by an endless causal nexus in which all design choices that shape architecture can have a significant greenhouse gas emissions contribution, as 37% of the current global emissions are attributed to the construction industry. (United Nations Environment Programme & Yale Center for Ecosystems + Architecture, 2023) Simultaneously, the frequency and intensity of unpredictable weather events associated with climate change make the built environment increasingly vulnerable both externally (due to environmental catastrophes which accelerate the decay of construction systems and diminish materials' properties) and internally (due to increased indoor temperatures and humidity) (Hacker et al., 2005).

Climate change is not the only factor accelerating the external weathering of the built environment. The architectural details which were once conceived for retarding the deterioration processes caused particularly by water (such as sills and cornices) were gradually removed from the construction of modern buildings because they were regarded as "faults" in the design, according to Le Corbusier. (Mostafavi & Leatherbarrow, 1992) These details were then replaced by sealants and various weatherproofing strategies which seem to have reduced the durability of contemporary architecture by allowing water to reach and reside on the façade for a longer time, thus aiding a range of destructive physical and chemical processes to take place.

"Finishing ends construction, weathering constructs finishes." (Mostafavi & Leatherbarrow, 1992, p.5)

However, a close examination of the weathering process which occurs in the built environment suggests that it is not only a destructive event, but rather a material exchange between buildings and their surrounding environment. By shifting the focus from the destructive consequences to the process as a whole, this dynamic relationship sheds light on its constructive capabilities and the possibility of creating protective finishes by facilitating the growth of biological actors, such as moss and lichens, which prevent acid rain and pollution from further decaying the place they are inhabiting, thus contributing to the protection of the built environment. (Gadd & Dyer, 2017)

In light of climate crisis, the contemporary design approach in the construction industry needs to be reassessed in order to create a more resilient built environment. It is crucial that this industry acknowledges the impact of climate change on the physical longevity of buildings and adapts accordingly, by implementing design strategies which embrace and make use of materials' dynamism. These new strategies should consider both the destructive and constructive impact of long-term weathering, while harnessing the processes which lead to the formation of protective layers and mitigate further degradation.

1.2. Thematic research question

The novel focus on the dual consequences of weathering in the built environment - perceiving it as a material exchange rather than solely a subtractive process - highlights the need to research and identify optimal design strategies and material behaviours which balance both aspects. The research aims to explore how architecture can transition from being designed as a static, decaying element to a dynamic one, capable of reacting constructively to changing climate conditions and allowing its constituent materials to evolve alongside their surroundings - key aspects for enhancing the building's physical longevity.

The aim of the paper is to define a set of material requirements and design strategies which, when implemented in an architectural project, can contribute to extending its lifespan in a changing climate with minimal maintenance by harnessing the surrounding ecological dynamics to strengthen the outer skin of the building. Having this in mind, the following research question was shaped:

How can materials' protective mechanisms be integrated with design strategies into a holistic design approach that extends a building's lifespan in a changing climate?

Sub-question 1: *What materials have self-protective mechanisms and in which environmental contexts are they triggered?*

Sub-question 2: *How can architectural details facilitate the creation of environmental conditions that are beneficial for material's self-protective mechanisms?*

II. METHODOLOGY

In order to answer the proposed research question and following sub-questions, a thorough analysis of the latest research papers on material behaviour and the protective mechanisms which are triggered when materials are exposed to various climatic factors is undertaken. A key aspect in this part of the research is understanding the specific environmental conditions in which these protective behaviour takes place and the potential for long-term durability.

2.1.Literature analysis - positioning within existing concepts and limitations

The research on material weathering is closely tied to the study of microorganisms and their relationship with the built environment, often overlapping. For this reason, the analysis of constructive processes which result from weathering implies a study on the integration of microorganisms in architecture and their constructive and protective behaviour, a field which has been steadily growing in the recent years.

While it has developed on various paths and framed new concepts, such as self-growth (e.g. bacteria and mycelium can create various structures), bio-receptivity (e.g. bio-receptive concrete panels and mortar facilitate the growth of microorganisms), self-healing (e.g. self-healing concrete covers its own cracks) and bioprotection (e.g. physical protection and biomineralization), the term which would ideally encompass all the protective behaviours of microorganisms - bioprotection - is underused. Moreover, the research papers which address this topic focus on finding more sustainable and effective strategies to preserve the heritage rather than assessing the longevity of materials on a larger scale. For this reason, the research papers which provide insights into bioprotection are rather scattered and tied to specific case studies of heritage buildings.

Considering this, an assessment of the self-healing and bioprotection principles led to the conclusion that both concepts fall under the umbrella of constructive processes and material longevity and can offer insights into how it can be achieved, while knowledge on bio-receptivity can be used as an intermediary step to achieve bioprotection. Consequently, these are the key terms which have been used to filter the most relevant academic papers for this research niche. (self-healing, bioprotection, bio-receptivity)

2.2.Design framework development

When the research paper is concluded, the materials which have the biggest constructive potential when weathering along with architectural details aimed at creating the ideal conditions for this process to happen will be integrated with one another into a cohesive design strategy. The process of transferring the theoretical conclusions which stemmed from the analysis of various, scattered concepts to a practical application can benefit from an iterative design process.

2.3. Further limitations

Since the literature is dispersed, the research in this field is limited, the behaviour of microorganisms and the underlying materials are dependent on various climatic factors which can be unpredictable, and the lack of case studies in which a methodology for "controlled decay" is implemented, the proposed design approach can have shortcomings. However, the aim of the paper is to bring together most of the information available on the topic at the time of its writing. It intends to propose a new way of designing by incorporating knowledge of ecological flows into the creation process of the building's outermost layer as a way of ensuring its longevity in a changing climate.

III. Results

3.1.Overview of bioprotective strategies

As mentioned by Gadd & Dyer (2017), bioprotection can be classified as physical bioprotection and biomineralization. On one hand, physical bioprotection refers to the occurrence of microorganisms whose physical presence creates a barrier that shields the place they inhabit from weathering. On the other hand, biomineralization, or chemical bioprotection, refers to the chemical reactions which take place on the surface of a material and contribute to the development of a coating that is stronger than the material on which the reactions take place. (Gadd & Dyer, 2017) This simple classification of protective strategies generated by microorganisms led to the conclusion that the concepts of bio-receptivity and self-healing can fall under this categorization as well. While bio-receptivity can be a stepping stone for achieving physical bioprotection, self-healing material behaviour can be considered a biomineralization process as well. However, a key difference between the bio-receptivity and self-healing concepts and the phenomena discussed by Gadd & Dyer (2017) when talking about bioprotection is that the processes described in the latter article are occurring naturally and were not intended when the analysed materials were created, while the literature on bio-receptivity and self-healing focuses on materials engineered to have this kind of behaviour. (Figure 1)

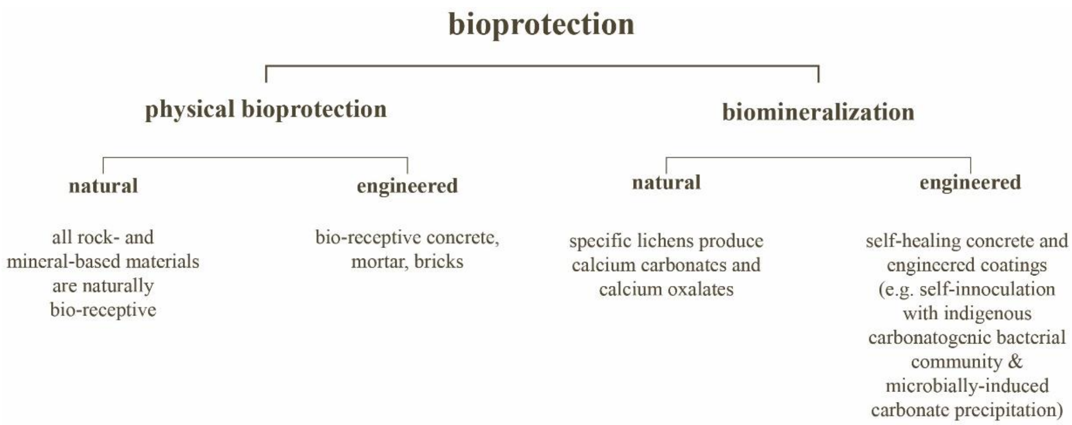

Figure 1. Overview of bioprotective strategies

3.2.Physical bioprotection

3.2.1. Natural physical bioprotection

According to Gadd (2017), microorganisms settle on all types of rocks and mineral-based materials in both the natural and man-made environments, and they have various ways to invade the host material: on its surface, in between its fissures or infiltrate within the surface layer. Their growth has protective consequences because they form a layer which stabilizes the substrate they are inhabiting, shielding it from extensive weathering. The most efficient microorganisms at offering physical bioprotection are the fungal systems, such as lichens, fungal biofilms and coatings. (Gadd & Dyer, 2017) These microorganisms do not only impede rainwater weathering (McIlroy de la Rosa et al., 2014) but also wind erosion, pollution and salt aerosols. (Gadd & Dyer, 2017) Another advantage of this transition layer is that it creates a thermal buffer, maintaining the surfaces hot and dry for a longer time and absorbing harmful chemicals (Casanova Municchia et al., 2018), thus reducing the risk of mechanical and chemical deterioration.

While some studies show that lichens have proved to be very efficient in protecting carboniferous limestone (De la Rosa et al., 2014) microorganisms can populate all the materials which have a rock- or mineral-based composition, be it either in the natural or man-made environment. Even though the chemical structure of materials which make up the outer skin of a building has been continuously adapted over time, most of them still have a rock- or mineral- based composition (Gadd & Dyer, 2017), which means that most of the materials used nowadays in the construction industry can be inhabited by microorganisms. However, the host material needs to be porous, as they fill the pores with their root network. For that reason, fired clay ceramics, brick masonry and mortar can be optimal growing surfaces as well.

Even though fired clays are more resistant to chemicals, they are susceptible to chemical and mechanical weathering caused by salts and frost respectively because of their porosity (Gadd & Dyer, 2017), leading to the conclusion that the growth of mosses and lichens on them could have an important role in prolonging their lifespan. Moreover, the chemical composition of mortar is similar to that of calcareous stones (Gadd & Dyer, 2017), aspect which suggests that it is more inclined to weather compared to the bricks and concrete blocks it binds together. For this reason, a strategy that implies physical bioprotection would contribute to the longevity of the mortar layer and thus, of the entire structure.

3.2.2. Limitations of natural physical bioprotection

There is a very thin boundary between the bioprotection and biodeterioration offered by lichens, as these processes can take place simultaneously in different ratios and the balance between the two can be quickly turned over by environmental changes. (Pinna, 2021) For example, the deterioration caused by the lichen hyphae is compensated for by the protective effect the layer has, shielding the substrate that it inhabits from abiotic factors which can further erode it. However, the removal of the biological layer can lead to an accelerated deterioration of the underlying material (De la Rosa et al., 2013), particularly because the root network which keeps it attached to the substrate can go as deep as a few centimetres. (Gadd & Dyer, 2017)

3.2.3. Bio-receptive materials (engineered bio-receptivity)

3.2.3.1. Bio-receptive concrete

Fresh concrete is often not ideal for moss growth, and it only becomes an optimal environment for it once it has weathered and changed the chemical structure of its surface layer, as well as its level of porosity. (Veerger et al., 2023) For this reason, scientists have developed bio-receptive concrete. It is an engineered material whose purpose is to favour the growth of microorganisms on its surface, particularly mosses, with the scope of integrating more nature in cities and of improving the overall quality of the environment.

There are three types of bio-receptive concrete which have been studied: marine concrete and two types of terrestrial one. Marine concrete is ideal for underwater use, as well as an intertidal area. Its chemical structure and porosity level are changed compared to the terrestrial one in order to increase its bio-receptivity. Consequently, a part of the Ordinary Portland Cement (OPC) used in its composition is replaced in a small amount with granulated blast-furnace slag (GBFS). (Veerger et al., 2023)

Fungal growth on bio-receptive terrestrial concrete is dependent on the presence of water on its surface. The key strategies proposed to address this matter are the use of more porous aggregates or binders and changing the texture on the surface of the material. (Veerger et al., 2023) Moreover, the addition of bone ash also showed improvements in its bio-receptivity. (Veeger et al., 2021)

The third type of bio-receptive concrete mentioned by Veerger et al. (2023) has not been discussed as it cannot self-sustain its water requirements.

3.2.3.2. Bio-receptive mortar and bricks

A recent study which focuses on the bio-receptivity of quay masonry walls (Mulder, 2023) suggest that they have a high potential for being engineered to stimulate the growth of herbaceous plants, particularly due to their proximity to water. The factors which have a key role in allowing vegetation to grow are direct contact with wet soil, as it keeps the environment moist for a longer time, and the type of mortar used. The research shows that a soil substrate layer placed in between the brick cladding and the main structure is key in providing enough water for the vegetation to grow. Moreover, the bio-receptivity capacity of the mortar was improved through its novel chemical composition: natural hydraulic lime (NHL) and air-hardening lime mixed with vermiculite and organic materials (e.g. clay or barley straw). Furthermore, the geometrical irregularities and the roughness of the mortar also had a beneficial role in creating an optimal environment for plant growth from seeds. (Mulder, 2023)

While this study focused on the growth of herbaceous plants, the suggested strategies can benefit the growth of lichens and mosses as well, as their requirements are less demanding than the ones of fully developed plants. Mosses stop all their metabolic functions in case they have no access to water and restart them upon rehydration (Proctor et al., 2007) as opposed to herbaceous plants.

3.2.3.3. Limitations of engineered bio-receptive materials

The lime-based mortar is weaker than other types and thus it can impede the longevity of the structure that it holds. Consequently, this kind of mortar needs to be applied in combination with a mechanically stronger one in order to keep the structure both bio-receptive and strong. (Mulder, 2023)

Another shortcoming stems from the research being a pilot study, as more analysis needs to be conducted in order to assess the optimal dimensions of the substrate layer, as well as the durability of the bio-receptive mortar in order to prevent its decay. (Mulder, 2023)

Moreover, a key limitation which needs to be acknowledged when it comes to bio-receptive concrete is that most experiments are done in a controlled environment, such as a laboratory. When these indoor-grown samples are moved outside, their survival rate is poor. (Veerger et al., 2023)

3.3.Biomineralization

3.3.1. Natural biomineralization

Some microorganisms can naturally precipitate calcium carbonate, a process whose results proved to protect stone-based materials both on the surface and in depth, as laboratory and in situ results suggest (Jroundi et al., 2021) Sometimes lichens can also produce substances at the interface with the rock they inhabit, such as calcium oxalates, insoluble chemicals which also have protective behaviour. (Pinna, 2021)

3.3.2. Limitations of natural biomineralization

The limitations of natural biomineralization processes lie in the fact that the protective layer cannot withstand long-term weathering, thus leading to further degradation after a while of being exposed to various climatic factors. Moreover, the production of such protective chemicals by microorganisms is easily influenced by variations within the chemical composition of the materials which are colonized, as well as by climatic conditions, making it difficult to control or predict their behaviour.

3.3.3. Engineered biomineralization

3.3.3.1. Self-healing concrete

Self-healing concrete is a material which was fabricated in order to address the issue of its limited durability caused by crack formations which, regardless of their size, allow water and various chemicals to penetrate it, leading to its degradation. (Jonkers, 2011) The ability to heal itself lies in the use of a self-healing agent in its composition. (Mors & Jonkers, 2019)

3.3.3.2. Limitations of self-healing concrete

While self-healing concrete is able to heal 0.8mm cracks, this process has taken place in the controlled environment of a laboratory. (Mors & Jonkers, 2019) Moreover, the mechanical strength of self-healing concrete is reduced because of the integration of self-healing agents. (Wang et al., 2014) For this reason, surface coatings seem to be able to extend the life of concrete even more than its self-healing agents. (Gadd & Dyer, 2017)

3.3.3.3. Engineered coatings

A novel, environmentally friendly bacterial biomineralization strategy which proved to be highly effective both in the laboratory and in situ is called self-inoculation with indigenous carbonatogenic bacterial community. This method proved to be very efficient in protecting and consolidating salt weathered stones. The process consists of in-situ spraying of activated indigenous bacteria, followed by a nutritional solution called M-3P which triggers the rich formation of a strong organic-inorganic hybrid cement. This treatment also minimizes the amount of bioorganisms which are responsible for biodeterioration (Jroundi et al., 2021) This method is effective on stones which have carbonate composition, such as limestone and marble.

Another kind of engineered biomineralization is microbially-induced carbonate precipitation (MICP) a process through which calcium carbonate is formed as a result of microbial activity and can aid concrete in healing itself (Jin et al., 2018) Fungi are key sustainable actors which can be used to prepare protective coatings, as they are well known for their capacity to form calcite via MICP. (Li et al., 2015) Research shows that the fungus Neurospora crassa is able to create an efficient coating through the precipitation of calcium carbonate on mortar and cement. The biocement it generates fills up the pores and cracks of the material on which it lives and is suitable for any kind of porous mineral-based materials used in construction. (Zhao et al., 2022)

IV. CONCLUSIONS

4.1.Material selection and geometry

Material selection, textures and environmental conditions play a key role in defining design strategies which can support both natural and engineered bioprotective processes. Based on the research, rock- and mineral-based porous materials such as limestone, fired clay ceramics, brick masonry, mortar and concrete provide an ideal substrate for natural fungal growth. However, the integration of engineered bio-receptive materials, such as concrete, mortar or bricks, as well as the integration of engineered coatings which result in biomineralization, such as self-inoculation with indigenous carbonatogenic bacterial community and microbially-induced carbonate precipitation, reduce the dependency on environmental conditions for natural occurrence, resulting in faster and stronger protective layers.

Stone and mineral-based materials, particularly porous ones, would benefit from the bioprotection offered by microorganisms as they are more susceptible to weathering due to their nature. That is true for limestone, fired ceramics, and particularly for mortar. The latter is a weak point in a structure, as it weathers faster than the elements it holds together, such as bricks or stones. For this reason, a bio-receptive mortar would be able to withstand weathering for longer, due to the physical bioprotection provided by the vegetation that grows on it.

Not only porous materials, but also rough, grooved and undulating ones can provide an optimal anchorage point for microorganisms, as their recesses can prevent them from being too exposed to harsh environmental conditions.

4.2.Microclimate design and ideal material placement

Material placement is critical for leveraging natural processes like biofilm development and beneficial chemical reactions. Light exposure and humidity play a key role in creating the ideal environment for fungal growth. For this reason, the north and east elevations will be designed to take advantage of their cooler and more humid conditions in order to leverage microbial growth. Materials which are naturally susceptible to fungal growth such as mosses and lichens will be integrated here on textured surfaces. Conversely the west and south facades will perhaps need shading strategies and recesses to mitigate possible drying effects, thus engineered bio-receptive materials such as concrete and mortar can be placed there on an even more textured surface that allows microorganisms to retain water and be shaded in hot summer days.

Another key aspect which needs to be considered in the microclimate design is the water management. The drainage system and other architectural details aimed at preventing water from reaching or residing on the facade for too long, such as sills and cornices, are pivotal in managing the interaction between water and building materials. The right materials and design strategies can turn them into key actors, as they have potential to promote microbial colonization where it is desired by redirecting water in those areas.

Due to prolonged exposure to water, the only studied material which can sustain protective weathering processes and have a longer lifespan when placed in direct contact with the ground is bio-receptive marine concrete.

4.3.“Controlled decay” – weathering as a key design feature

In order to prevent users and stakeholders from removing the biological layers formed on buildings, the paper proposes a new strategy of embracing weathering, that of “controlled decay”. The core idea of this concept is that weathering, as an inevitable process, is not only acknowledged, but it rather becomes a key feature which increases the aesthetic value of the project in time. If this is achieved, the building will not only attain a long physical lifespan due to its material longevity, but due to the increased value that it has in the eyes of its stakeholders as well, aspect which will motivate them to maintain it and refrain from demolishing it in the future.

4.4.Limitations

The concept of bioprotection and everything that it entails, ranging from naturally occurring microorganism growth and chemical reactions to engineered bio-receptive materials and biomineralization processes, stemmed from recent studies. The research on materials which can withstand such processes and the environmental conditions in which they take places is limited, as it is either based on very specific case studies of heritage buildings or on tests conducted in highly controlled environmental conditions in laboratories. Consequently, even though the proposed design strategies are based on literature review, the success in achieving bioprotective material behaviours is rather speculative.

Moreover, the main limitation encountered in finding relevant literature on this topic is the lack of a key-term which would bring together all the relevant sub-concepts. While the articles referenced in this paper are brought together for the common goal of achieving bioprotection, most of them originated from various other fields of interest, such as heritage preservation or integration of nature in the urban environment.

4.5.Suggestions for further research

More research needs to be conducted on engineering more types of materials which can develop bioprotective mechanisms in broader environmental conditions. Furthermore, a topic that can stem from the integration of microorganisms and their constructive abilities into systemic design strategies would be the assessment of potential material pairings that can form synergies when they weather together. By pairing them, the chemicals resulting from one’s decay could contribute to the protection of the material adjacent to it.

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The aim of the research paper is to analyse if and how the built environment can achieve a longer life-span in an ever-changing climate, and it concludes with a selection of materials that can support both natural and engineered bioprotective processes and a broad understanding of the environmental conditions which facilitate them, with a focus on the sun and wind exposure, as well as the humidity level on the building's façade. The circumstances corresponding to each elevation were initially assessed in a standard scenario, in which the facades were considered to be perpendicular to the ground and have no shading devices nor recesses, in order to understand the base conditions which would later need to be altered or not through design strategies in order to achieve ideal conditions for microbial growth. Another key aspect which was concluded from the research paper is the careful management of rainwater on the façade.

Key takeaways: material selection, textures, broad analysis of environmental conditions on each elevation, water management on the elevation

During the design development phase I have realised that these takeaways were firm starting points which needed to be further explored individually, in extreme scenarios, then brought together to form a cohesive design. However, they resulted from an analysis conducted through the lens of only one of the two "users" of the building – the microbes – and they were missing the human perspective and input.

A crucial aspect which surfaced in the early design stages is the conflict between the requirements for microbial growth on the elevation and the ones required for human comfort inside the building, which do not always coincide. The dynamic relationship between the two can be best observed in how the overall building skin is designed, from large to small scale strategies, as it is the element which manipulates the amount of light, heat, wind and humidity that reaches both its outer and inner surfaces.

Having this in mind, the first part of design process was dominated by the attempt to tackle the needs for both microbes and humans in terms of comfort. After having discussed the results with the tutors, the next suggested steps were to integrate them with design choices underpinned by the way a user would experience the building holistically. As a result, the latter part of the design development focused on incorporating the scientific and rational requirements from the previous step with aesthetics and design choices which are addressing the relationship of the project with the dunes, the bunker and the sea from a human perspective, as well as the one between the project and its users. The feedback received from the tutors throughout the entire design process was always very helpful and allowed me to jump from large to small scale design strategies and from microbes to humans' perspective, thus sharpening my distributed attention.

The final part of the graduation period will be used to showcase the project from a user's perspective on all scales, which includes elements such as furnished plans and sections that suggest various activities, as well as the interaction between both humans and microbes with the building, aspect reflected through the material choices which will be visible not only in sections but also in renders. Moreover, a detailed model (e.g. 1:20) would also emphasize the main aspects that the project is addressing: the relationship with the context in which it sits and with its two users: microbes and humans.

My graduation project aims to address the issue of accelerated material decay in a changing climate by focusing on the design of facades, including aspects such as material selection and strategies for rainwater management. The impact of these strategies can benefit the entire architecture industry, and their implications would not only change the way architects design, but also the aesthetic values and architectural qualities we, as users, are accustomed to. A large-scale implementation would also have consequences for all the fields related to the architecture industry, such as urbanism, building technology, landscape and management in the built environment.

The conducted research resulted in key takeaways focused on microbial growth, which became the starting points for the design development of the project. Simultaneously, the design brought up a more human-centred perspective and design choices, which eventually intertwined with the more scientific ones. The approach and methods I have used were, at the beginning, rational and scientific, and they benefited from the realisation that the aesthetic choices and the desired atmosphere inside a building does not always have to have a numeric or scientific underpinning reason.

The conclusions stemming from literature analysis, as well as from research by design, consist of easily transferable strategies, such as material positioning based on environmental conditions, overhangs which reduce the amount of direct sun exposure while allowing for indirect daylight, as well as water management strategies. All these aspects can be implemented anywhere in the world and can be changed according to the requirements specific to each site.

Lastly, since the literature on bioprotection is limited, the aging process of such a project is still speculative and would need extensive research to be conducted through the implementation and analysis of 1:1 building fragments on various sites. Moreover, designing with microorganisms in an environment which is facing climate change is also speculative, as each fluctuating factor can lead to an even broader range of environmental consequences. As a result, the project is not affirming to be the correct answer for the stated problem, but it rather aims to trigger discussions and open up the possibilities of designing with the inevitable events that the built environment is facing: climate change and material weathering.