Bioreceptive Habitats

Engineering a bioreceptivity-oriented design strategy
through digital and physical experimentation.

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Abstract

Keywords:

bioreceptivity, biophilic architecture, data-driven design, lime-based mortars, digital fabrication, additive manufacturing, bioreceptivity-oriented design

Abstract

Bioreceptivity is a natural phenomenon that has been observed on building material for many years. Bioreceptivity is when materials are being colonized by one or more species of living organisms without necessarily going under biodeterioration. (Guillitte, 1995) Based on the literature, bioreceptivity depends on three main factors: on climatic conditions, the topology of the colonized element and the material.

By considering these variables, this research focuses on engineering a workflow capable of supporting bioreceptivity-oriented design. More specifically, it investigates how computational performance analysis and optimization can support the integration of bioreceptive materials in customizable building elements, which could be produced by digital fabrication.

For research purposes, the research is split in two main parts which run in parallel. This research takes as a case study mosses, which generally cannot withstand high solar radiation and are dependent on water for their survival and reproduction.

The first part, investigates on a digital model, how surface topology modifications could improve bioreceptivity by reducing the solar radiation of a surface while directing water over them. This is approached by a script which examines through a case study, to what extent the solar radiation of a surface topology could be reduced through topological modifications and which factors influence it. Even if the average solar radiation of the case study was significantly reduced through an optimization process, it is not clear to what degree topology can contribute to the improvement of bioreceptivity because this fact can only be validated physically.

The second part, focuses on lime-based mortars and examines how their composition can affect bioreceptivity. Based on the literature, material properties like high water capacity, high water retention, permeability and high total porosity can benefit bioreceptivity. Four different lime-based mortars were tested, through laboratory experiments, seeking the relation between their water transport behavior and bioreceptivity. Grain size distribution in combination with binder to aggregate ratio are the main factors which influence mortars' transport behavior. In order to observe the relation between their water transport behavior and bioreceptivity, a moss growth experiment was conducted in a controlled environment. The short timeframe of the experiment makes it difficult to draw definitive conclusions.

The methodology that was developed in these two parts, is finally attempted to be combined in a bioreceptivity-oriented design approach in order to express a new architectural vocabulary. Through a research-by-design approach, three design approaches are conceptualized, compared and prototyped, raising the potential of bioreceptive applications.

Contents

0. Introduction

0.1 The concept of bioreceptivity

Bioreceptivity is a term that was coined in 1995 by Guillitte as "the aptitude of any material to be colonized by one or several groups of living organisms without necessarily undergoing any biodeterioration" (Guillitte, 1995). Many building materials and structures are frequently observed to be colonized by living organisms and a plethora of factors can influence their bioreceptivity including climate, water proximity, material properties, human actions and surface topology. (Tran et al., 2014) These factors will be further analyzed in chapter 2.5. Although bioreceptivity is not a considerably new finding, a prominent gap exists in the possibilities of its implementation in architectural applications.

0.2 Urban greening

A constant increase in Earth's air temperature has been noticed since 1880. More specifically, according to the ongoing air temperature analysis that is being conducted by NASA's GISS (Data.GISS, 2022), over the last 30 years the average global temperature has risen by 1.1°C. Multiple proof of evidence indicate that human activities are mainly responsible for this continuous heat increase, mainly because heat is trapped by greenhouse gases in the atmosphere. (earthobservatory.nasa.gov, 2020)

Contemporary urban settlements have become the main sources of these greenhouse gas emissions and in combination with the urban heat island (UHI) effect contribute significantly to the global warning. UHI effect occurs when land cover is replaced by buildings and infrastructure made of materials that absorb and retain heat. In order to resolve this problem, innovative ways of urban design and new materials need to be realized in order to improve the environmental quality of the cities. According to (Johnson et al,2014) by strategically attaching "green skins" on existing buildings, a "green network" can be created by connecting *"roofs, facades, courtyards, streets and open spaces."* There are numerous benefits associated with urban greening related to ecological, economic and social sustainability, including storm water management, energy conservation and UHI effect mitigation. (Johnston et al., 2004)

In this fashion, vertical green applications have become more and more popular in the architectural field. These are achieved by incorporating plants on vertical surfaces aiming for the full coverage of walls with vegetation. More specifically, in the current industry there are two primary categories of vertical green walls entitled "green facades" and "living wall systems". (Ottelé, M. et al. 2011) Green facades (GFs) consist mainly of creepers that climb on building facades or around a framework, such as a mesh, cables and wires. On the other hand, Living Walls (LWs) are potted plants that are attached on a secondary structure next to a wall. (S A Palermo and M Turco, 2013).

0.3 Bioreceptive facades

The majority of green wall applications could be seen as "gardens" attached on vertical surfaces creating an additional "architectural skin". The term of an "architectural bark" could take the concept of the "skin" a step further by including living organisms in the skin of a structure with a more biologically integrated approach. This would result in the establishment of bioreceptive elements capable of *"meditating between internal and external conditions."* (Cruz & Beckett, 2015) In order to implement this concept in a realistic manner, bioreceptive materials in combination with their living organisms need to be developed and assessed in terms of environmental performance, durability, energy sustainability, production and cost.

0.4 Bioreceptive materials

In the existing literature, various porous materials have been found to be bioreceptive, including concrete, mortars, wood and stones. Even though the majority of the studies focus on stones, in the last decade there is a growing interest regarding bioreceptive concrete and mortars because of their wide use in the construction industry. Within the scope of this thesis, lime-based mortars are selected to be investigated for a number of reasons related to their high bioreceptivity performance which will be fully explained in chapter 5.

0.5 Surface Topology in relation to bioreceptivity

As mentioned before bioreceptivity is influenced by many variables. An important variable is surface topology. This is because a surface can be capable of creating self-shading spaces but also regulate rainwater. For instance, the majority of bryophytes and especially mosses thrive in low-light and humid environments because they cannot tolerate constant and direct sun exposure as they dry out. Additionally, water is crucial for moss growth. Firstly, because they absorb nutrients that are transported by it directly into their skins. Secondly, because porous materials can absorb water and as a result they increase their water moisture content which is beneficial for moss propagation. Finally, water helps mosses' reproduction; either sexually or asexually. This will be analyzed in depth in chapters 3.3 and 3.4.

0.6 Surface topology optimization and fabrication

By utilizing computational performance analysis and optimization, different surface topologies can be generated, evaluated and compared, taking into account environmental variables. In this sense, computational and generative scripts can become toolpaths for indicating the most ideal spaces for bioreceptive mortars by fulfilling specific conditions such as desired solar exposure levels and water accessibility. Several topologies characterized by high complexity can be generated on that wise. In this instance, digital fabrication which is becoming more and more popular today, can place the foundation for innovation through the level of accuracy that it offers. Consequently, there is a need to experiment, research and adopt innovative, circular and environmentally benign strategies along with new materials in a more holistic design approach from small to large scale.

1. Research Framework

1.0 Problem Statement

Climate change has emerged as one of the most challenging environmental problems today. In principle, human factor has held the main responsibility for the strengthening of the greenhouse effect since the 1800s due to the burning of fossils, including gas, coal and oil but also because of cement production and deforestation. (UN, n.d.) According to the analysis from Mauna Loa observatory, CO_2 concentrations have increased from 313 parts per million that was recorded in 1960 to 400ppm in 2013. (NOAA, 2019) As important as it is to reverse or delay this situation, it is just as important to ensure good living conditions for humans. Hence, it is essential to adopt climate change as the key driver for decision making in the architectural field, as well.

The high energy demands of the existing building industry outweigh environmental sustainability. As reported by World Green Building Council (WGBC, 2016) 39% of all carbon emissions in the world are generated by the construction sector, which is majorly consuming more than 50% of the raw materials and natural resources. (J. Lozano-Miralles et al., 2018)

Several strategies of introducing vegetation and photosynthetic systems in the urban tissue have been implemented, including building facades and roofs, aiming for passive climate control, reducing carbon dioxide, aiming water and storm management and offering biodiversity on an urban scale.

However, in many cases vertical greening systems have been proven unsuccessful in the long term due to the non-adaptability of the chosen plants, weather conditions, incorrect maintenance or a combination of these factors. Even when successful, they require extra costs and energy for structural, maintenance and irrigation systems.

The present research aims to develop a more efficient method of integrating greenery in building structures through the use of bioreceptive materials.

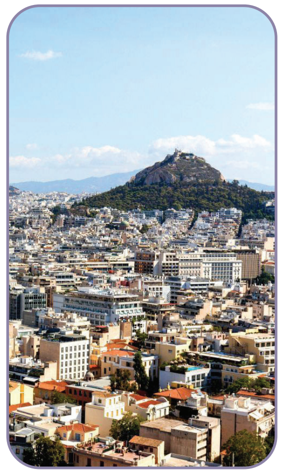


figure 1:
Loss of biodiversity.
(www.greeka.com, 2021)

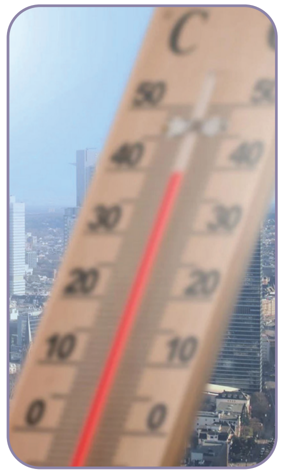


figure 2:
Increasing Heat-Stress.
(cdn.pixabay.com, 2019)

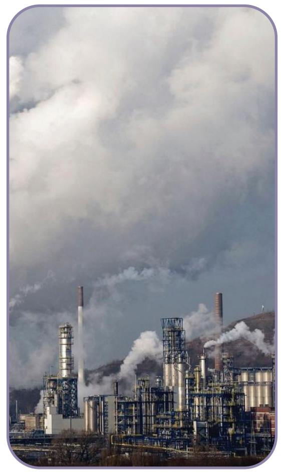


figure 3:
Air pollution.
(static.euronews.com, 2020)

figure 4:
Example of existing greening system.
(ozbreed.com.au, 2021)

1.1 Research Questions

Bioreceptivity is a multivariable process, which is strongly linked to materials' composition but also to the topology of the biocolonized elements in combination with specific climatic conditions. All the existing scientific research mainly focuses on the study and the development of bioreceptive materials. However, these bioreceptive materials cannot be successfully biocolonized within any environment. They can only be biocolonized under appropriate conditions. In order to cultivate a better understanding of this natural phenomenon and list down these conditions, the following research is split in two levels. The first level is studied in-silico[1] through computational software which have enabled us to simulate, analyze, optimize and visualize climatic data. The second level deals with the identification of material properties which promote bioreceptivity. This is investigated in-vitro[2] through the examination of different lime-based mortars as a case study material. (the reasons for this material choice are mentioned in chapter 5) By considering that digital fabrication can create new possibilities in architecture through innovative workflows, as it is mentioned in 0.6, the following research questions are formulated.

Main research Question:

- How can computational performance analysis and optimization, in combination with digital fabrication support the application of bioreceptive materials in building envelopes?

Sub-questions:

Related to surface topology:

- How can surface topology modifications improve bioreceptive performance of building envelopes, by taking into account environmental variables?

Related to material properties:

- How does the composition of lime-based mortars affect their bioreceptivity and how can this be improved?

Related to digital fabrication:

- How can digital fabrication support the production of customizable bioreceptive mortar elements?

1.2 Objectives

The ultimate objective of the present thesis is to engineer a methodology which has as its starting point a surface topology study on a digital model and a material study in physical space. By studying the influence of surface topology modification and the impact of material properties on bioreceptivity, various remarks and conclusions can be drawn. Then, these can be used in order to construct a bioreceptivity-oriented design strategy for building elements. By adopting this strategy on an urban scale, structures with high bioreceptivity performances can be generated. These could contribute to environmental sustainability and people's well-being in the long term.

1:"in-silico": Experiment which is performed on a computer or via computer simulation. (source: Wikipedia.org)
2:"in-vitro": Studies which are performed with microorganisms, cells, or biological molecules outside their normal biological context. (source: Wikipedia.org)

1.3 Methodology

The structure of the present thesis is divided in four main parts which are correlated. Firstly, a literature review is being conducted. Literature review is valuable in order to gain insight into the concept of bioreceptivity, bioreceptive materials, existing applications and the factors that contribute to its initiation and propagation. These factors are split into two categories, regarding climatic conditions (micro and macro climate) and material properties, in order to be studied separately in-silico and in-vitro. Consequently, the research continues in digital space through computational performance analysis and data-driven simulations. In this stage, similar locations that would theoretically support bioreceptivity are indicated (macroclimate). Then, a script is made which takes into consideration two parameters (solar radiation and water flow analysis) in order to evaluate, compare and optimize different topologies, in terms of bioreceptivity potential.(microclimate) In parallel, the research is also being conducted on a material level. Hence, lime-based mortars are chosen to be studied (according to specific criteria that were set in 5.2) in order to investigate, through laboratory experiments, how mortars' composition can affect bioreceptivity. Having as a basis the most optimized topology (generated in the second part) and the most bioreceptive mortar (created in the third part), the last part seeks to engineer a bioreceptivity-oriented design strategy by combining these two elements. This is carried out by using digital fabrication. More specifically, additive manufacturing is used, a process which is becoming more and more popular in architectural projects since it allows the creation of customized solutions. Then, several designs are conceptualized by integrating bioreceptive mortars in 3d-printed building elements, through a research-by-design approach and multiple prototypes are built. Lastly, the project is completed with several conclusions of the existing potential but also remarks about the aspects requiring further development.

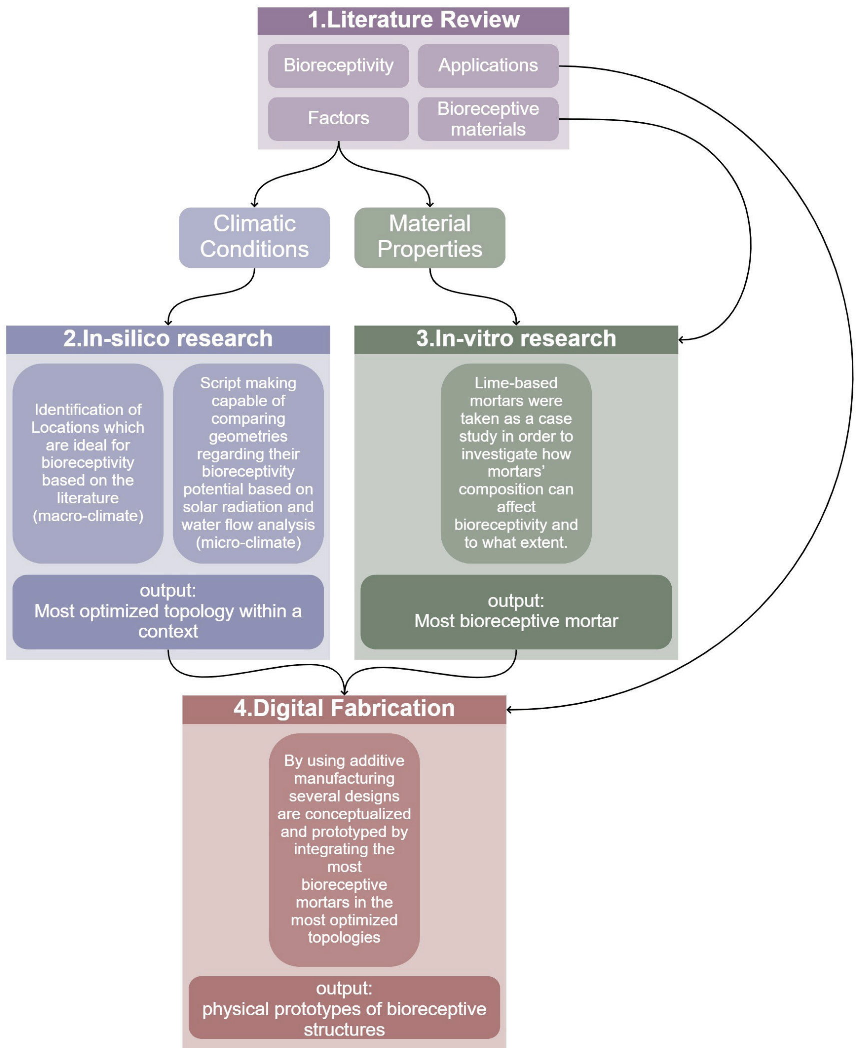


figure 5: Methodology Workflow (own source)

1.4 Timeframe

During P1 and P2, the main research is focused on the literature review. In parallel, several visits to Urban-reef were made (a Netherlands-based start-up company which produces bioreceptive elements using additive manufacturing) in order to get insight into the topic. What is more, physical experiments were set up in order to be conducted on-time after P2. During P3 all the experiments were finished in the Heritage & Technology Laboratory at TU DELFT. At the same time, data-driven simulations, computational performance analysis and optimization solvers were used in order to generate, compare and assess different alternative topologies. Additionally, several prototypes were created at the Laboratory for Additive Manufacturing in Architecture at TU DELFT. Finally, during P4 and P5 the main emphasis is placed on the refinement of the report and the final presentation. A more detailed record is presented in Figure 6.

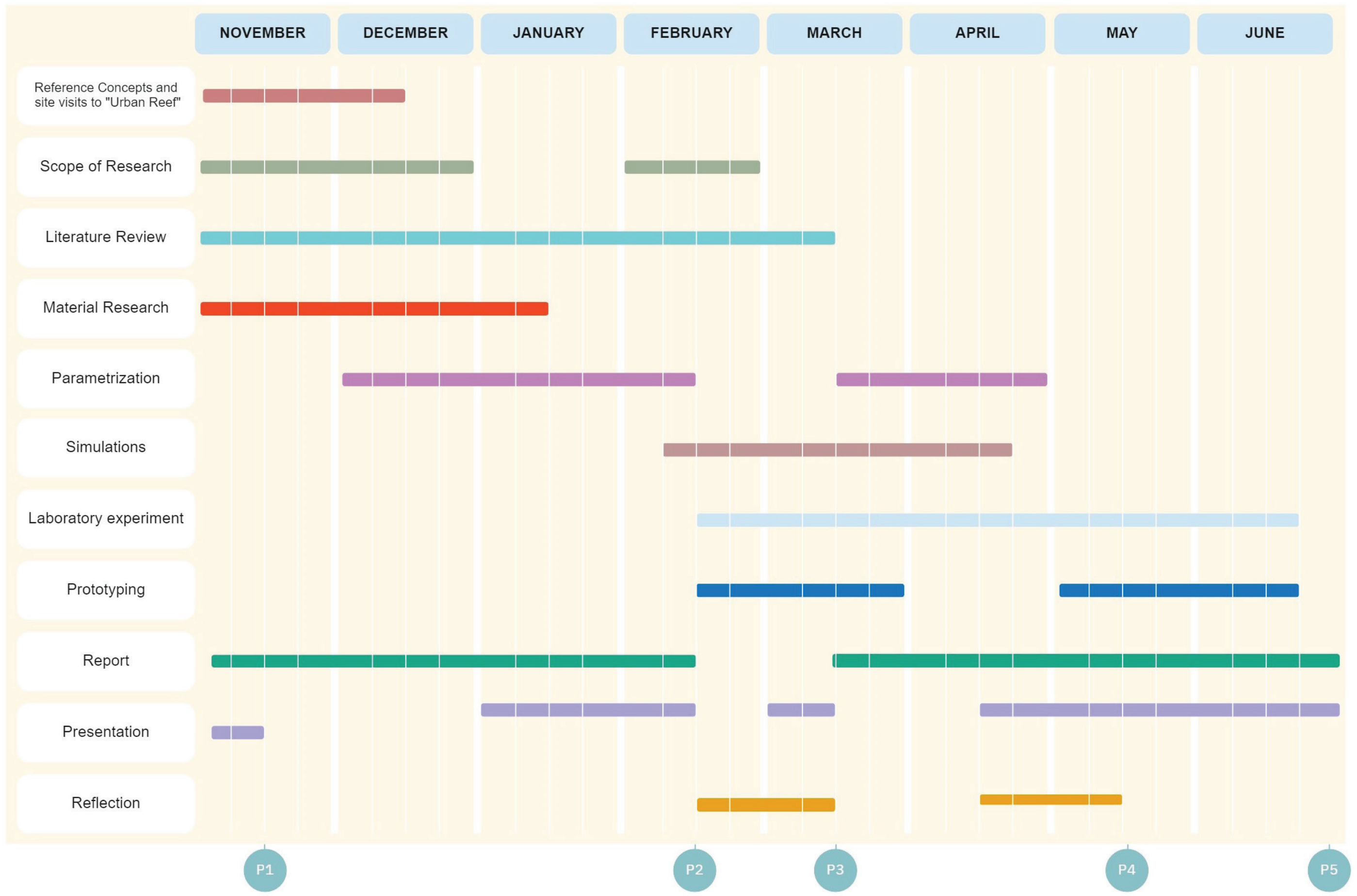


figure 6: Research Timeframe(own source)

2+3. State of the art

figure 7:
Biocolonized sculpture
(own source)

2. Bioreceptivity

2.1 Definitions

Several materials that are used in the construction industry sector are colonized by plants and living organisms. A term was coined for this natural phenomenon in 1995 by Guillitte. In his article "Bioreceptivity: a new concept for building ecology studies" the following two definitions were given. (Guillitte, 1995)

- *"Bioreceptivity is the aptitude of a material (or any other inanimate object) to be colonized by one or several groups of living organisms without necessarily undergoing any biodeterioration. "*
- *"Bioreceptivity can also be defined as the totality of material properties that contribute to the establishment, anchorage and development of fauna and/or flora."*

This interaction between living organisms and materials is capable of causing changes in their color but also in their physical and chemical attributes. In many cases, plants may cause damage to the material by the pressure of their roots or because of the chemical reactions that might take place. (M. Ford Cochran et al, 1996)

It is noteworthy that the materials' bioreceptivity is based upon a large set of cosmopolitan species of the following categories: autotrophic bacteria, heterotrophic bacteria, microfungi, macromycetes, cyanobacteria, green algae, chrysophytes, endolithic lichens, epilithic lichens, bryophytes, ferns and flowering plants. (Guillitte, 1995)

2.2 Biodeterioration

Hueck's definition of biodeterioration precedes chronologically the term of bioreceptivity for about 30 years. He defined biodeterioration as "any undesirable change in the properties of a material caused by the vital activities of organisms and is classified in three categories. i) physical or mechanical ii) chemical and iii) aesthetical." (Hueck, H.J., 1965) In contrast to Hueck's definition, Guillitte does not consider the third category as a type of biodeterioration because he states that there are authors who find color changes aesthetically pleasing and therefore it is a subjective agent. (Guillitte, 1995) He also states that biological growth could become beneficial for the environment due to the cleansing effect that it could potentially offer. (B. Toma, 1993) In this way, he separates bioreceptivity with other existing terms that are also related to the biocolonization but with a negative nuance, such as biodeterioration.

2.3 Categorization of Bioreceptivity

There are many categories of bioreceptivity and it is critical to understand on which type the research is focused. This choice is made after studying all the existing categories and deciding which one is more suitable for further investigation.

To begin with, Guillitte categorized bioreceptivity firstly based on factors that are connected with the material conditions and their properties and secondly based on whether bioreceptivity is influenced (or not) by exogenous factors.

The first categorization consists of primary, secondary and tertiary bioreceptivity. Primary bioreceptivity is the initial potential of building materials to be biocolonized. In short, this means that if a material is colonized and its properties remain identical to the properties of its initial state, then it is considered as primary bioreceptivity. (Guillitte, 1995) P. Sanmartín et al in their article entitled “Revisiting and reanalyzing the concept of bioreceptivity 25 years on” mention that primary bioreceptivity is related to the intrinsic properties of a material after being formed for a final operation/function. (Sanmartín et al, 2020)

It is quite evident that the characteristics of the properties of colonized materials are changed over time due to colonizers or other environmental conditions (i.e. humidity, temperature etc.) Secondary bioreceptivity is then derived because of this evolution caused mainly by weathering.

Many researchers, including Guillite and P. Sanmartín et al (Guillitte, 1995, Sanmartín et al, 2020), claim that secondary bioreceptivity could be considered more important than primary in the building and heritage sector since the materials are exposed to specific conditions for a long time. They also mention that it is quite complicated to define the breakpoint of passing from primary to secondary bioreceptivity, since the criteria of this transition are not set. Lastly, according to Guillitte any factor that is caused by human activities and influences the performance of a material, such as coatings, consolidation and surface polishing, results in tertiary bioreceptivity. (Guillitte, 1995)

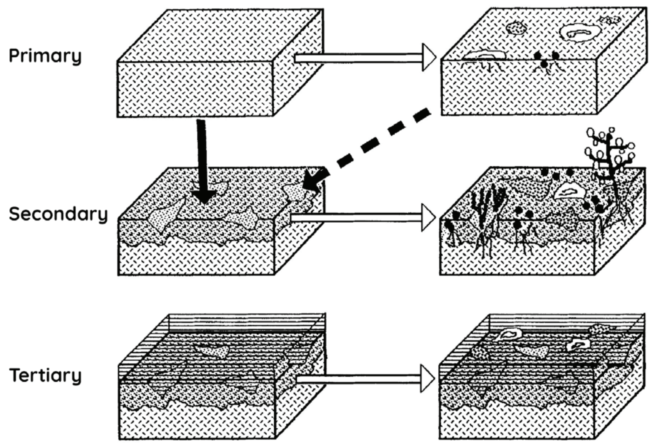


figure 8: Bioreceptivity on a stony material. White arrow, black arrow and dashed arrow indicate biocolonization, physicochemical deterioration and biodeterioration accordingly. (Guillitte, 1995)

P. Sanmartín et al. claim that not all human-caused actions have the same influence on the characteristics of materials. For instance, by applying biocide-embedded coatings and consolidants to materials, an element of different nature is being introduced to a present material. On the contrary, post-treatment methods like brushing and polishing can only affect its texture. Therefore, they propose an additional subcategory entitled as “quaternary bioreceptivity”. In this regard, tertiary bioreceptivity is considered to be the one that is influenced by human actions and can cause physical changes to a material (i.e. by post-treatment techniques) (Sanmartín et al, 2020) Quaternary bioreceptivity occurs when other materials are added to an existing one, leaving residues. This new addition is visible in the following figure which also explains their evolution in time more analytically.

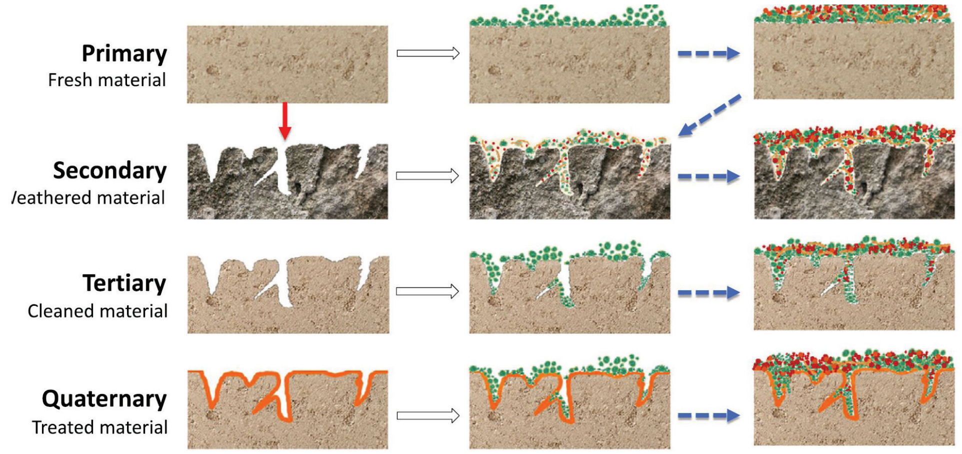


figure 9: Conceptualization of primary, secondary, tertiary and quaternary bioreceptivity (P. Sanmartín et al,2020)

The second categorization is composed of extrinsic, intrinsic and semi-intrinsic bioreceptivity. The initial conditions of bioreceptivity could potentially be affected by organic and inorganic particles like sand and soil. These may have a direct impact on the material attributes and hence on bioreceptivity. In this case the term of extrinsic bioreceptivity is introduced. Semi-extrinsic bioreceptivity, on the other hand, is when the bioreceptivity of a material depends mainly on its properties but it is also affected by exogenous factors. Lastly, when bioreceptivity occurs as a result of the material properties it is considered intrinsic bioreceptivity. (Guillitte, 1995)

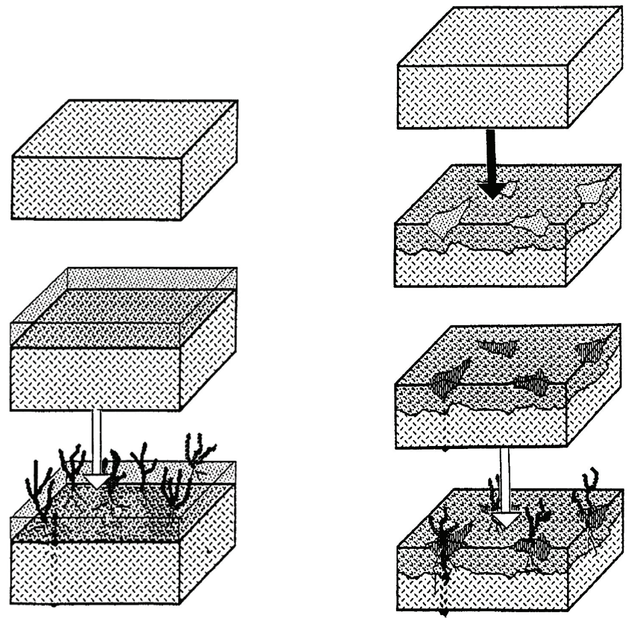


figure 10: (Left): Extrinsic bioreceptivity in the case of primary bioreceptivity. White arrow indicates biocolonization. (Right): Semi-extrinsic bioreceptivity in the case of secondary bioreceptivity. Black arrow indicates physicochemical biodeterioration and white biocolonization (Guillitte, 1995)

Sanmartín et al, propose that the terms of extrinsic, semi-extrinsic and intrinsic bioreceptivity, that are rarely used in the scientific field, to be replaced by the terms of “intrinsic factors” and “extrinsic factors”. According to the authors factors such as porosity, roughness, color and mineralogical composition are considered as “intrinsic factors”, whereas architectural agents (such as microhumidity and microtemperature) or added materials (such as dust or dead biomass) are considered as “external factors”. (Guillitte, 1995) These changes are tabulated below in order to improve the existing terms after extensive review by Sanmartín et al. (Sanmartín, P. et al, 2020)

In conclusion, the research will be focused on primary bioreceptivity because it is clearer to understand to what extent the initial material properties can contribute to its bioreceptivity. In all the other cases, the material needs either to be weathered or post-processed and that is a significant limitation for the short timeframe of this thesis.

1995	2020	Changes enacted	Description, cases and examples
Primary	Primary[a]	Definition improved	A sound or fresh material after manipulation (extraction from the quarry and cut) for a final function (e.g. be used in a construction)
Secondary	Secondary[a]	Definition improved	Material weathered by environmental factors and/or colonisers. This weathering can be artificially induced through accelerated ageing tests with solar or UV radiation, rain, humidity, temperature, pollutants, salts, etc.
Tertiary	Tertiary[a]	Split into 2 types of bioreceptivity: leaving tertiary for when the material is cleaned, and using quaternary when materials are added and integrated into the starting material	Mechanical cleaning techniques (brushing, washing with water, grinding), laser cleaning methodologies
	Quaternary[a]	Described as a new bioreceptivity type. Related to a coated or treated material, where the added materials have been permanently or semi-permanently integrated into the original material	Water repellents, biocides, consolidants, cleaning agents that leave residues, painting, stucco, plaster
Intrinsic	Intrinsic factors[b]	Intrinsic bioreceptivity dropped, replaced by intrinsic factors	Porosity, surface roughness, mineralogy, geochemistry, permeability, surface hardness, colour, pH Larger or building-scale factors
Extrinsic	Extrinsic factors[b]	Extrinsic bioreceptivity dropped, replaced by extrinsic factors	Surface deposits such as oil, dust, organic particulates, pollutants, guano, and also dead biomass and living organisms[c] Locational characteristics such as angle of surface, aspect, height above ground (factors which affect moisture and thermal regimes) Larger or building-scale factors
Semi-extrinsic		Dropped term	
	In subaerial environment		Buildings, monuments and structures in outdoor environment
	In submerged environment	Inclusion of this environment in bioreceptivity studies	Archaeological sites immersed, floodprone area in buildings
	In subsoil environment	Inclusion of this environment in bioreceptivity studies	Archaeological sites buried, building foundations

[a] Under lab conditions the material is inoculated with living organisms, under field conditions it is placed onsite and exposed to the environment (in some cases also inoculated outdoors).
[b] According to current authors extrinsic and intrinsic factors potentially affecting the colonisation at all stages (Primary to Quaternary) – rather than Guillitte who related them as producing different pathways.
[c] Because the presence of one organism may make it easier for others to enter the community.

figure 11:Tabulation of changes in the existing terms (1995) and replacement by improved ones, cases and examples. (Sanmartín, P. et al, 2020)

2.4 Assessment of bioreceptivity

Guillitte recommended the establishment of a bioreceptivity index which could indicate the colonization risk of a material in case bioreceptivity is requested or not. In this sense, it could also provide information about the efficacy of different material treatments but also about their evolving material properties. (Guillitte, 1995). However he did not specify a unit of measurement and how bioreceptivity is expressed and quantified. In the first ever bioreceptivity-related experiment performed by him and Dressen, coverage percentage was used as a method of evaluating bioreceptivity. (Guillitte, O., Dreesen, R., 1995) More specifically, percentage values were used in order to compare bioreceptivity between natural stones and manufactured materials. This experiment lasted for 9 months and during this time they were providing specimens with nutrients by spraying them with a water-based mixture with colonizing plant diaspores.

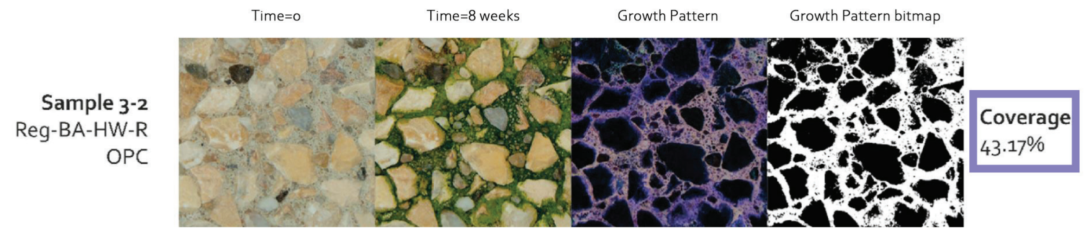


figure 12: Example of coverage percentage for bioreceptivity evaluation (M.Veeger et al, 2020)

Another evaluation method was developed By Prieto et al (B.Prieto et al, 2018); this method use the ratio of chlorophyll per surface unit to assess bioreceptivity. This way, comparisons between different experiments can be made. A considerable drawback is that this method can only be applied to phototrophs, organisms which use sunlight energy to synthesize organic compounds for nutrition. (LumenLearning, n.d.)

Due to the lack of experience and technical background, the assessment of bioreceptivity in this study will be done by monitoring visually and photographically the specimens that will be developed. In order to facilitate comparisons between them, similar lighting conditions are created.

2.5 Factors affecting bioreceptivity

Biocolonization is a complex, multifactorial and dynamic process and thus difficult to be fully understood. (Guillitte, 1995)

Factors possibly having an influence on bioreceptivity of building materials can be classified into 3 groups:

- Factors related to living organisms and their properties, including their dispersal mechanisms and their growth requirements.
- Factors linked to the environmental conditions, both in a small and a large scale (climate, microclimate) such as solar exposure, water and shading. In this respect, the term of "accessibility" was defined by Heimans in order to describe "the totality of conditions prevailing at a certain locality, that may influence the possibility of diaspores to reach a spot and settle there" (Heimans, J., 1954)
- Factors related to physical and chemical characteristics. (Sanmartín, P. et al, 2020)

All these classes of factors should act in combination in order to achieve biocolonization. Even if one of them is omitted then bioreceptivity cannot take place.

Even if bioreceptivity is an umbrella term that includes the biological growth on materials, not every material is bioreceptive regarding specific organisms and, vice versa, not all living organisms can colonize the same materials. This occurs because of biocompatibility, which is the capability of a living organism to inhabit an environment under specific conditions. For example, acidity is known to have a positive impact on the taxonomic content of living organisms but there are specific types of species that are adaptable in basic substrates as well, such as Tortula Muralis (Max Veeger, 2021) which belongs to the Pottiaceae moss family.

Currently, there is not a detailed record concerning the relation between materials' intrinsic characteristics and bioreceptivity. Each type of material can behave differently towards different organisms and therefore each material/organism combination needs to be studied individually. At the present stage, based on laboratory-based experiments there is light shed on particular materials (see 2.6)

2.6 Bioreceptive Materials

According to the bibliography survey conducted by Sanmartín et al. most of the material research and experiments are focused on stone. Concrete, mortars, ceramic, glass and plastic follow in this sequence. Besides, the majority of these are performed in laboratory conditions, investigating primary bioreceptivity. (Sanmartín, P. et al, 2020) A review of several bioreceptivity-oriented experiments is reported in the following sections, focusing on stones, concrete, ceramics and mortars, in order to clarify which intrinsic parameters can affect primary bioreceptivity. These factors will become the basis for defining the material to be further investigated in this research.

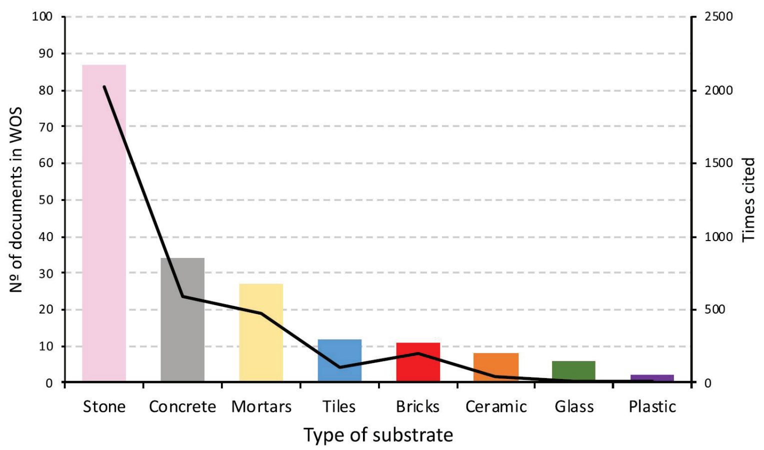


figure 13: Number of records for the combination of the term 'bioreceptivity' with the keywords related to building materials in the WOS database conducted by (Sanmartín, P. et al, 2020)

2.6.1 Stone

According to the experiments carried out by A.Z Miller et al (A.Z. Miller, 2012) on different varieties of limestone, intrinsic material properties, like high porosity, high capillary absorption, high permeability surface roughness, and chemical composition in combination with the degree of materials' weathering can create protective habitats in which living organisms can thrive. More precisely, in their research five types of limestone with different petrographic properties were taken into consideration and they were inoculated with biofilms of phototrophic microorganisms. Biological growth was more rapid within the stones having the coarser pores and the highest permeability.

2.6.2 Concrete

In M. Veeger's et al. research several concrete mixtures were tested in order to identify which variables influence their bioreceptivity performance. (M.Veeger et al, 2021) Different aggregates (Crushed Expanded Clay (CEC) and bone ash), additional chemical elements (phosphorus and surface retarder) and water-aggregates-cement ratio were taken into consideration. The research showed that surface retarders and the use of CEC as an aggregate enhanced the bioreceptivity performance of concrete. Contrary to existing literature, it was found that pH, which exceeded 10 in all concrete specimens, did not have a negative impact on the biological growth.

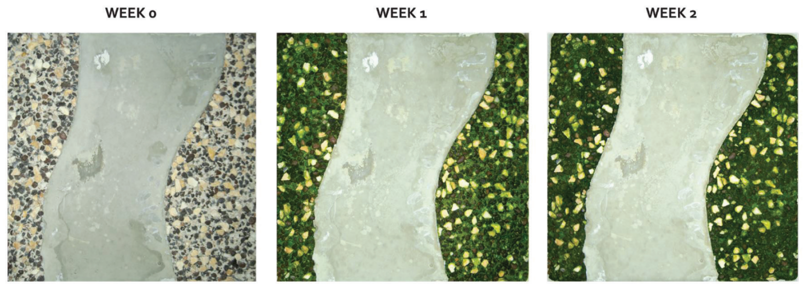


figure 14: Biofilm growth on the bioreceptive part of a concrete panel in a period of 2 weeks. (M.Veeger et al, 2020)

2.6.3 Ceramics

In Marco D'orazio's et al laboratory experiments different ceramic bricks, with different water absorption, roughness and total porosity values were tested in order to find out which of these properties influence their bioreceptivity performances. (M. D'orazio et al, 2014) The specimens were biofouled with algae biofilm and under ideal conditions they were being sprinkled constantly over 60 days in a glass chamber. The chamber's conditions simulated a two year natural exposure and bioreceptivity was evaluated by its fluorescence intensity that was emitted from biofilms.

The authors have concluded that, water absorption is positively proportional to bioreceptivity. The higher water retention, the more nutrients are accessible to the biological content and thus the growth is more rapid. Furthermore, total porosity and roughness are also positively proportional to bioreceptivity. Roughness contributes in superficial water retention while porosity contributes in water retention inside of each material.

2.6.4 Mortars

B.Lubelli et al have examined the bioreceptivity of several types of lime and cement-based mortars towards seeds of ivy-leaved toadflax and yellow corydalis. (B.Lubelli et al, 2021) The conclusions that were drawn from the experiments are related to the chemical composition and water transport behavior of the tested mortars.

On the one hand, chemical composition was proven to be critical for plants since no plant growth was observed in the cement-based mortars. On the contrary, lime based mortars had the best performances and especially hydrated lime with trass when combined with vermiculite, a lightweight aggregate. This occurs most likely due to the high porosity of vermiculite which functions as a water reservoir but also thanks to its high ion exchange capacity supplying nutrients to the plants. Binder to aggregate ratio had a minor influence on plant's growth.

Water transport behavior plays a major role on the bioreceptivity of mortars. Specimens which were characterized by fast drying and low water retention had a worse biorecepvity performance. Conversely, those with a high rate of capillary absorption and higher open porosity had a better performance.

2.7 Discussion about materials

In figure 15, all factors with experimental evidence related to primary bioreceptivity are listed. Most of them are related to the water transport behavior of the materials, to the chemical composition and surface roughness. As far as water transport behavior is concerned, water absorption, water retention and water absorption rate are key-elements. High water absorption in combination with high water retention are accountable for the absorption and retention of nutrients and water moisture within the substrate.

Material Attributes	Stones	Concrete	Ceramics	Mortars
Chemical Composition	✓	✓	✓	✓
Surface Roughness	✓	✓	✓	✓
Water Absorption Capacity	✓	✓	✓	✓
Water Retention	✓	✓	✓	✓
Total Porosity	✓	✓	✓	✓
Wheathering	✓	✓	–	–

figure 15: Factors related to primary bioreceptivity with experimental evidence. (own source)

2.8 Bioreceptivity - Potential and applications in architecture

As previously stated, the concept of bioreceptivity is not novel. However, only in the past few years more and more architectural proposals are emerging. All of them are in experimental phases and currently there are only a few small-scale applications in the built environment. Some case studies will be listed below.

2.8.1 Urban-Reef

Urban-Reef (https://www.urbanreef.nl, 2021) is a start-up Netherlands-based company which uses new technologies such as additive manufacturing and a digital workflow in order to produce 3d printed clay geometries capable of being colonized by mycelium. Mycelium is a network of fungal threads or hyphae that could benefit environment with various means as for example breaking down toxic substances and purifying air. Its creators, Pierre Oskam and Max Latour have developed a bio-material from a mixture of clay, coffee beans and mycelium which results in a bioreceptive material able to boost mycelium growth. According to them, baking their geometries is undesirable in order to prevent the high amount of embodied energy that is produced during the firing procedure. Their ultimate goal is to enrich urban cities' biodiversity and create a circular and sustainable future. As far as the potential applications are concerned, they envision their creations being integrated in the existing urban tissue creating structural ecosystems in the existing build infrastructure giving as example existing water sources like fountains.

figure 16: Urban reef prototypes demonstrating mycelium growth. (urbanreef.nl, 2021)

2.8.2 Bioreceptive Concrete Façade Paneling systems

Marco Cruz and Richard Becket, architects and professors at Bartlett, UCL, have been collaboratively conducting research in biodesign and bioreceptive materials. Their research group consists of scientists with different backgrounds in biology, architecture and engineering. Through their academic investigation, they have developed a bioreceptive concrete paneling system which strives to advance buildings' facades performances via bioreceptivity. The final product is a bumpy concrete panel with concaved craters aiming for bioreceptivity. Two types of cementious mixtures were used in order to manufacture the prototype, a non-bioreceptive ordinary Portland cement-based (OPC) mortar and a bioreceptive mortar with good water retention capabilities. Unfortunately, the binder of the bioreceptive mortar is not specified. Bioreceptive mortar was implemented with the addition of magnesium and phosphates which reduced significantly the pH value of the mixture, from 13 to 7. Material specifications and biocolinization tests' results are not published yet but it is mentioned that the panels are going to be exposed in real conditions for at least one year outdoors to evaluate more accurately their performance.

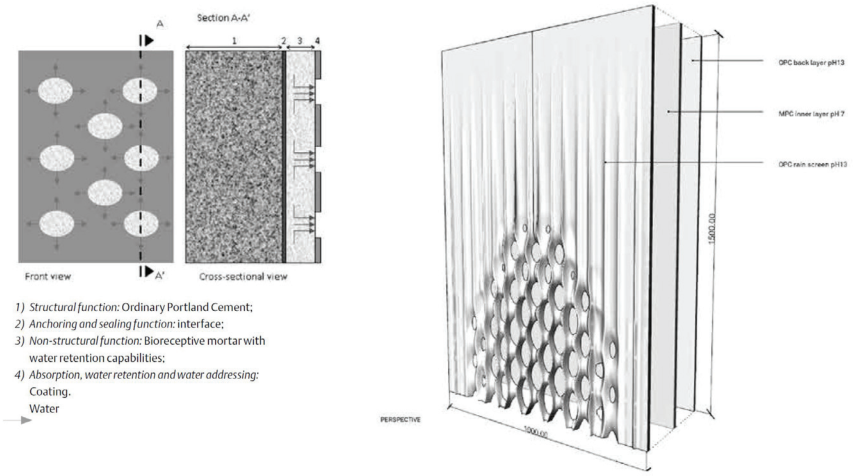


figure 17: Concrete Façade Panel material composition (Cambridge University Press, 2016)

Authors state that a critical aspect of bioreceptive materials which should be taken into account for forthcoming tests is their age-performance. Cruz presumes that bioreceptive architectural projects will have as a starting point small and low-risk applications which in time will find more potential functions in the urban environment such as rainscreens. In addition, they both underline that magnesium oxide is a waste product (obtained from the calcination of naturally occurring minerals) and it could be integrated in the fabrication of bioreceptive concrete panels, promoting circularity and cost efficiency. Finally, they mention that in order to use new materials more wisely, new technologies should keep up with them. Cruz quotes that "there's a demand from society for this shift and a technological capability for this to happen and that's what we're facing." (R.Becket, M.Cruz et al, 2016)

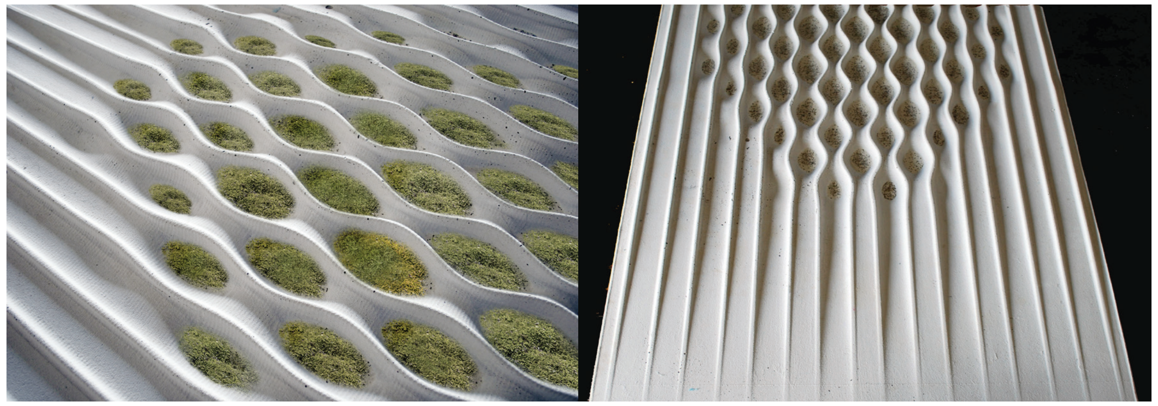


figure 18: Rendering (on the left) and prototype (on the right) of the final product. (R.Becket, M.Cruz et al, 2016)

Max Veeger et al have used a similar approach to the above-mentioned project but with a more clear focus on the material composition rather than the topology and geometry of the final product (M.Veeger et al, 2021). They have developed a bioreceptive concrete mixture with materials that are used widely in the building sector. Their ultimate goal was to control which parts of the panel could be biocolonized and vice versa. Hence, an in-depth research has be done in order to point out which conditions should be adopted in both cases. Roughness, good hydraulic properties (i.e. water retention and porosity), and phosphorous were proven to boost bioreceptivity and thus these were the main targets of their material study. Roughness, which contributes in microorganisms' and nutrients' attachment on the substrate, has been achieved through a surface retarder. Secondly, good hydraulic properties (i.e. high water retention and porosity), are achieved with the addition of sand, bone ash and CEC in the concrete mixture. Finally, phosphorous in the substrate, acting as a nutrient, has proven to speed up the biological growth.

In the same way to the previous bioreceptive concrete paneling system which was fabricated in layers, Veegers' et al panel is created in three main layers. First step of the process is the mold of the non-bioreceptive concrete part. After being demolded it is placed inside the final panel mold and then bioreceptive concrete is poured on top. The bioreceptive parts of the panel were inoculated with biofilm and were exposed under laboratory conditions optimized for biological growth. In a period of 2 weeks they were fully covered in biofilm. Non-bioreceptive parts did not show any biological content growth at all. Authors then, continued the experiment in external conditions to validate whether this product works in real conditions. This sudden shift of the environmental conditions (known as lag-phase) harmed bioreceptivity by causing biodeterioration in biofilm. However, in long term bioreceptive panel indicated biofilm recover.

2.8.3 Sea-wall Units

Marine biologists Dr. Shimrit Perkol-Finkel and Dr. Ido Sella have set-up ECOncrete, a start-up company which offers environmentally friendly and sustainable solution to minimize marine's infrastructure ecological footprint. (econcretetech.com, 2018) ECOncrete has developed a bioreceptive concrete mixture which offers optimal environmental conditions to marine flora and fauna and in parallel it complies with the existing requirements for seawalls' structural performance. After being exposed to marine conditions for about two years, seawalls (elements of coastal defense) made by their concrete mixture demonstrated significant colonization of various invertebrates including sponges, bryozoans, bivalves and coralline algae. ECOncrete strives to take the place of unsustainable concrete structures which harm marine biodiversity and replace them with elements that fit in with their surroundings. Their bioreceptive concrete mixture decreases by 45% greenhouse emissions compared to the standard Portland cement mixture. Both of them note that the final paneling design, including its textures, shapes and pattern size is achieved through biomimicry. In this fashion, seawalls covered in marine fauna are capable of absorbing

big quantities of pollutants and in the meanwhile they are utilizing biocalcification, which results in the reinforcement of the concrete structures. Perkol-Finkel clarifies that the skeletons of specific living organisms like oyster, tube worms and so on reinforce concrete by the biogenic crust they are covered with. This crust offers protection to concrete by decreasing scour and chemical erosion risk, a natural phenomenon named "bioprotection". More specifically Perkol-Finkel states that "These same skeletons also create an active carbon sink, with every kilogram of calcium carbonate generated offsetting 300 gr of CO2 from our oceans. A kilometer of seawall on a typical Mediterranean coast will offset up to2 tons of CO2 a year, equivalent to the sequestration of 100 adult trees". Thereafter, it is quite evident that the potential of this application can have a forceful impact on the future built environment. (ECOncrete, 2018)

figure 19: Sea-wall units being biocolonized. (econcretetech.com/projects, 2018)

2.8.4 Discussion of case studies

The above-mentioned case studies act as a source of inspiration and observation for the final design proposal that will be developed in chapter 5. A design aspect that is considered is the differentiation of the geometry in bioreceptive and non bioreceptive parts through the use of different materials in one composite element. (See 2.8.2) This has as a result that the final building element can be biocolonized in a predictable and scalable way. Additionally, the mechanical performance of bioreceptive materials does not create any problem in the structure because it can be integrated in the building structure as a filling material. Moreover, the direct relation between bioreceptivity and water is taken into account, since it provides nutrients to the microorganisms while offering moisture within the material. (See 2.8.3) Finally, all the above-mentioned case studies have aesthetically pleasing values, a core design principle in architecture.

figure 20: Principles that are taken into account in chapter 6 (own source)

3. Bryophytes

3.1 Introduction

Over the last decades biophilic architectural design is becoming more and more popular in the architectural community. Architects and designers seek to incorporate natural elements into building spaces and urban environments in order to achieve connectivity to nature and improve the health and well-being of the occupants. So far, the majority of the green urban applications are implemented by introducing natural landscapes, plants and green walls in the city.

There are many other living organisms that could contribute to urban greening. Among these, bryophytes are plants that could become beneficial for the urban environment due to the benefits they offer. One of these benefits consist in the fact that they are highly adaptable. Moreover, they have no roots which makes them ideal to incorporate into building materials because they are not capable of generating damaging mechanical pressures in them. These are the main reasons why bryophytes are selected as the living organisms to be used for the development of a bioreceptive element in the present thesis.

Therefore, the conditions under which bryophytes thrive, reproduce, disperse and grow need to be investigated, in order to integrate them well into the final design. The specific type of bryophytes will be chosen in chapter 5.6. Favorable environmental conditions for their growth will also be taken into account for the script making and the case study in chapter 4.

3.2 Bryophytes

Bryophytes is a taxonomic group of non-vascular plants which consists of liverworts, hornworts and mosses. The term comes from ancient Greek words "βρύον" and "φυτόν" which stand for "tree moss, liverwort" and "plant" respectively. In modern flora there are more than 18000 species as described by Goffinet and Shaw (Goffinet, B., Shaw, A.J., 2009) making it the second most diverse land plant group following flowering plants. They are considered non-vascular because they have no roots or vascular tissue and thus they absorb water and nutrients from the atmosphere through their outer skin (i.e. their leaves). Instead of roots they have rhizoids, which help them colonize bare surfaces without necessarily having soil as a substrate. In this regard, they can anchor on most porous materials and even start the soil formation process. (Vanderpoorten & Goffinet, 2009).

Furthermore, bryophytes are considered poikilohydric as a result of which their water content changes depending on the moisture content of their environment. Consequently, they fall into a dormitory state being capable of restarting their metabolic action after being rehydrated. (Vanderpoorten & Goffinet, 2009). According to K.R.Wall, several types of mosses can survive desiccation even for months, reviving within a few hours of rehydration. (R.W.Kimmerer, 2003) This particular property of bryophytes can be taken into consideration for upcoming architectural applications because bryophytes are very adaptable and they require low maintenance. This could be beneficial for green structures where access for maintenance is quite challenging.

3.3 Bryophytes' structure and reproduction

It is essential to understand how bryophytes generate their nutrient materials and how they are reproduced so they can be integrated successfully within building elements in the long term. The following text gives a concise overview of bryophytes' structure, underlines the vital role of water in their survival and explains shortly their reproductive system which

is differentiated from common vascular plants.

To begin with, bryophytes are cryptogams because, unlike most of the plants, they are reproduced by spores and not with seeds or flowers. In the following figure, a basic moss structure is depicted. It consists of two principal parts. The upper part named sporophyte includes the operculum, capsule and seta whereas the lower part named gametophyte includes leaves and rhizoids.

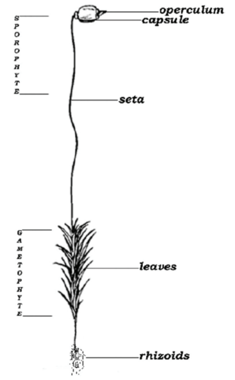


figure 21: Basic Moss structure (Tortula Muralis) *(bryophytes.science.oregonstate.eduojects, n.d.)*

Bryophytes can be reproduced both sexually and asexually (or vegetative). Sporangia are found inside the capsule which is connected to the top of the seta. When spores become mature enough they spread over the capsule opened by the operculum and land in the surroundings. As previously mentioned, rhizoids do not really help in nutrient uptake but instead these are being collected by moss' leaves. (Glime, 2017) Moisture encourages their growth. Some bryophytes are male plants and they have cups which produce sperm. Female plants have eggs between overlapping leaves. In order to be reproduced sexually water is required so sperm can be transported and fertilize eggs. As mentioned, bryophytes can be reproduces asexually as well. In short, they can shoot new spores from last year or it can be reproduced by fragmentation. Fragmentation can occur when a segment of gametophyte breaks, either accidentally (i.e. animals' activity) or by erosion, and grounds in a spot which has high moisture levels. (J.P. Frahm, 2008)

3.4 Dispersal Mechanisms

These vegetative propagules, in most cases, are too big to be dispersed by wind in long distances. Usually, these fragments of the plants are dispersed by water, insects or other animals while spores can be transported in longer distances easily by wind. Without any doubt, there are some exceptions.

However, bryophytes' spores can be carried over by wind really long distances in the same way that wind moves soil particles. Available data indicates that spores with a diameter smaller than 12 μm could travel distances over 12,000 km. (Muńoz, J et al, 2004) In this sense, it is quite evident that numerous types of bryophytes' spores are capable of travelling such huge distances. A proof of evidence is the fact that spores of a specific type of microfungus (wheat rust) were wind-dispersed from Africa to Australia by high-speed winds in 1968-69, a distance of approximately 12,000 km. (ANBG,n.d.)

In this regard it could be assumed that bryophytes can spontaneously (without human action) colonize bioreceptive materials through their dispersal mechanisms.

3.5 Advantages of bryophytes

Bryophytes are beneficial for biodiversity and sustainability because they offer similar advantages to plants used in green facades but with less cost and maintenance. Bryophytes' good capacity to adapt to a wide range of climatic conditions, in combination with the fact that they have no roots and cannot cause mechanical pressure to building material, makes them a powerful alternative for green walls. Furthermore, by integrating bryophytes in building elements, they could offer several advantages in the urban environment.

Air purification

Scientific findings proved by a team of researchers at the Max Planck Institute and University of Kaiserslautern in Germany that cryptogams (such as moss, algae, or fungus) uptake globally huge amounts of carbon and nitrogen. More specifically they absorb more than 3.9 Pg carbon per year which represents 7% of the net primary production and 59Tg of Nitrogen. (Wolfgang Elbert, 2012) Bryophytes, and more specifically mosses, have the capability of absorbing dissolved substances thanks to their high ion-exchange properties. (R.Gerdol et al, 2002) On top of that, because of their high surface to mass ratio they purify air from dust particles and several types of pollutants that are being transported by the wind. (Z.Jeran et al, 2003) For instance, Tortula Muralis is capable of absorbing 2µmol CO_2 per gram when dry. (R. S. DHINDSA et al, 1985) These pollutants that are being emitted by industry and households can cause various adverse health outcomes including lung cancer, heart diseases etc. It is also noteworthy that the finer the dust particles the deeper it could potentially penetrate and cause problems to the respiratory system. More specifically, particulate matter is a particle mixture of solid or liquid particles in air that can only be precipitated by wet deposition. In this regard, bryophytes can absorb water, such as acid rain, more efficiently than other artificial surfaces because these particles can be captured inside mosses' skin.

Acoustics

Bioreceptive materials could contribute to sound mitigation in the same way with green walls and plants and more precisely through sound absorption, sound deflection and sound refraction. Urbanization has played an important role in the accelerating ascending levels of sound pollution in the cities mainly due to transportation noise. In an attempt to control these levels, different guidelines have been set such as 55dB during day and 30dB during night. (CARE-CEDIA, 2017) The architectural community has been trying consistently to discover new methods and products that would significantly contribute in noise reduction, such as new top layers for the roads, but despite all this effort sound pollution is still a daily phenomenon. Additionally, green facades improve the exposure to elevated sound levels particularly but there are many opportunities for improvement. Materials and plant species along with their overall thickness take the leading role for this change and should be investigated further in several conditions and locations. Bioreceptive materials could become a key element for innovation in the acoustic insulation market. More and more evidence of the good acoustic performance of "moss-walls" is being published.

Cooling Methods

Natural organic matters, including mosses, have low thermal conductivity and high water holding capacity. (H.Park et al, 2018) They act as a water reservoir and as a result they boost vegetation transpiration. As such, transpiration leads to the cooling of the surrounding air as the water goes from the liquid into the gaseous phase (vapor). This natural process is widely known as "cooling transpiration». The water holding capacity of moss is considerably high and in combination with a high water retentive material could act synergistically and reduce the Urban Heat Island effect.

Aesthetics

Even though for several years biological growth was associated with biodeterioration, many researchers have underlined bryophytes' high aesthetic value. Indeed, there are authors who have stated that color changes could become aesthetically pleasing and they have connected these changes with a protective role against anthropogenic and weather-induced activities. (J. Granier, 1975, R. Lallemant and S. Deruelle, 1978) Not only that, bryophytes and more specifically mosses are deeply rooted in Japanese culture and architecture, possessing more than 2500 species of moss. Their gardens, known as Zen, are considered to be incomplete without moss because of their vibrant colors and soft surfaces. Mosses' properties and adaptability are core elements for this preference and the fact that moss can gradually cover surfaces, according to Japanese culture, gives to them something inherently virtuous.

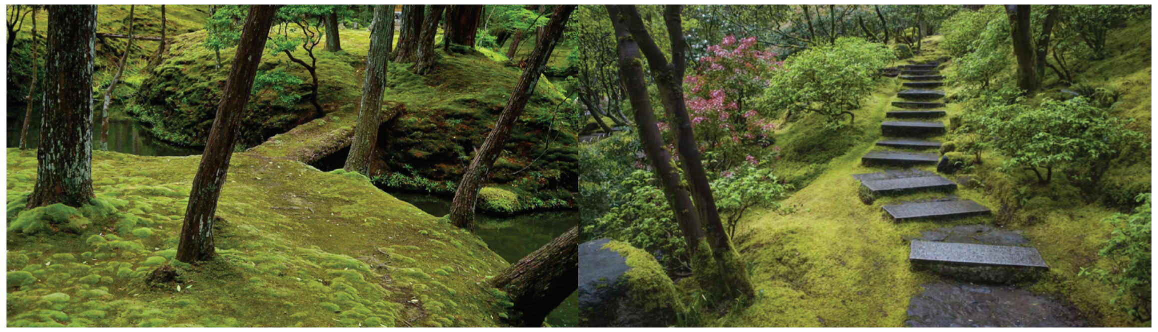


figure 22: Zen Gardens in Japan (shutterstock.com, n.d.)

3.6 Bryophytes' Applications in Architecture

Apart from the Japanese gardens that were mentioned before, mosses have not been implemented widely in architectural projects yet. Only two applications of the same material are found on the internet and its potential is presented below.

MUNICH RE OFFICE is an office department in Munich which was realized in 2002 with pre-grown roof and wall panels of a dioicous moss type known as Ceratodon purpureum. This particular moss species is remarkably adaptable and can be found in a wide range of habitats, from polluted highways to recently burned areas and from mine tailings to slopes located in Antarctica. (Tesky, Julie L. 1992) The innovative technique of inoculating micro-organisms and micro-organisms with high level productivity on panels was developed and patented as "bryotec technology" by MCK ENVIRONNEMENT which owns a license for its development. A biological crust made of moss is created on the surfaces of the panel which can contribute to pollutants' absorption and ground/soil media stabilization depending on if the panels are applied on the floor or on the roof respectively. MCK ENVIRONNEMENT's ultimate goal is to create bryophytic covers on various building components such as walls and roofs but also to be applied in restoration-oriented purposes like revegetation. Moss growth speed is exceptionally fast since it only demands a period of 10 weeks to show its initial potential under a humid, mild climate. (greenroofs.com, 2002) Another application of the same technology has been applied in Aargauer Kunsthaus in Switzerland in 2003.

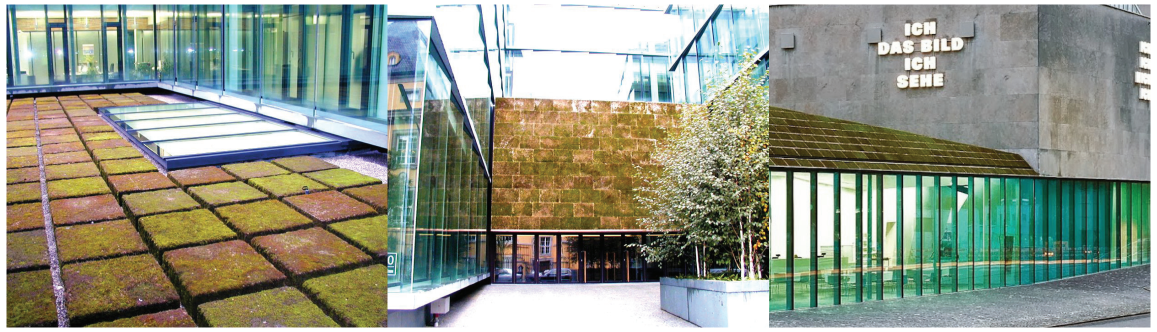


figure 23: (left and middle): MUNCH RE OFFICE (right): Aargauer Kunstahaus (greenroofs.com/projects, n.d.)

3.7 Overall conclusions (chapters: 2 and 3)

The fact that different materials may have different bioreceptive performances in the same conditions, but also, the same material may be colonized in another way in different locations and orientations makes bioreceptivity a parametric phenomenon. The variables influencing bioreceptivity can be grouped in two main categories.

The first category is associated with the surface topology (macroscale) in a defined environment. Relevant parameters in this category, as resulting from the literature research, include: temperature, relative humidity, wind, water accessibility and sunlight. In this research the effect of these parameters on bioreceptivity will be researched on a digital model (see chapter 4)

The second category is related to materials' properties (microscale). Relevant parameters in this category, as resulting from the literature research, include: water absorption capacity and rate, water evaporation rate, biological growth and surface roughness. The effect of these parameters on bioreceptivity will be investigated through laboratory experiments (see 5.9-5.10). Based on the results of both research parts, a bioreceptive building element will be designed and prototyped.

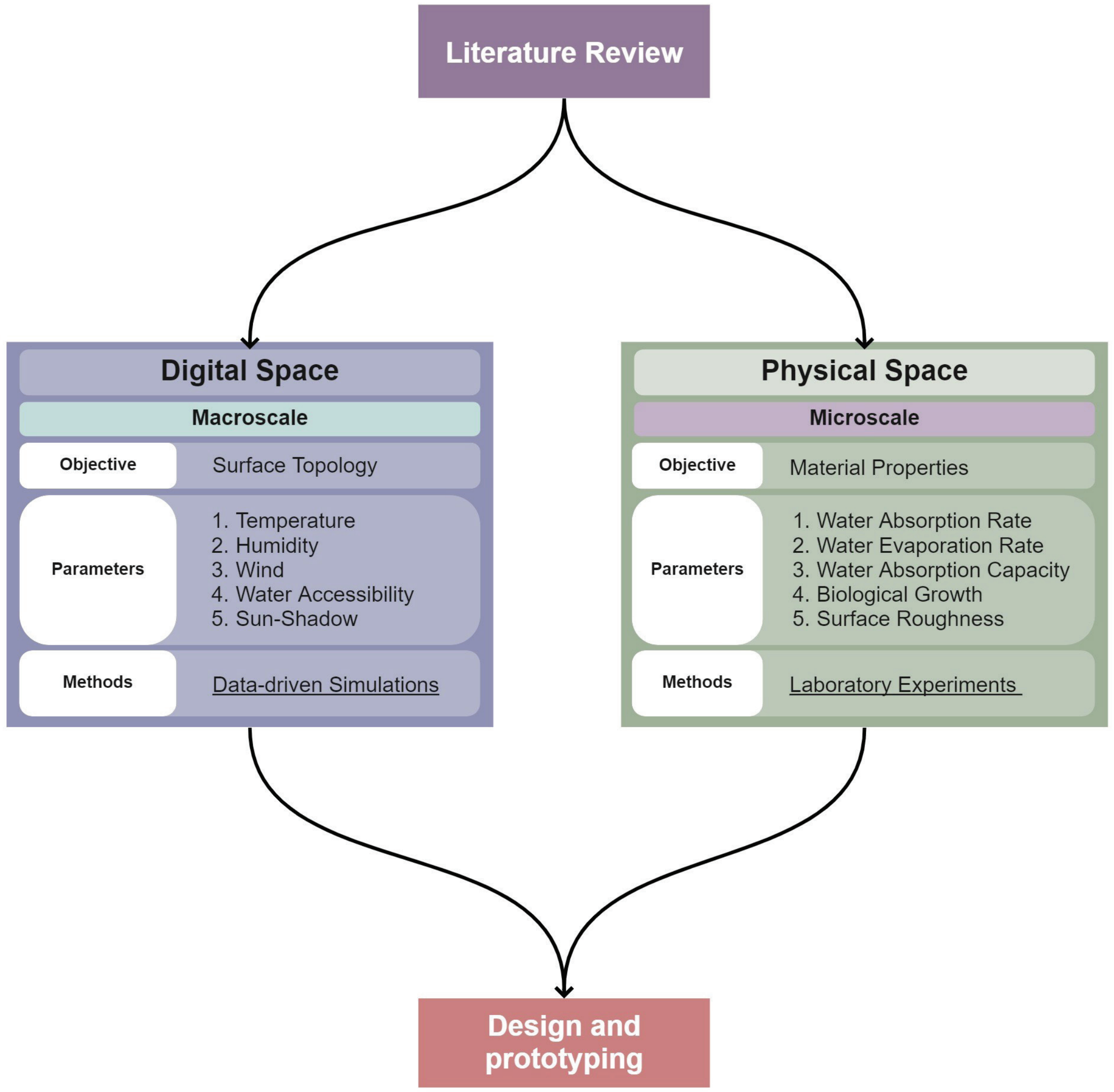


figure 24: Grouping the variables influencing bioreceptivity in two main categories (own source)

4. Topology Study

figure 25:
3D Printed Tile designed by IVH
(Daria Scagliola & Stijn Brakkee, 2020)

4.1 Methodology

4.1 Methodology

The present chapter investigates how surface topology can support the use of bioreceptive materials and more specifically how a surface's topology could be modified to favor mosses' growth. This will be studied in digital space using parametric modeling software in combination with data-driven simulations.

The methodology that has been followed is divided in two parts. The first part is about identifying possible locations where mosses can thrive, based on climate-related requirements. A specific location will be chosen in order to run a case study.

The second part of this chapter is about engineering a systematic way of manipulating surfaces taking into account two main factors: solar radiation and water flow. On this basis, a script will be firstly set up, capable of indicating parts of a geometry that are the most favorable for mosses' growth mainly due to the solar exposure levels and water accessibility. Secondly, a qualitative comparative analysis will be conducted between design alternatives, concerning their potential of bioreceptivity performance based on their levels of solar exposure. In this sense, a computational optimization will be performed in order to make some conclusions and remarks about their output but also in order to use the most optimized topology for the design proposal.

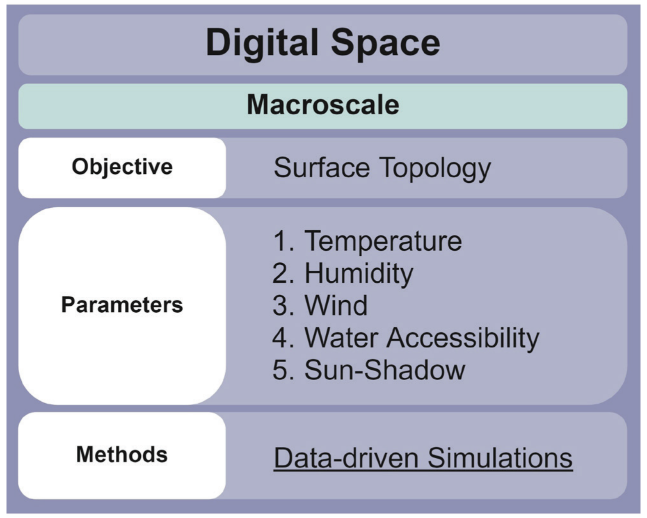


figure 26: Objectives, parameters and methods that will be applied in digital space. (own source)

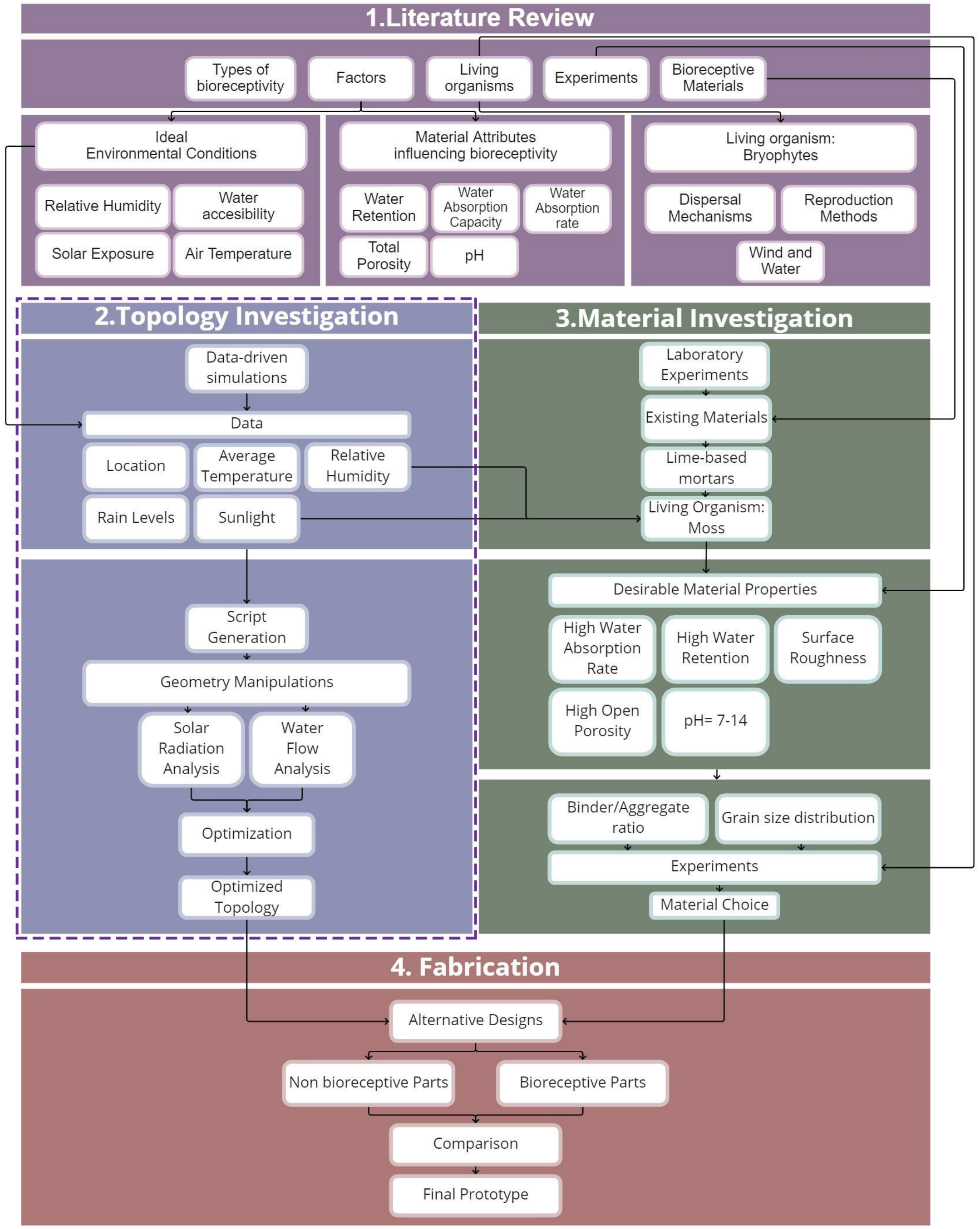


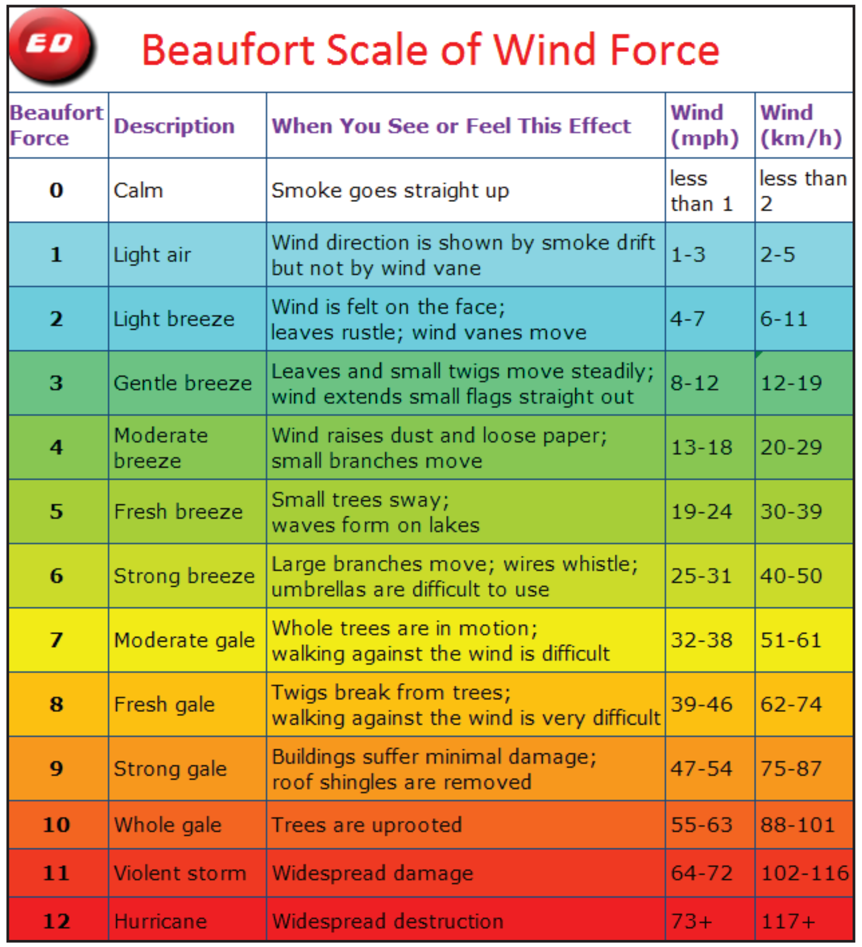
figure 27: Topology investigation in relation to the other chapters of the thesis. (own source)

4.2 Location Identification

In order to identify ideal locations for mosses' growth, specific climate requirements need to be determined from the beginning. Apart from the limits that are related to the air temperature and relative humidity which are based on the literature, the remaining ones have been set either intuitively or based on general observations.

- Air Temperature: The optimal temperature is in the range from-5 to 25°C.
- Relative Humidity: High RH is required for mosses 'sustenance and thus a minimum of 75% RH is set.
- Wind speed: Minimum wind speed has been set to 20km/h (= moderate breeze), which means that wind can raise dust particles. As such, mosses' sporangia or segments can travel great distances and thus being reproduced either sexually or asexually. (Figure 28)
- Rain frequency: 5 days per month is set as the minimum limit for rain's frequency. In this manner, mosses can uptake their nutrients from rain.
- Sunlight: 5% sunlight per day which corresponds to 1,2h per day would be beneficial for mosses' photosynthesis.

The above-mentioned criteria have been set as inputs in a climate-finder engine in order to find locations that fulfil these and have similar environmental conditions. (www.climate-finder.com) (figure 29) The following monitored locations were given as a result. (figure 30) Amsterdam was selected as a case study due to the proximity in combination with the fact that its climatic data were available online. (figure 31)



Beaufort Scale of Wind Force

Beaufort Force	Description	When You See or Feel This Effect	Wind (mph)	Wind (km/h)
0	Calm	Smoke goes straight up	less than 1	less than 2
1	Light air	Wind direction is shown by smoke drift but not by wind vane	1-3	2-5
2	Light breeze	Wind is felt on the face; leaves rustle; wind vanes move	4-7	6-11
3	Gentle breeze	Leaves and small twigs move steadily; wind extends small flags straight out	8-12	12-19
4	Moderate breeze	Wind raises dust and loose paper; small branches move	13-18	20-29
5	Fresh breeze	Small trees sway; waves form on lakes	19-24	30-39
6	Strong breeze	Large branches move; wires whistle; umbrellas are difficult to use	25-31	40-50
7	Moderate gale	Whole trees are in motion; walking against the wind is difficult	32-38	51-61
8	Fresh gale	Twigs break from trees; walking against the wind is very difficult	39-46	62-74
9	Strong gale	Buildings suffer minimal damage; roof shingles are removed	47-54	75-87
10	Whole gale	Trees are uprooted	55-63	88-101
11	Violent storm	Widespread damage	64-72	102-116
12	Hurricane	Widespread destruction	73+	117+

figure 28: Beaufort scale of Wind force. (strenlg.blogspot.com, 2019)

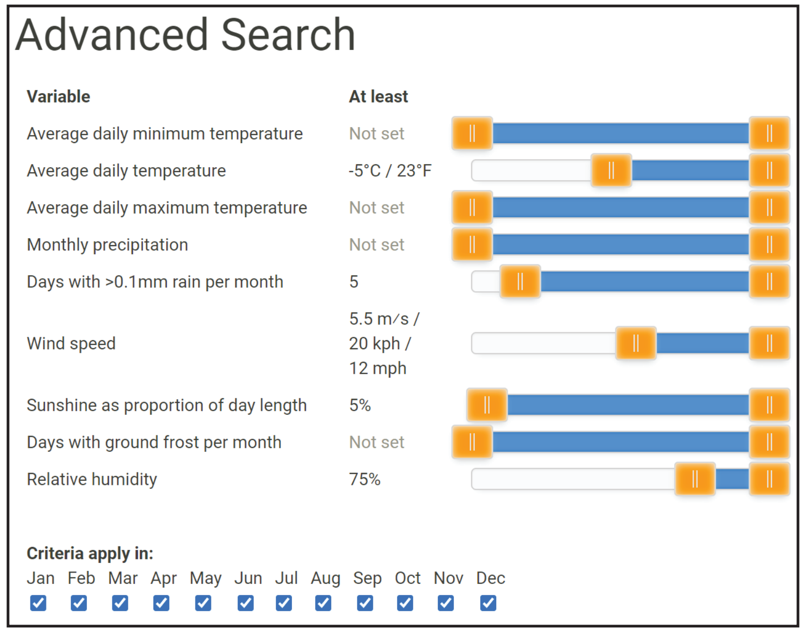


figure 29: Advanced Search (climatefinder.com, 2022)

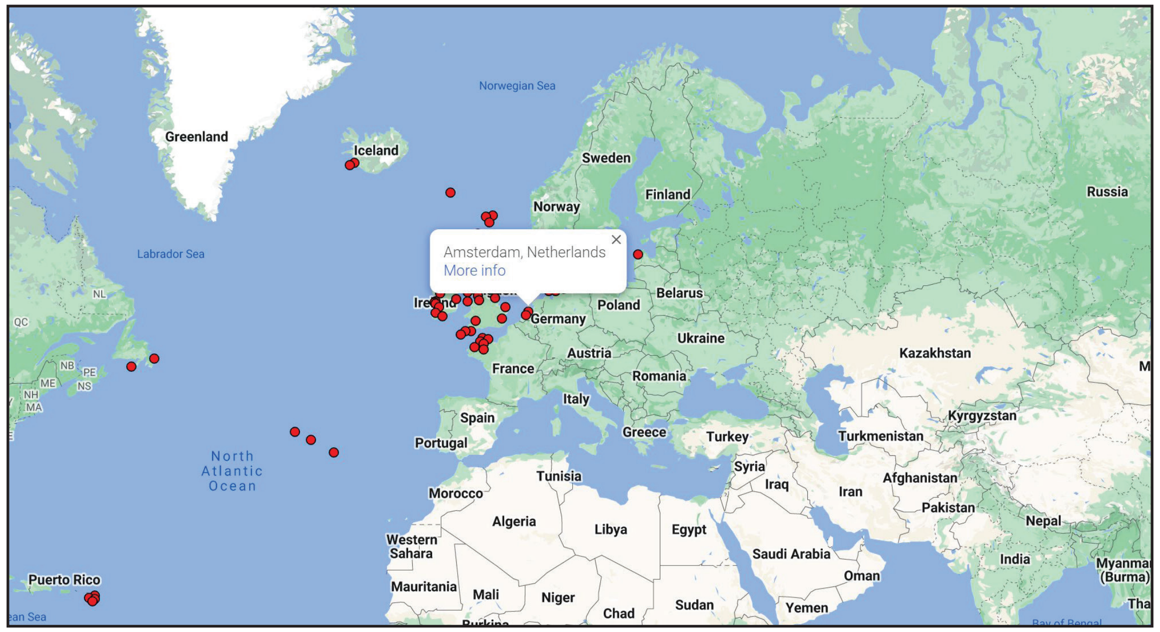


figure 30: Map of locations with desirable conditions. (climatefinder.com, 2022)

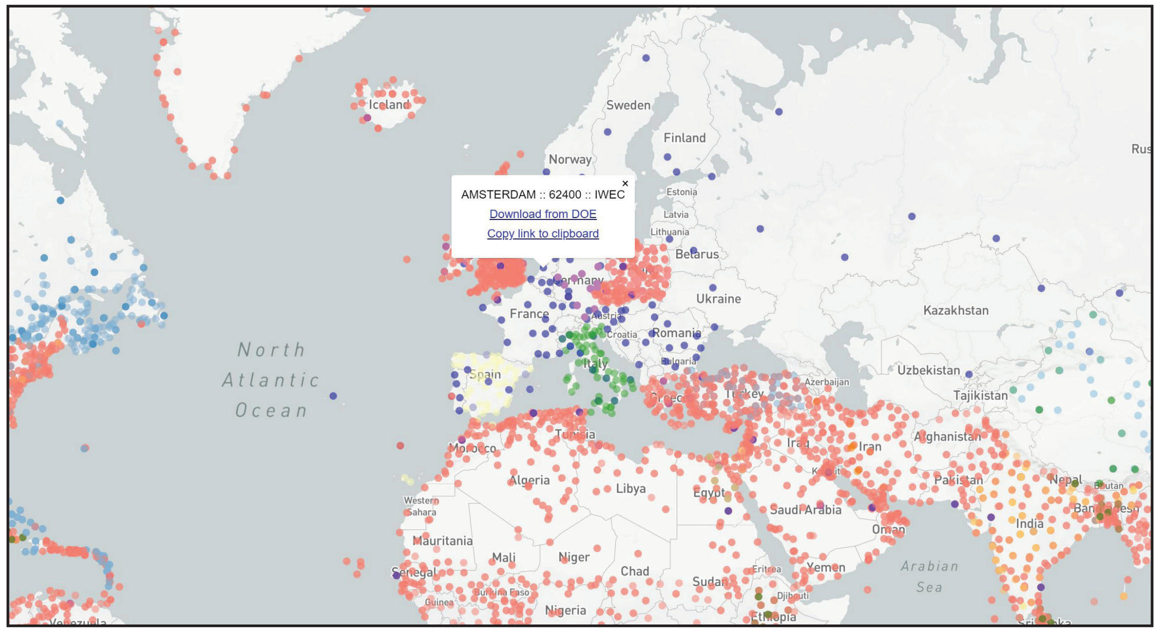


figure 31: Map with accessible climatic data. (www.ladybug.tools/epwmap, 2022)

4.3 Form-finding principles and script set up

4.3.1 The concept

The majority of mosses thrive in shaded environments because intense sunlight can burn their skin and leaves but also dry their rhizoids. Thus, the main objective of this chapter is related to the topological modifications of a surface with the intention of creating self-shaded spaces. The following research is motivated by solutions offered in nature and more specifically by termites' settlements. Termites construct their settlements in a way similar to figure 32 in order to create shady spaces since they cannot survive in sunlight. (M. M. Shahda, 2020) Therefore, having as a starting point these patterns found in nature, a script will be generated accordingly.

figure 32: Habitats of termites' settlement. (M.M.Shahda, 2020)

Script's generation is based on two main principles. The first takes into account the importance of indirect sunlight for mosses' survival. The second design principle is related to the element of water and more precisely to its direction. Water has a dual role in bioreceptivity since it contributes drastically to plants' photosynthesis but also provides moisture content within the substrate, something that promotes biocolonization.

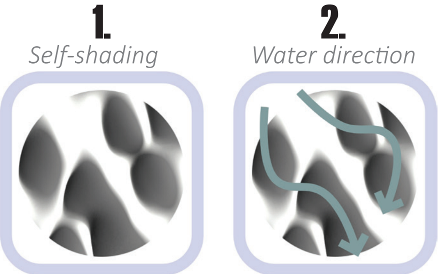


figure 33: Script's main principles. (Own source)

By scripting an algorithm which targets these two main goals, it can support bioreceptive materials in acting as toolpaths for digital fabrication by dictating biological growth on bioreceptive surfaces. The software that will be used for the following steps is grasshopper in combination with two plugins; Ladybug 1.4.0 for solar radiation analysis and Anemone 0.4 for creating the loops needed for water flow analysis.

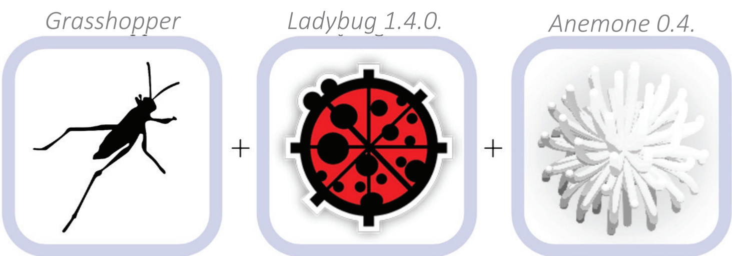


figure 34: Software used for script's generation. (food4rhino.com, 2022)

4.3.2. Proof of concept

The fact that a surface's topological modifications can reduce the amount of the receiving solar radiation by creating self-shaded spots is the proof of principle for the concept's feasibility. In figure 35, the topology of a flat vertical surface is transformed in order to evaluate how this affects its solar exposure. By running a solar radiation analysis on both surfaces it is evident that the amount of solar radiation received can be reduced by more than 15%. Several self-shaded spots were created which are mainly responsible for that decrease. The method that was applied in this example will be explained analytically in order to investigate how far this reduction could go but also which parameters are accountable for that. In parallel, it will be combined with a simplified water flow simulation in order to study how easily these self-shaded spots are accessible by water. Water supply is proven to be beneficial for the living organisms that inhabit on and within the substrate.

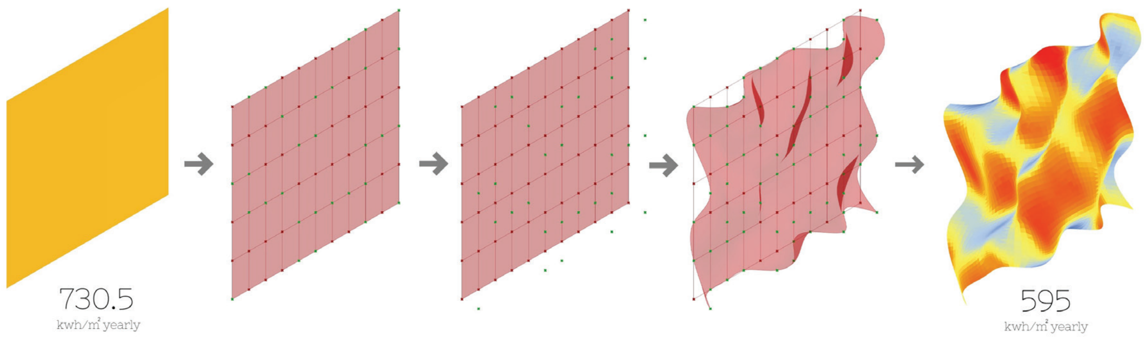


figure 35: Proof of concept visualized. (Own source)

4.4.3. Script's generation for flat vertical surface

The overall script is divided in four main steps as seen in figure 36 (geometry formation, water simulation analysis and solar radiation analysis, cross-referencing and evaluation). A continuous flat vertical square surface is the starting point of the study. Having a simple surface as input facilitates the generation of the script. For studying purposes, the overall grid size is set to 2,5 by 2,5 meters, the number of maximum control points is set to 40 out of 66, while the longest distance they can reach is set to 0,3 meters. The control points can be moved only on the y axis.

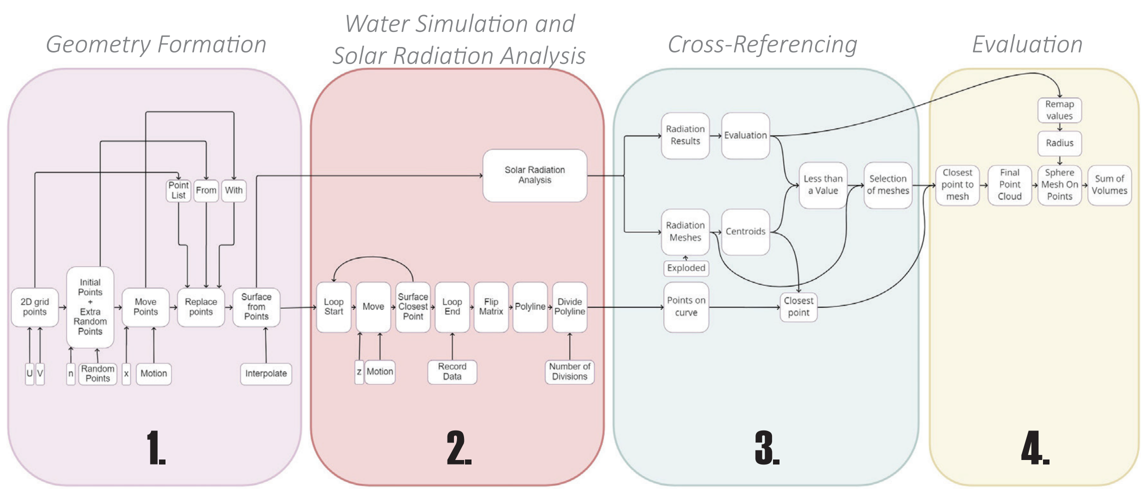


figure 36: Script's flowchart. (Own source, appendix)

Geometry formation (steps: 1-4)

The first step is to subdivide the surface in a rectangular grid and set its intersections as the surface's control points (step 1). In this sense, by selecting (step 2) and moving any control point (step 3), the surface's topology is modified (step 4).

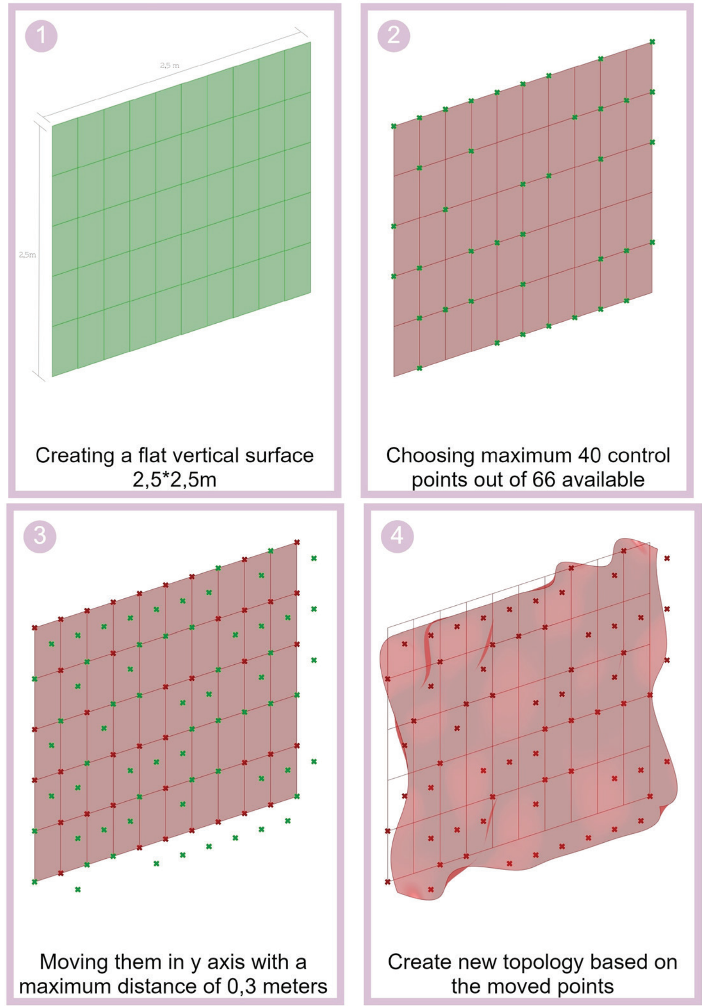


figure 37,38: steps 1-4. (Own source)

Water flow simulation and solar radiation analysis (step: 5-6)

Having as a basis the topology that is formed above, two processes occur simultaneously, water flow and solar radiation analysis, which are crossed-referenced for the topology evaluation. The first step of the water flow analysis is to determine a set of points that will act as water droplets flowing down on the surface. The logic behind the script is depicted in figure 39.

The idea is that in theory water follows the most available path of the least resistance. More specifically, the bold line represents the section of a surface. A single water droplet starts from the highest level and in order to imitate its flow, the points are moved vertically downwards by the same distance and then they are projected back to the closest point of the surface. Thus the more starting points are set, the more accurate the analysis is. By repeating this process, monitoring and connecting the paths of each droplet, a simplified water flow analysis can be conducted. The output is derived as polylines which can then be used for the next steps.

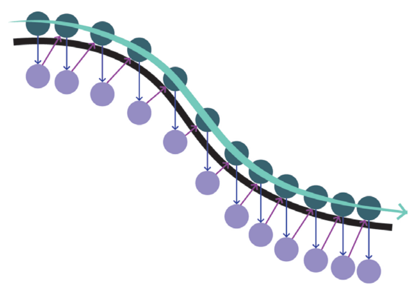


figure 39: Concept behind the water flow simulation. (Own source)

Despite that some parameters are not taken into account (i.e. water velocity), water flow analysis is still a valuable approximation that can demonstrate the method of integrating computational analyses in generative design.

In parallel, solar radiation analysis is performed. Climatic data, surface topology and the grid's size of radiation analysis are the main variables that need to be defined. These result in a colored mesh which indicates the amount of solar radiation in kWh per square meter falling on the topology in the specific location.

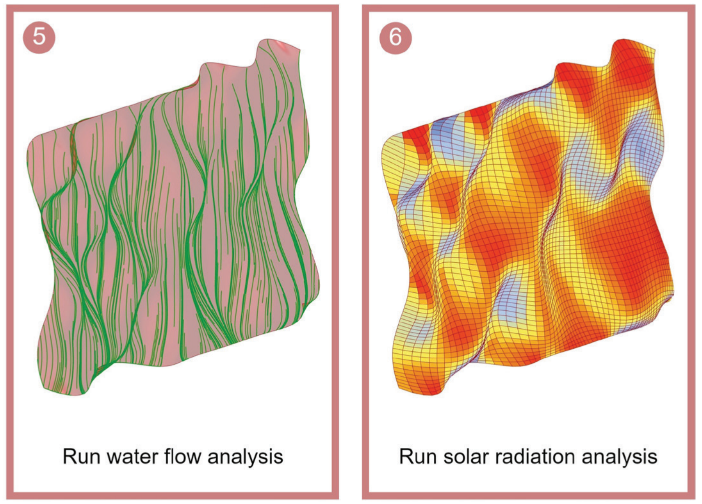


figure 40: steps 5-6. *(Own source)*

Cross-referencing (step: 7-8)

By running these two analyses on the same topology, two kinds of outputs are generated. Several polylines which represent principal water-flows and a colored mesh which represents solar radiation exposure levels. In order to cross-reference them, polylines act as attractors, isolating the sub-meshes that are close to each curve. The attractors' level of proximity needs to be defined, which expresses how many neighbors (sub-meshes) of the curve will be selected each time. Finally, in order to take into account only the sub-meshes with the desirable solar exposure level, a maximum limit is set and those who exceed that are omitted.

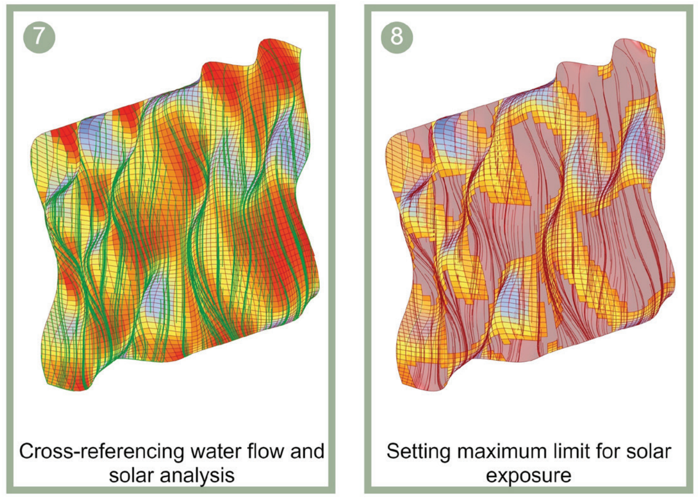


figure 41: steps 7-8. *(Own source)*

Evaluation (step: 9)

The last step of the script is related to the topology evaluation. This step is crucial because in order to make comparisons possible, a method of assessment needs to be constructed. The main principle of the evaluation is that the less amount of the solar radiation received, the more favorable conditions. This is because mosses thrive better in shaded spots. However, since the exact solar exposure limits of mosses have not been recorded

yet, they have been set intuitively. More specifically, it is done by observing the maximum received solar radiation on the flat surface facing a specific orientation and setting a limit that is considerably smaller. Surfaces' topological modifications can drop down the overall solar radiation due to the creation of self-shaded spots. In order to compare and evaluate different geometries all the sub-meshes which are in between the limits are isolated. The number of sub-meshes within the limits is not sufficient for comparison because the value of solar radiation in combination with the proximity of the main water flows need to be taken into account. With the aim of doing that a sphere is put as an index on each sub-mesh. The diameter of each sphere depends on the amount of its solar radiation. Finally, all the sub-meshes which are not easily reachable by water are left out and the volume of the present spheres is added.

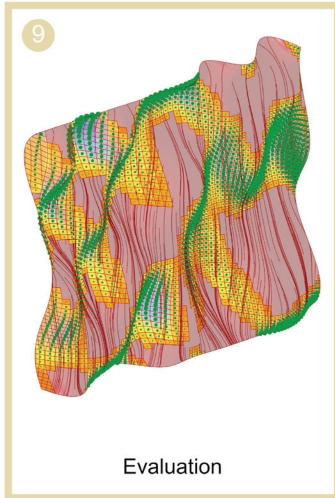


figure 42: step 9. *(Own source)*

4.4 Optimization set up and results

By following the above-mentioned steps repeatedly many alternatives can be generated and be compared through their evaluation's score. In order to do so, Opossum 2.2.4 is used, an optimization solver which records all the results. In this sense by observing which factors contribute to the score's improvement some worthy conclusions can be drawn and some empirical observations can be verified.

Opossum 2.2.4

figure 43: Software used for optimization. *(food4rhino.com,2022)*

Optimization set up

Each iteration begins by determining the variables that will be constantly changing (known as "genomes") in order to find the best combination which would result in the highest score. (known as "objective")

In this case, the genomes that will be examined are:

- Orientation (0 – 360 ° in xy plane)
- Distance of control points' deflection (0-0,3 meters perpendicularly to the initial surface)
- Number of control points (max 40 out of 66 available control points)
- Combinations of different control points (more than 1000 different configurations will be tested)

The objective is:

- The total sum of the spheres' volume that are used for evaluation. (sphere's ⌀=0-0.04m)

Evaluation limit:

- 113kwH per square meter for the reasons mentioned in 4.4. This is set as the evaluation limit only for the following optimization and can be changed depending on the orientation and location. This signifies that only geometries with segments which have a receiving solar radiation below that limit can be evaluated. The smaller the value, the bigger the sphere. At the end of each configuration all spheres' volumes will be added and the configuration with the highest score will be selected as the most optimal one.

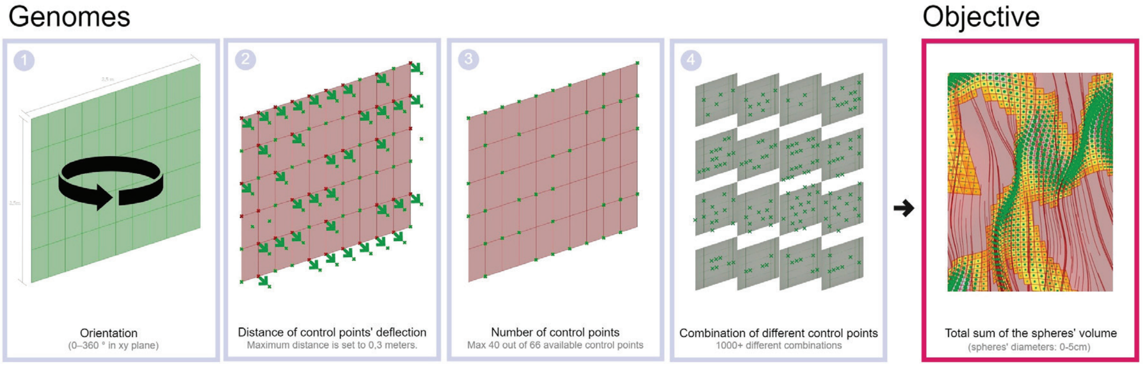


figure 44: Genomes and objective (Own source)

Limitation:

As mentioned before, water flow analysis (step 5) is a loop process. However, present optimization solvers which are compatible with grasshopper do not "wait" for internal loops to end and automatically leave the score as "null" because the script cannot be completed. In order to overcome this obstacle, the script is simplified and does not take into consideration water flow analysis for the optimization. Nevertheless, when optimization is finished, water flow analysis will be tested manually on the best topologies to evaluate if the self-shaded spots that were created are easily accessible by water and will be used for the design proposals in chapter 6.

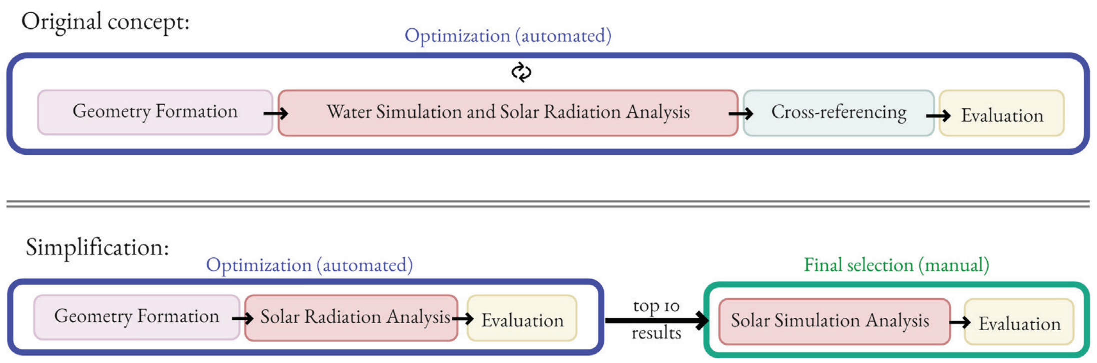


figure 45: :Original concept of the script's workflow and its simplification. (Own source)

Results:

By running the optimization, some remarks can be made instantly. North orientation in combination with a large number of selected control points and a big distance contribute to a higher score. Firstly, all the topologies with the highest scores face north, because the target is low sunlight levels. It is a fact that north-facing surfaces that are located in the northern hemisphere, and in this case Amsterdam, receive the least amount of sunlight.

In addition to this, from an empirical viewpoint, it is a quite old idea among hikers that mosses grow on the northern side of the trees due to less sunlight in combination with moisture. Secondly, a combination of many control points and a large distance have as a result the creation of more self-shading spaces which also result in high scores. Some of the configurations along with their scores and genomes are depicted below.

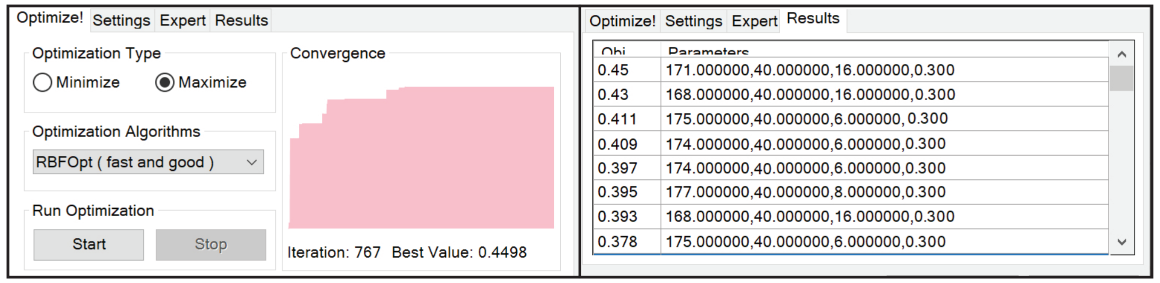


figure 46: :Optimization's results. (Own source)

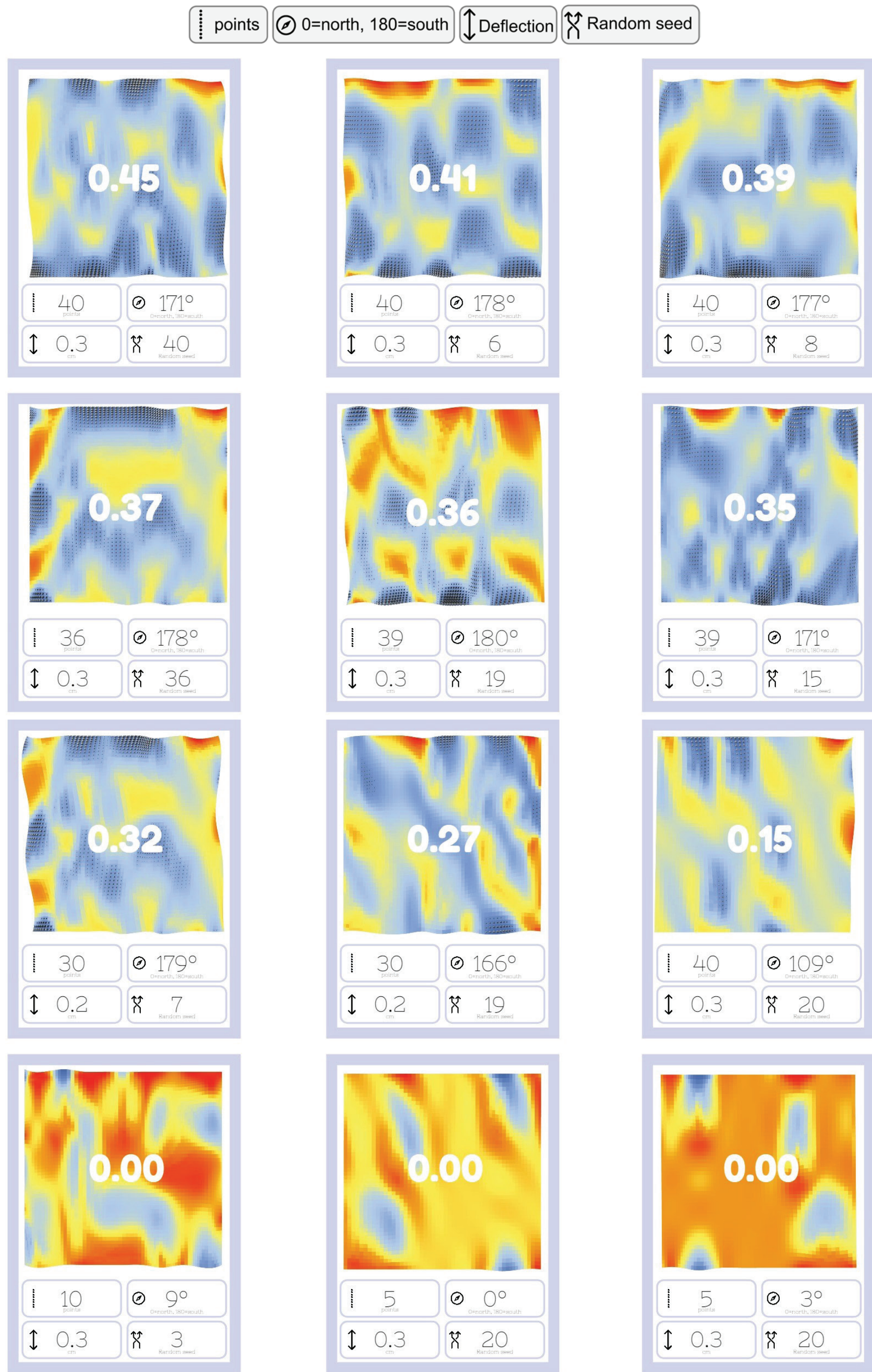


figure 47: Comparison of different configurations (Own source)

4.5 Qualitative Comparative Analysis

The optimization process outputs as the most successful orientation north because of the small evaluation limit that was set before. It is reasonable and expected that when seeking for the lowest average solar radiation values in all directions, north-facing topologies will have a better score. In order to investigate how solar radiation's patterns are influenced by the topological modifications in the opposite condition, when solar radiation has the highest values, the same optimization process will be performed on south-facing surfaces following the above-mentioned principles.

4.5.1. North-facing topologies

Before optimization, solar radiation was equally distributed on the topology. After optimization, it appears that the topological modifications changed solar radiation's pattern distribution and that occurs thanks to the creation of self-shaded spaces. Even though the annual average solar radiation is not reduced substantially, several self-shaded spaces are created. To be more precise, after the topological modifications, 56% of the solar radiation values are lower than before. It is also noteworthy that 15% of the optimized surface topology has an average solar radiation value lower than 130kwH per square meter yearly, which means lower than 50% of the average solar radiation of the initial surface. Additionally, by running water simulation analysis, it is obvious that water is directed over these self-shaded spaces, something that would act beneficially for mosses and other living organisms with similar requirements. 44% of the surface topology is higher than the annual average solar radiation of the flat surface because in the attempt to create the self-shading spaces some parts of the surface topology face the sun. These parts are not suitable for mosses' growth due to the direct sunlight throughout the day.

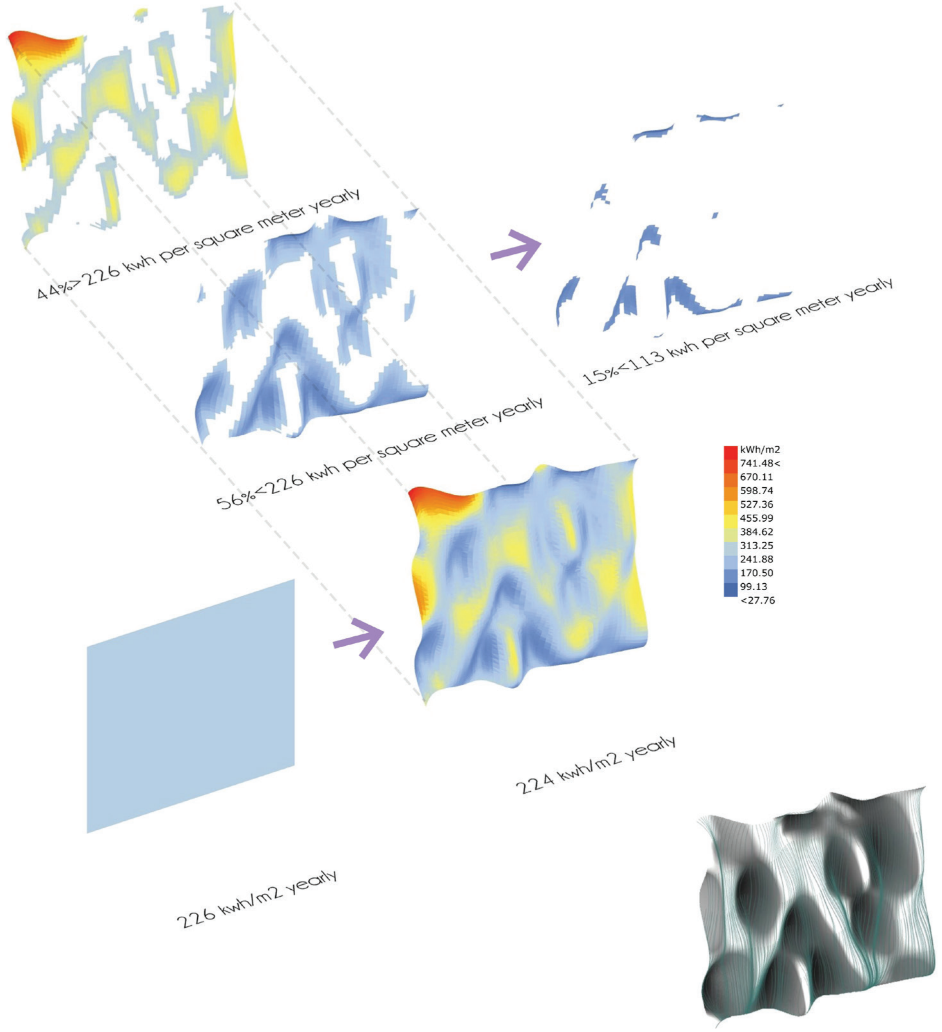


figure 48: Comparison between the initial surface topology and the optimized one (North) (Own source)

4.5.2. South-facing topologies

By applying the previous optimization process to south-facing surface topologies some supplementary remarks can be made. Even though at first glance the results seem to be similar, in this case the average solar radiation is reduced by 15%. This observation is valuable because by implementing the script in form generation strategies, it is apparent that it can act advantageously for the creation of shaded spaces even for south-facing surfaces which are the most exposed to the sun. In figure 49 it is shown that 70% of the optimized topology has lower solar radiation levels than the initial flat surface while only 30% has higher values. Once again, 15% of the new optimized surface topology has solar radiation values lower than 365 kWh per square meter which implies that on specific segments, solar radiation is dropped by more than 50% when compared to the beginning.

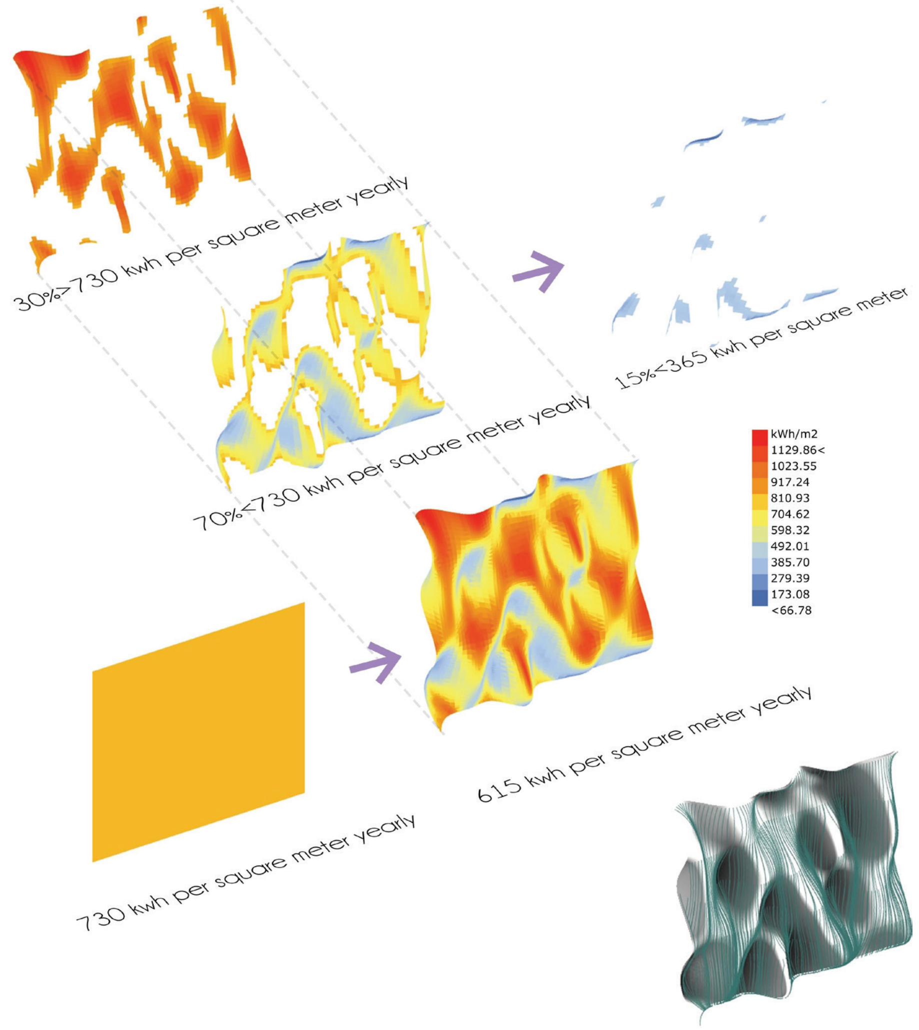


figure 49: Comparison between the initial surface topology and the optimized one (North) (Own source)

4.6 Script's advancement

The above-mentioned script has as a starting point the modification of a vertical flat surface but this approach can be applied to three dimensional continuous surfaces, as well. For instance, the potential of its application to a dome is going to be examined since it faces all possible directions and can provide a clear insight into the topic and the accuracy of the script. Once again, in order to modify the dome's topology and compare alternatives some requirements need to be set. For study purposes, its diameter is set to 4 meters. In order to create the control points, the dome is sliced vertically every 0,1 meter and each contour is then divided into 15 control points. The maximum number of points that can be moved is 50 and the biggest distance is 0,3m. Points are only moved towards the center of the circular basis. The methodology followed is similar to the previous one, as seen in figure 52.

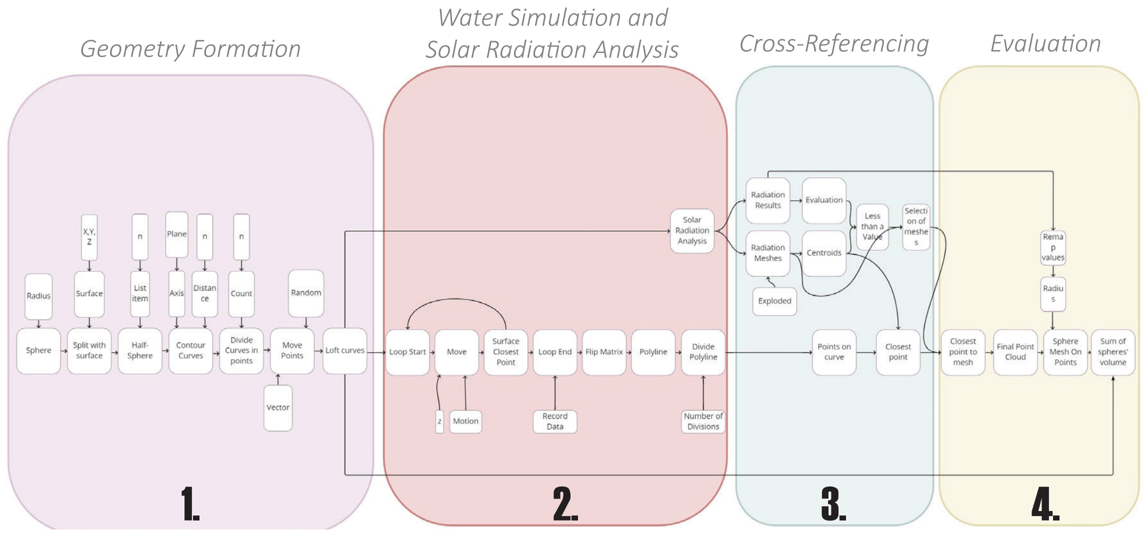


figure 51: Script's workflow (Own source, appendix)

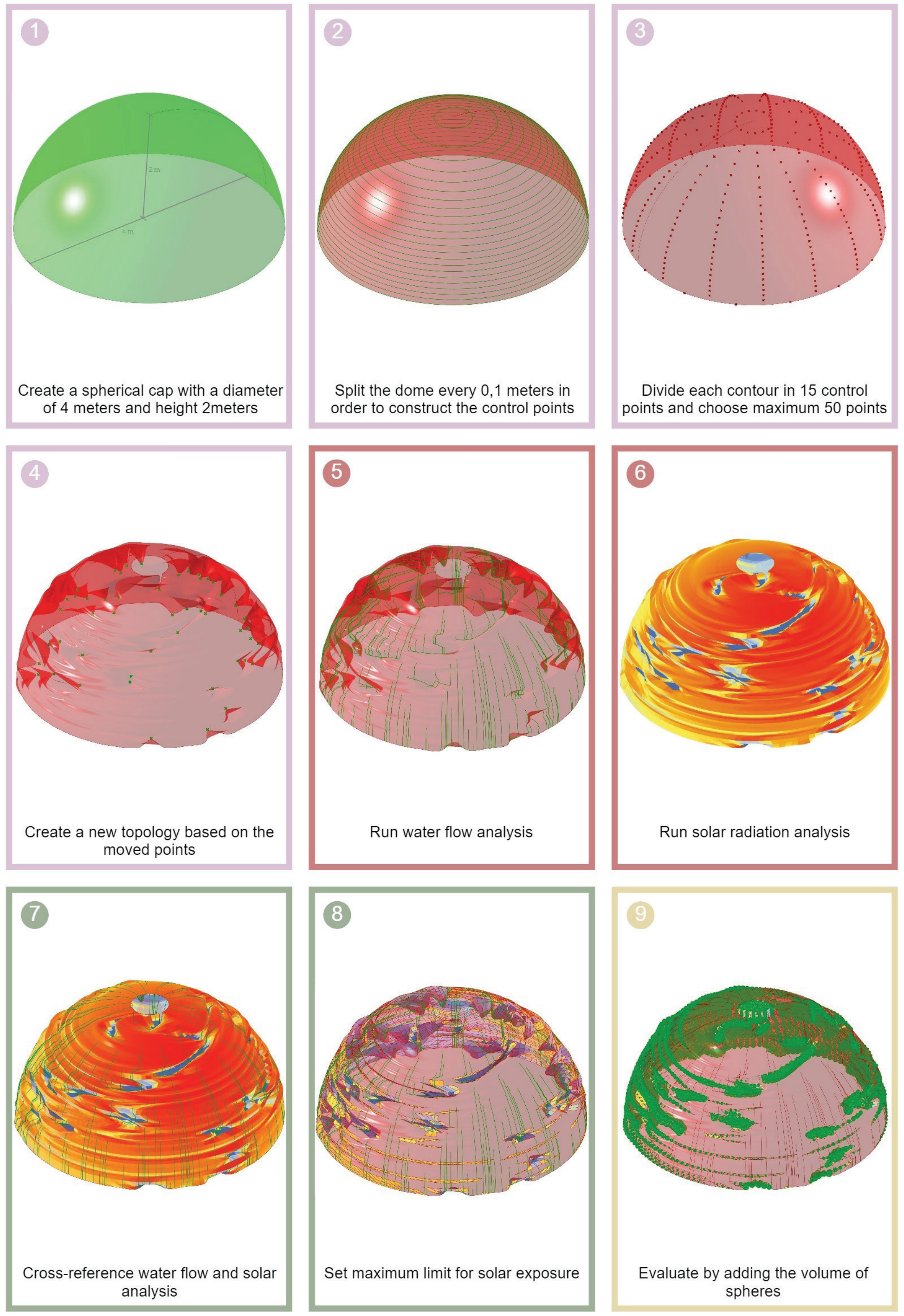


figure 52: Steps for the topology modification of the hemisphere (Own source)

Optimization set up

In this case, the genomes that will be examined are:

- Number of control points (max 50 control points)
- Distance of control points' deflection (0-0,2 meters towards the centroid of the circular base)
- Combinations of different control points (more than 1000 different configurations will be tested)

The objective is:

- The total sum of the spheres' volume that are used for evaluation.

Evaluation limit:

- 150 kwH per square meter for the reasons mentioned in 4.4. (sphere's ⌀=0-0.10m)

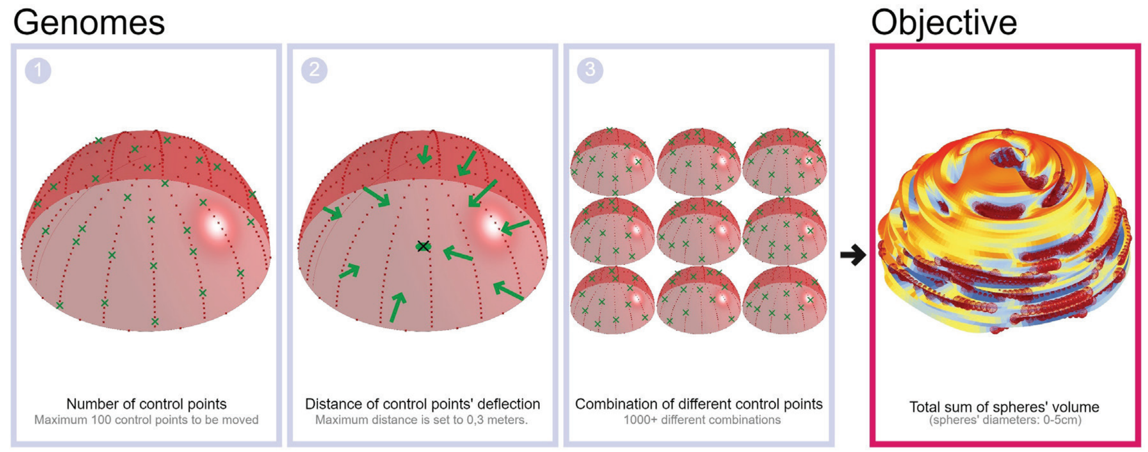


figure 53: Genomes and objective (Own source)

Results and Qualitative Comparative Analysis

By running the optimization to the hemisphere, it is concluded that once again the number of the moved control points determine to a high extent the configurations' scores. Additionally, the bigger the deflection, the more shadow is created. Finally, figure 54 indicates that it is easier to create self-shading spots in the northern side of the hemisphere because of the less sunlight levels. In general, except for the fact that orientation plays a vital role for a high score, it is really tricky to make further conclusions because of the high complexity of the generated forms. However, it is accurate to mention that the above-mentioned framework offers a new digital capability by comparing, modifying and evaluating alternatives having as a goal the creation of self-shading forms.

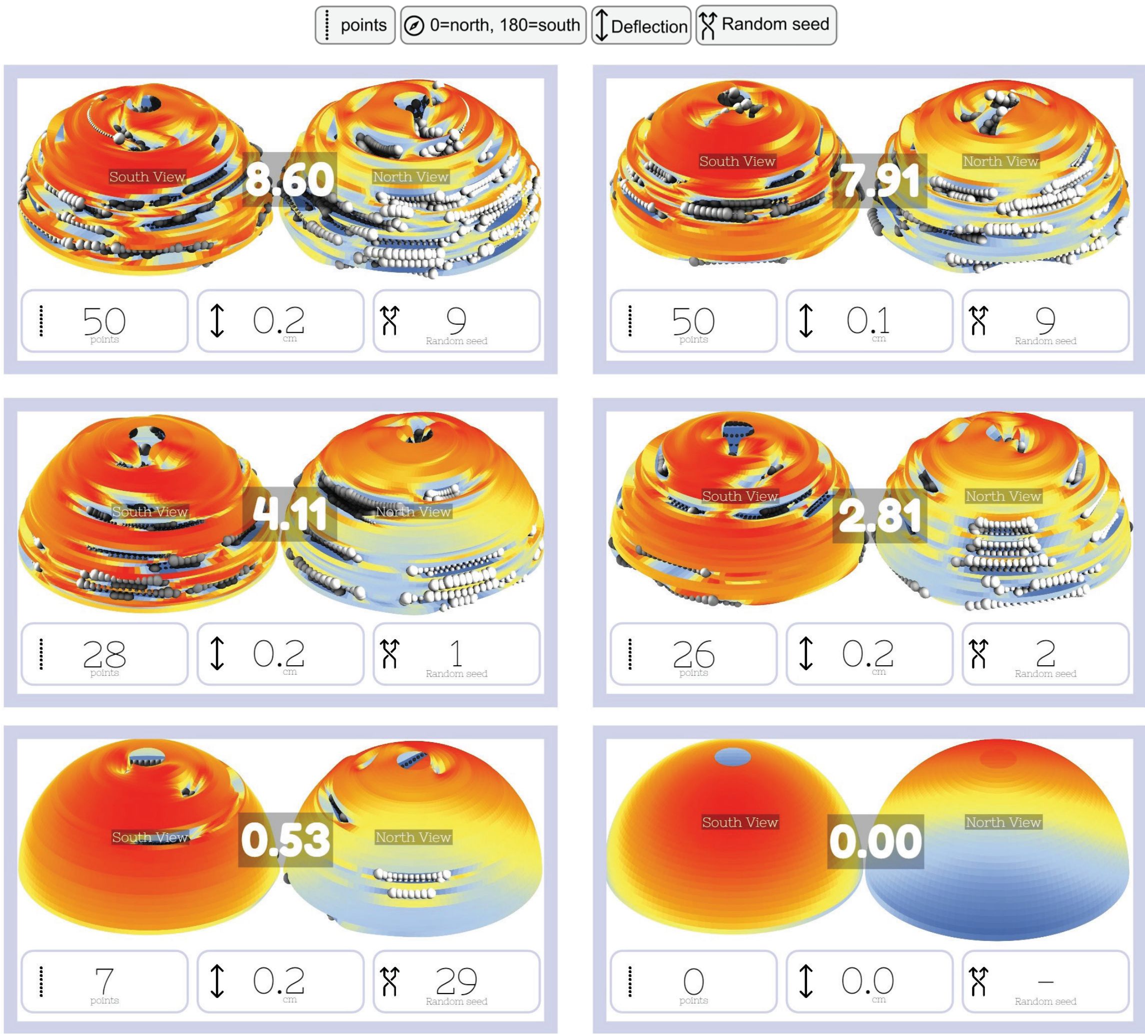


figure 54: Comparison of different configurations (Own source)

4.7 Discussion

To sum up, the above-mentioned methodology is useful because it can be adapted for various architectural purposes. To begin with, it can act as a digital "tool-box" capable of indicating the most suitable environments for targeted living organisms; mostly based on solar radiation. Thus, it can be implemented in landscape architectural projects, especially in an urban design level for greening existing and future cities. In this sense, it can help architects and designers in their decision-making strategies by guiding them in the integration of green in their designs more efficiently. For instance, it could act conversely to the way it is used before and indicate spots for plants that need direct sunlight. Moreover, it can support the use of bioreceptive materials by acting as a consulting mechanism for comparing alternatives in terms of expected environmental and bioreceptivity performance through qualitative comparative analysis. Finally, it can contribute to the establishment of a new architectural vocabulary, thanks to the integration of bioreceptive materials in the building industry. As such, it can become the means of generating toolpaths for fabrication and controlling biological growth within bioreceptive substrates. This will be further investigated in chapter 6.

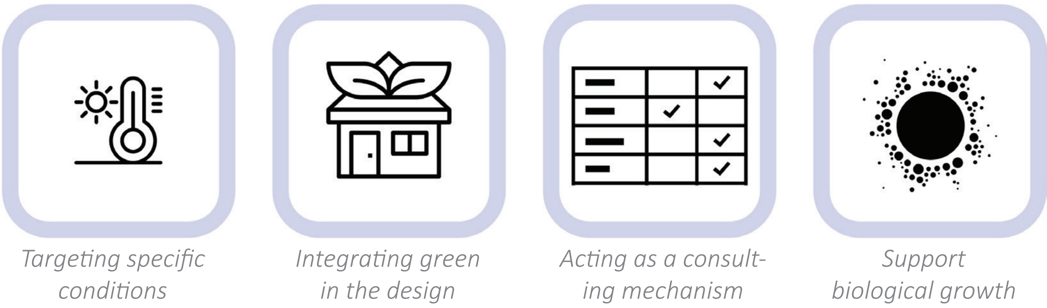


figure 55: Potential application of the script. (Own source)

4.8 Material and fabrication technologies

4.8.1 Digital Fabrication

There is a need to define the method of fabrication that can transform these digital forms (see 4.4 and 4.6) into real physical elements and to determine the material/s that could be used in the present framework conditions. (see Chapter 5) In order to validate the aforementioned topological research (4.3-4.6), it is critical to ensure that the produced geometries will be as similar to the ones that were simulated digitally. This can be achieved through digital fabrication, the process of transforming CAD data into real physical products through machine control. As seen in the following figure, digital fabrications is a general term that includes many different processes including additive, formative and subtractive methods depending on the material properties.

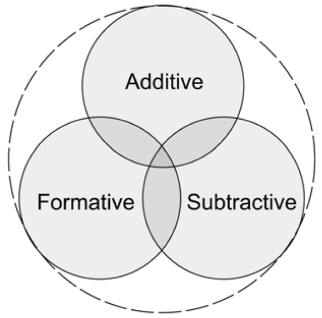


figure 56: Digital Fabrication Technologies. (Todd Grimm, 2014)

Digital fabrication offers a bidirectional relationship between design and fabrication and hence it allows the detection, correction and improvement in a very direct and comprehensible manner. (Todd Grimm, 2014) It can be really beneficial in freeform and customized geometries where a high level of complexity is required in order to create intricate elements.

4.8.2 Additive Manufacturing

In this project, additive manufacturing (instead of formative or subtractive) will be used for prototyping. Its ease of use and availability in the Laboratory for Additive Manufacturing in Architecture of TU Delft facilitated the experimentation. There is a growing interest to explore the potentials of additive manufacturing in the construction industry.

figure 57: 3d printed structures by SWNA and WASP using concrete and adobe accordingly (theswna.com, 2022 and www.3dwasp.com, 2022)

The main motivation of using additive manufacturing for this project derives from the fact that the topological manipulations and the optimization method are based on customization. The fact that the script suggests different optimized topologies in every location/orientation makes each produced element unique. This is because the design of the optimized surfaces depends on several variables (climatic data, shadow created by the surroundings etc.) The advances of additive manufacturing have made possible to produce customized elements with a high level of detail on a bigger scale. These complex geometries can be produced easier and with less material wastage in comparison to traditional manufacturing. This is because elements are produced in a layer-by-layer basis approach and considering the hollow cross sections or the use of lattice structures in the elements that are printed, less material is required.

By all means, there is space for improvement regarding the energy consumption during operation and the limited materials but the potential that it arises will be investigated through a research-by-design approach in chapter 6.

4.8.3 3d-printed green walls

Even though 3d-printing technologies are already in use for buildings, architectural features and other construction projects, there are only a few attempts of introducing green in 3d-printed structures.

A representative example of a 3d-printed green system is developed by Yingchuang. (winsun3d.com, 2020) Along with cement, they used fly ash, steel slag and other solid waste as raw materials for their printable mixture. Their wall design is divided in seven horizontal zones creating spaces for the greenery, acting as flowerpots and an integrated water irrigation system is in charge of their water supply. Its fabrication is rapid since the 200 meter wall was printed in pieces only in three days, installed in one and planted in three. The majority of the existing 3d-printed green structures that were available on the internet follow the same “flowerpot” design principle.

To sum up, even though the concept of reusing material waste is an innovative recycling approach, greenery is not biologically integrated in the existing designs. Moreover, a mechanical irrigation system in combination with plants’ and structure’s maintenance make it energy unsustainable. Lastly, external parameters, such as the surroundings and amount of sunlight, do not influence the design approach and can potentially damage the plants in the long term.

figure 58: 3d printed green walls by Yingchuang. (winsun3d.com, 2020)

4. Topology Study

5. Material Study

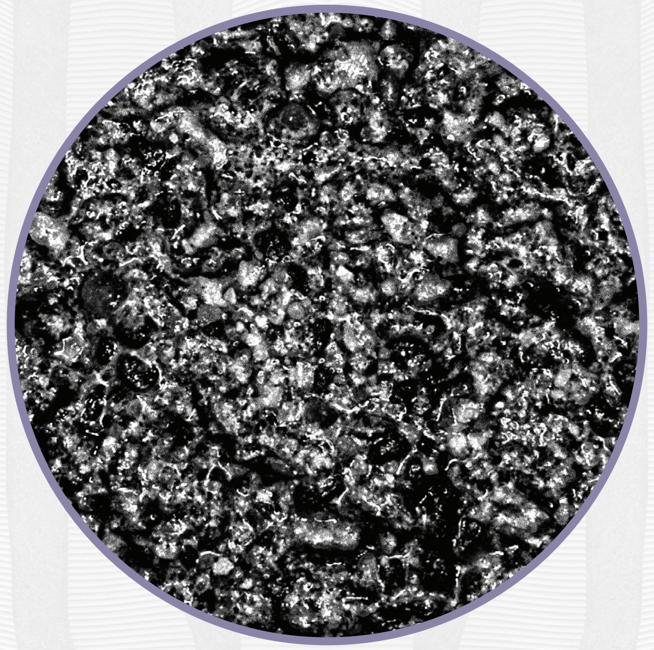


figure 59:
Lime-based mortar under electron microscope. *(photograph was captured by Georgina Giassia)*

5.1 Methodology

This chapter deals with the selection of a bioreceptive material in order to contribute along with the topology research in the final bioreceptivity-oriented design approach. Firstly a comparison between different materials will be made and lime-based mortars will be chosen as the material with the highest potential of bioreceptivity. Then, the bioreceptivity for moss growth of different lime-based mortar mixes and the effect of their moisture transport properties will be investigated through lab experiments.

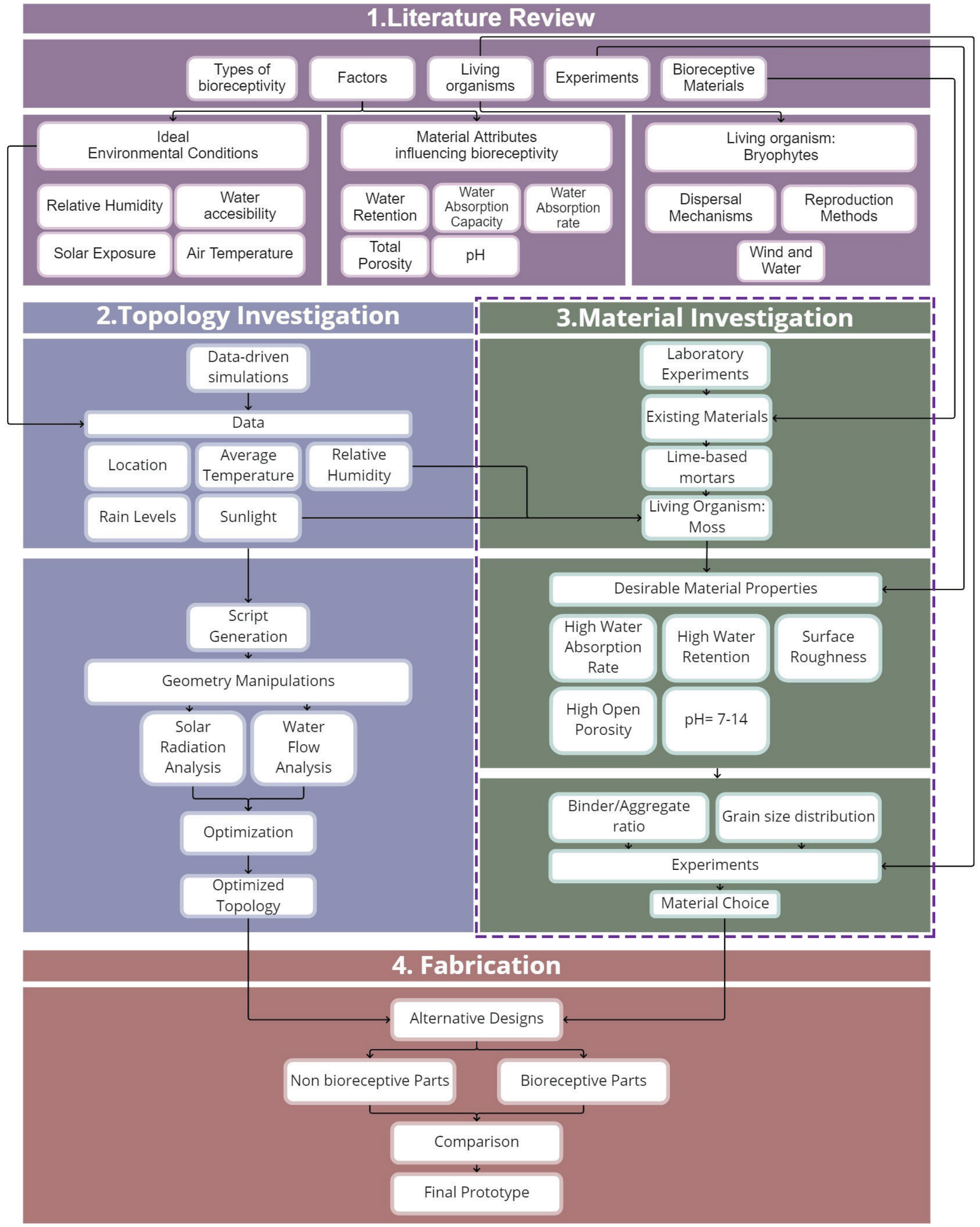


figure 60: Material study in relation to the other chapters of the thesis. *(own source)*

5.2 Criteria of material selection

The materials that have been found to be bioreceptive with experimental evidence based on the literature (2.6) are stone, ceramics, mortars and concrete. The following criteria have been used in order to choose among them, a material which can fulfill the requirements imposed by the fabrication and be more environmentally friendly than existing alternatives.

- Form Complexity
- Material Composition
- Circularity

Form Complexity

The most desirable and highly prioritized objective is the capability of the material to reach a high level of complexity and form intricate geometries. Mortars and concrete can be casted and hardened quickly and this is beneficial for forming complex geometries in a realistic manner. Ceramics can also achieve a high complexity and thus they could also be considered another promising material. Lastly, stone can potentially achieve complex shapes through carving but it is a really time-consuming and energy-demanding process. What is more, it is really difficult to integrate stone in the present research framework due to the absence of stone carving equipment.

Material Composition

As it derives from the literature review, material properties are strongly linked to bioreceptivity. In this sense, mortars' and concrete's properties can be engineered easier by modifying their compositions when compared to ceramics. In the case of stone, properties cannot be engineered. Moreover, it is remarkable to mention that another fact which makes lime-based mortars more bioreceptive is that they weather faster than ceramics, stone and concrete. As such, plants and living organisms can potentially grow faster within them.

Circularity

Concrete cannot be recycled because cement has reacted and cannot return to its initial state. However, it can be crushed down and be downcycled as an aggregate. The same occurs with mortars. The advantage with mortars is that other materials can be recycled in it, such as mineral wool fibers, plastic waste, ceramics, recycled bricks and concrete. It is also remarkable to mention that in the case of pure lime plaster (composed of sand, water, and non-hydraulic hydrated lime), lime can theoretically be recycled by being refired but it is hard to be realized. Moreover it can be ground up in order to improve the soil. (Bjorn Berge, 2000) Ceramics cannot be recycled because once they are fired they are not biodegradable. They can also be crushed down and reused as aggregates. Finally, stones can be reused, repurposed and downcycled into new applications.

	Stone	Concrete	Ceramics	Mortars
Form Complexity	-	++	++	++
Material Composition	-	+	+	++
Circularity	+	+	+	+

figure 60: Comparison between stone, ceramics, concrete and mortars. (own source)

5.3 Selection of binder

In order to determine the final mortar composition the most suitable binder needs to be selected. The most common binders that are used nowadays in mortars are lime, either hydrated or hydraulic, and cement. In order to choose the most appropriate binder in terms of bioreceptivity, two main criteria are set.

- Bioreceptivity performance
- Embodied energy

According to the existing literature, mortars that are based on cement are less likely to be biocolonized than hydrated lime-based ones. (K.van Balen et al, 2003) This is probably a result of lime-based mortars' faster carbonation, and thus reduction of pH, in opposition to cement-based ones. The faster carbonation also contributes to a generally better permeability in comparison between natural hydraulic lime and cement-based mortars. (K. van Balen et al., 2003 , J.J. Hughes et al., 2010) Furthermore, the generally higher water retention of lime-based mortars generally result in higher water retention which could also support bioreceptivity by offering a sufficient and stable water content within the material. (A. Isebaert et al., 2003)

Next to better bioreceptivity, lime has a much lower embodied energy and CO2 than cement, mainly because it is fired at a lower temperature (around 900-1100°C) than cement (around 1300-1400°C).Therefore, lime-based mortars show a higher potential than cement-based ones regarding bioreceptivity. Overall, it is obvious that lime-based mortar shows a higher potential regarding the above-mentioned criteria and as such this will be further examined.

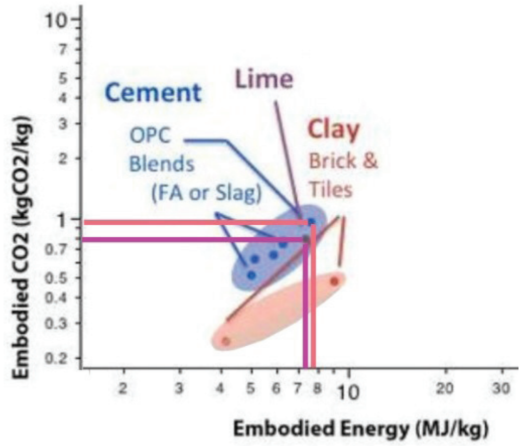


figure 61: Embodied energy and CO2 of lime vs cement. (S.Pavia et al,2005)

	Cement	Lime
Bioreceptivity	-	+
Embodied Energy	-	+

figure 62: Comparison between cement and lime regarding bioreceptivity and embodied energy. (own source)

5.4 Hydraulic or non-hydraulic mortar

Another aspect to be considered concerns whether the examined mortars need to be hydraulic or non-hydraulic. The main difference between these two is the manner that they harden. The first ones are set by hydration, a chemical reaction between water and hydraulic components. The latter ones are set by carbonation, a chemical reaction between $Ca(OH)_2$ and atmospheric CO2. One of the main drawbacks of hydrated lime mortars is their slow hardening process and low mechanical strength. (S.Pavia et al, 2005) Since the present research investigates the potential of bioreceptive materials in external conditions in a limited timeframe, lime-based hydraulic mortars are more suitable for the experiments.

5.5 Targeted material properties and method of approach

In order to compose the material mixtures in a way that acts beneficially to bioreceptivity, specific properties should be targeted that are associated with their water transport behavior. According to 2.7 these are:

- High water absorption capacity (high porosity) in combination with high water retention (fine pores) so water and nutrients are absorbed in large amount and kept within the substrate for a longer period of time.
- High water absorption rate (high porosity and coarse pores) so that water can be absorbed fast.
- Surface roughness because it contributes to the anchorage and protection of the microorganisms from undesirable environmental conditions like solar exposure and wind.

In order to control their water transport behavior, the parameters that need to be taken into consideration are:

- Grain size distribution of aggregates
- Ratio of binder/aggregate

<u>Grain size distribution of aggregates:</u>

Grain size distribution influences pores' size which in turn affects water transport behavior. In detail, by using small size and/or well-graded aggregates, a mortar with a relatively low open porosity and a high percentage of fine capillary pores will be obtained. This mortar will have a slow and lower capillary absorption, but a high water retention. Differently, the use of coarse and/or gap graded aggregates results in a mortar with a relatively high open porosity and a large percentage of coarse pores. This mortar will have a high water absorption capacity and fast rate of capillary absorption, but a low water retention.

<u>Ratio of binder/aggregate</u>

The ratio between binder and aggregate has a strong impact on the total porosity of mortars. The use of a lower ratio of binder/aggregate leads to a higher porosity. (B.Lubelli et al, 2020)

5.6 Material Composition

Three main conclusions derived from (B.Lubelli et al., 2020) (figure 64)

- Binders with lower b/a (=1/4) ratio had better overall bioreceptive performance during the 8 weeks of monitoring.
- Mortars based on Natural Hydraulic Lime had the best bioreceptivity performance.
- Vermiculite's addition boosted the bioreceptive performance of the mortars.

code name	binder	aggregate	b/a	code name	binder	aggregate	b/a
Hst2	NHL	0.08-2 mm	1:2	ATst2	Hydrated lime and trass	0.08-2 mm	1:2
Hsf2	NHL	1-2 mm	1:2	ATsf2	Hydrated lime and trass	1-2 mm	1:2
Hvt2	NHL + vermiculite	1-2 mm	1:2	ATvt2	Hydrated lime and trass + vermiculite	1-2 mm	1:2
Hst4	NHL	0.08-2 mm	1:4	ATst4	Hydrated lime and trass	0.08-2 mm	1:2
Hsf4	NHL	1-2 mm	1:4	ATsf4	Hydrated lime and trass	1-2 mm	1:4
Hvt4	NHL + vermiculite	1-2 mm	1:4	ATvt4	Hydrated lime and trass	1-2 mm	1:4

figure 63: Tabulation of all the examined lime-based mortars based on (B.Lubelli et al, 2020)

	Hst2	Hsf2	Hvt2		ATst2	ATsf2	ATvt2
porosity	21,5%	30,8%	42,7%	porosity	24%	30,6%	47,5%
water absorption rate	0,16 g/cm2 per 160s	0,18 g/cm2 per 160s	0,34 g/cm2 per 160s	water absorption rate	0,20 g/cm2 per 160s	0,22 g/cm2 per 160s	0,40 g/cm2 per 160s
bio receptivity ☆	1/5	-	2/5	bio receptivity ☆	2/5	-	4/5
	Hst4	**Hsf4**	**Hvt4**		**ATst4**	**ATsf4**	**ATvt4**
porosity	27,9%	39,2%	50%	porosity	26,5%	30,6%	54,1%
water absorption rate	0,14 g/cm2 per 160s	0,17 g/cm2 per 160s	0,30 g/cm2 per 160s	water absorption rate	0,17 g/cm2 per 160s	0,20 g/cm2 per 160s	0,32 g/cm2 per 160s
bio receptivity ☆	-	2/5	3/5	bio receptivity ☆	5/5	-	-

figure 64: Comparison of all the porosity, water absorption rate and bioreceptivity betweent the examined lime-based mortars based on (B.Lubelli et al, 2020)

Based on these, in this research a binder to aggregate ratio of 1/4 is used and vermiculite is added. The effect of the grain size distribution and the type of binder on the water transport behavior of the mortar and, subsequently, on its bioreceptivity is investigated (figure 65).

As binders:

Natural Hydraulic lime

Hydrated lime with trass

Ratio of hydrated hydrated lime/trass = 1/1 (in volume)

As Aggregates:

Vermiculite with fine sand grain (0.08-1mm)

Vermiculite with coarse sand grain (1-2mm)

Ratio of vermiculite/sand = 1/1 (in volume)

Ratio between binders and aggregates:

Binder/Aggregate = 1/4 (in volume)

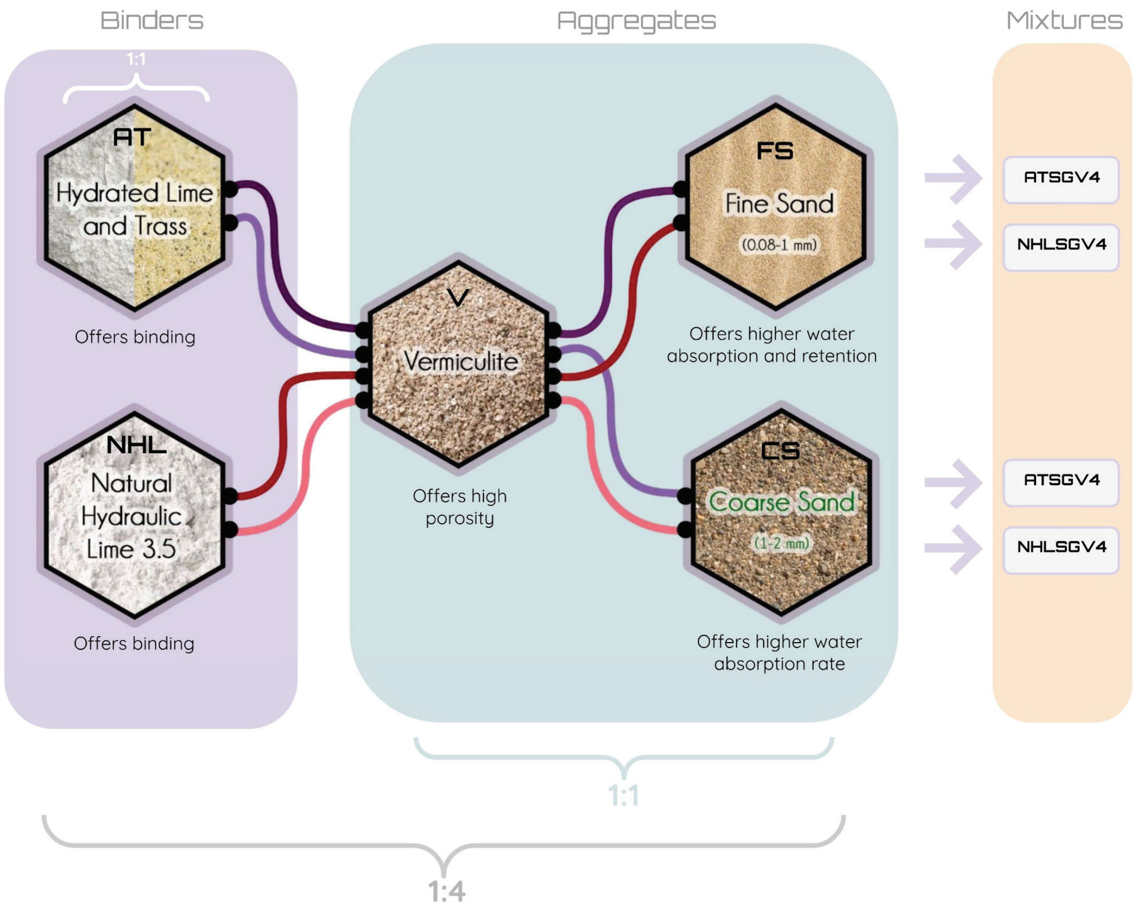


figure 65: Final mortars compositions and their titles. (own source)

5. Material Study

5.7 Choice of living organism for experiment

The work by Lubelli et al 2020 examined two vascular plants (with roots) and more specifically Cymbalaria muralis and Pseudofumaria lutea. However, vascular plants have high requirements in terms of nutrients and photosynthesis, which makes it more difficult for them to survive. Differently, mosses (non-vascular) can withstand harsh weather conditions and require less nutrients and indirect sunlight.

Therefore in this research the bioreceptivity of the above mentioned mortars for moss growth is investigated. One of the most common moss species is Tortura muralis. This moss type is usually detected on base-rich substrates like concrete, limestone etc (Fletcher, 1995), therefore it can be expected to be able to grow on the mortar selected in this research.

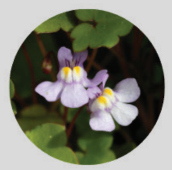
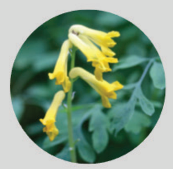
Cymbalaria muralis	Pseudofumaria lutea	Tortula Muralis	
Light, medium and heavy soils	Light, medium soils	Do not necessarily need soil as a substrate.	✓
Mildly acid, neutral and basic (mildly alkaline) soils	Mildly acid, neutral and basic (mildly alkaline) soils	Base-rich substrate, like limestone, concrete, bricks. (Fletcher, 1995).	✓
pH: 3-11	pH: 3-11	pH:7-14	✓
Semi-shade, no shade	Semi-shade	Semi-shade, Light shade	✓
Moist substrates	Moist substrates	Moist substrates	✓
			

figure 66: Comparison between cymbalaria muralis, pseudofumaria lubea and tortura muralis. (own source)

5.8 Experiment set up

5.8.1 Mixing

Two different binders were used in order to create hydraulic mortars, hydrated lime (Supercalco 90) with trass and natural hydraulic lime (Saint Astier NHL 3,5). As far as the aggregates are concerned, quartz sand (CEN Standard Sand 196-1) in combination with vermiculite (Voorzaaivermiculiet, Agra F2, Makkelijke Moestuin) were used in all mixtures in a ratio 1:1 (in volume). Sand was sieved in order to separate fine (0.08-1mm) from more coarse sand grains (1-2mm). Each binder was mixed either with fine or coarse sand grains, in a ratio b/a=1/4. Therefore four different mortars were made, as seen in the figure below. Mortars were blended using a laboratory mixer and water was added until the mortar reached a paste-like consistency. The exact quantities are listed in the table below.

figure 67: Preparation of mortars. (own source)

Materials	Weight per 500mL (gr)	ATsgv4 (gr)	ATbgv4 (gr)	NHLsgv4 (gr)	NHLbgv4 (gr)
NHL 3.5	345,1			172,55	172,55
Hydrated Lime	375,5	93,88	93,88		
Trass	391,8	97,95	97,95		
Fine Sand (0.08-1mm)	832,4	832,40		832,4	
Coarse Sand (1-2mm)	794,4		794,4		794,4
Vermiculite	67,8	67,80	67,80	67,8	67,8
Water	500	360	360	360	360

figure 68: Materials weights before the experiment. (own source)

5.8.2 Flow test

Then, a manual flow table apparatus was used to measure the workability of the mortars. The steps that were followed were in accordance with *"Methods of Test for Mortar for Masonry (EN 1015)"* and are listed below, in short.

1. Filling the cone in two layers, compacting each with 10 strokes.
2. Lifting and jolting table for 15 times.
3. Measuring diameter in two directions.
4. Recording results.

All of the mortars' consistencies were similar, reaching a diameter of approximately 17cm in each direction at the end of the flow test.

		ATsgv4	ATbgv4	NHLsgv4	NHLbgv4
Workability (cm)	Workability (cm)	17,1	17	16,9	17,1

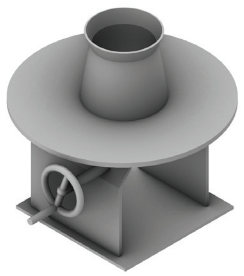


figure 69: Workability test and tabulation. (own source)

5.8.3 Casting

Soft mud moulded bricks (Wienerberger Terca Heteren- Avenue Rood Naturel Onbezand strengpers WF) were used as substrates for the mortars' casting.

The bricks were submerged in water for 5 minutes prior to casting of the mortar. A polystyrene mold was put around each brick exceeding its height by 2 cm. When the mortars were casted two additional polystyrene boards were placed in them so each specimen was divided in three similar pieces. Each mortar was casted on two bricks, resulting in 6 pieces per type of mortar.

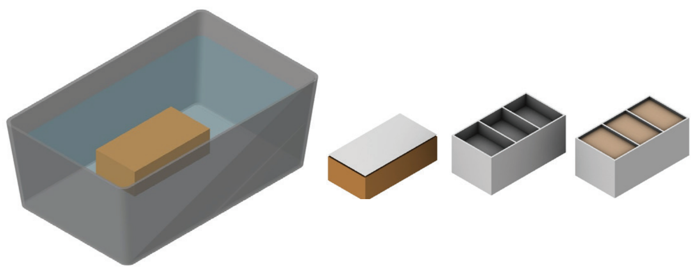


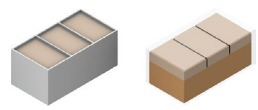
figure 70: Preparation and casting. (own source)

5.8.4 Curing

The curing of the mortars is an essential process that needs to occur under specific conditions so they harden properly. In order to make this certain, the curing process was based on NEN-EN 1015-18. In our case, hydraulic binders were used and hence the instructions underlined in the table below were followed. Along these lines, all specimens were covered with plastic foil in order to keep them moist and ensure that RH is 95%+. After 2 days, the mortars were demolded and kept inside the plastic foil for 5 more days.

Type of mortar	Curing time at a temperature of 20 °C ± 2 °C in days		
	95 % ± 5 % RH (relative humidity)		65 % ± 5 % RH
	in the mould[a)]	with the mould removed	with the mould removed
Lime mortars	5	2	21
Lime/cement mortars in which the amount of lime is greater than 50 % of the total binder weight	5	2	21
Cement and other lime/ cement mortar	2	5	21
Mortars with other hydraulic binders	2	5	21
Retarded mortars	5	2	21

[a)] In some cases an extended period of storage in the mould may be necessary.



figures 71: (up) Conditions for mortars' curing (NEN-EN 1015-18, 2003) *(down) Mortars' curing.* (own source)

In order to create an environment with stable RH, salt was dissolved in water based on the fact that the equilibrium RH of NaCl at 20 °C is 75% (https://mdcs.monumentenkennis.nl/wiki/page/18/equilibrium-rh-of-salts), which is close to the desired one. The dissolved salt was put inside a plastic box for 3 days until RH was stable. The specimens were then put inside the box on perforated trays and the box was sealed. RH was monitored by a RH-sensor (DHT11 Arduino) daily and the values were recorded for 21 days. The specimens were then removed from the box and weighed daily until their weight remained stable in order to certify that there is no water content in them.

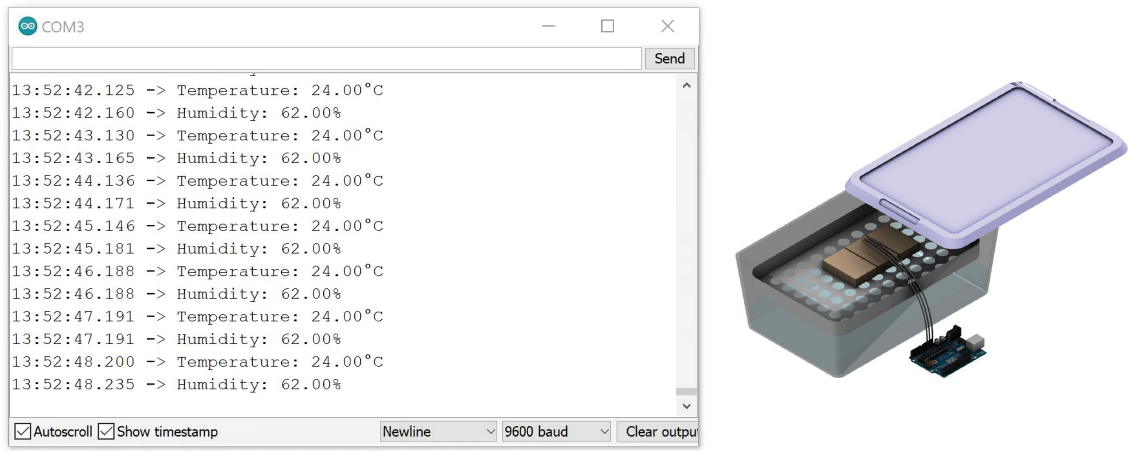


figure 72: Left: Arduino sensor indicating R.H. and Temperature. Right: Curing and sensor's set up (own source)

5.9 Test methods

The following experiments are crucial for this research because they have a dual target. Firstly, they test if moss is compatible with lime-based mortars. Secondly, they examine if water transport behavior can influence moss growth in a small period of time. All specimens which were tested in experiments 5.91-5.9.3 were sealed on their lateral and bottom sides, using a waterproof coating (Mapegum WPS) and a waterproof utility duct tape (Tesa Duct Tape). The following experiments have been conducted on the mortar specimens, in the following order.

1. Water absorption rate
2. Water absorption capacity
3. Water evaporation rate
4. Moss growth

specimens	width (cm)	length (cm)	height (cm)	area (cm^2)	volume (cm^3)	dry weight (gr)	dry weight after coating (gr)
NHLBGV4							
1a						190,20	
1b	7,10	9,30	2,10	66,03	138,66	148,33	162,74
1c	7,20	10,50	2,10	75,60	158,76	176,10	192,28
2a						94,02	
2b						117,85	
2c	6,80	9,80	1,80	66,64	119,95	132,65	140,52
NHLsgv4							
1a						156,43	
1b						145,64	
1c						99,97	
2a	7,00	10,00	2,40	70,00	168,00	178,93	196,19
2b	6,80	10,00	2,10	68,00	142,80	171,49	180,12
2c	7,00	10,00	2,40	70,00	168,00	170,03	179,02
ATBGV4							
1a	7,30	10,10	2,20	73,73	162,21	204,88	220,51
1b	6,80	10,00	2,10	68,00	142,80	172,51	188,13
1c	6,50	10,00	2,00	65,00	130,00	144,07	163,85
2a						117,65	
2b						117,85	
2c						135,74	
ATSGV4							
1a						188,61	
1b						109,92	
1c						117,72	
2a	7,10	10,00	2,30	71,00	163,30	178,56	186,23
2b	6,60	10,10	2,00	66,66	133,32	169,78	177,21
2c	7,00	10,00	2,00	70,00	140,00	167,17	175,04
specimens selected for water transport behavior experiments							
specimens selected for bioreceptivity experiments							

figure 73: Size and dry weight of specimens. (own source)

5.9.1 Water absorption rate

Water absorption rate experiment indicates how fast the specimens absorb water.

Inside a water tank, a 2cm thick grid support is placed. The tank is then filled with water up to 2,3cm and a water bottle is placed upside-down in order to maintain the water level stable. All specimens are put on the grid and their bottom surface is immersed in water to a depth of 3mm. All of them are weighted every 1,3,5,10,15,30,60,480 and 1440 minutes based on NEN-1925. When the specimens are removed from the water they are lightly dried with a damp cloth so all droplets are removed and then weighed.

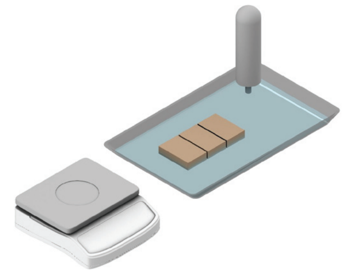


figure 74: Water absorption rate experiment set up. (own source)

5.9.2 Water absorption capacity

Water absorption capacity experiment indicates the amount of water that can be absorbed by the specimens. Specimens are immersed in water for 24 hours and then they are weighted under atmospheric pressure. However, due to the lack of equipment the specimens were not weighed hydrostatically but by using a regular scale of high precision. This is still adequate for making comparisons between specimens, but the total porosity cannot be estimated.

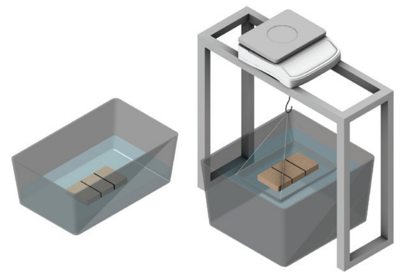


figure 75: Water absorption capacity experiment set up. (own source)

5.9.3 Water evaporation rate

Water evaporation rate indicates how fast water evaporates through the upper surface of the specimens (their lateral and bottom surfaces are sealed using a waterproof coating (Mapegum WPS) and a waterproof utility duct tape (Tesa Duct Tape) accordingly). All specimens are weighted every 4 hours daily during the first week and then once per week.

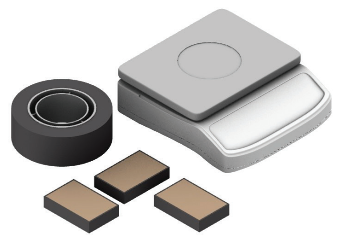


figure 76: Water evaporation rate experiment set up. (own source)

5.9.4 Moss growth

The first step of this experiment is the collection of Tortula Muralis from the northwestern masonry façade of the faculty of architecture & the built Environment at TU Delft. All the collected mosses were dried so they can be pulverized (using a food pestle set) until they turn into moss powder. Then, mortars' top surfaces are sprayed with a mixture of distilled water and sodium alginate (Special Ingridients – European Origin). This creates an adhesive paste which ensures that the moss powder will not detach from the specimens. Then, the moss powder is applied on the mortars covering the entire top surface. The specimens are then put in a horizontal position next to a window in order to receive indirect sunlight. Specimens are sprayed with water for 2 minutes once per week.

figure 77: Water evaporation rate experiment set up. (own source)

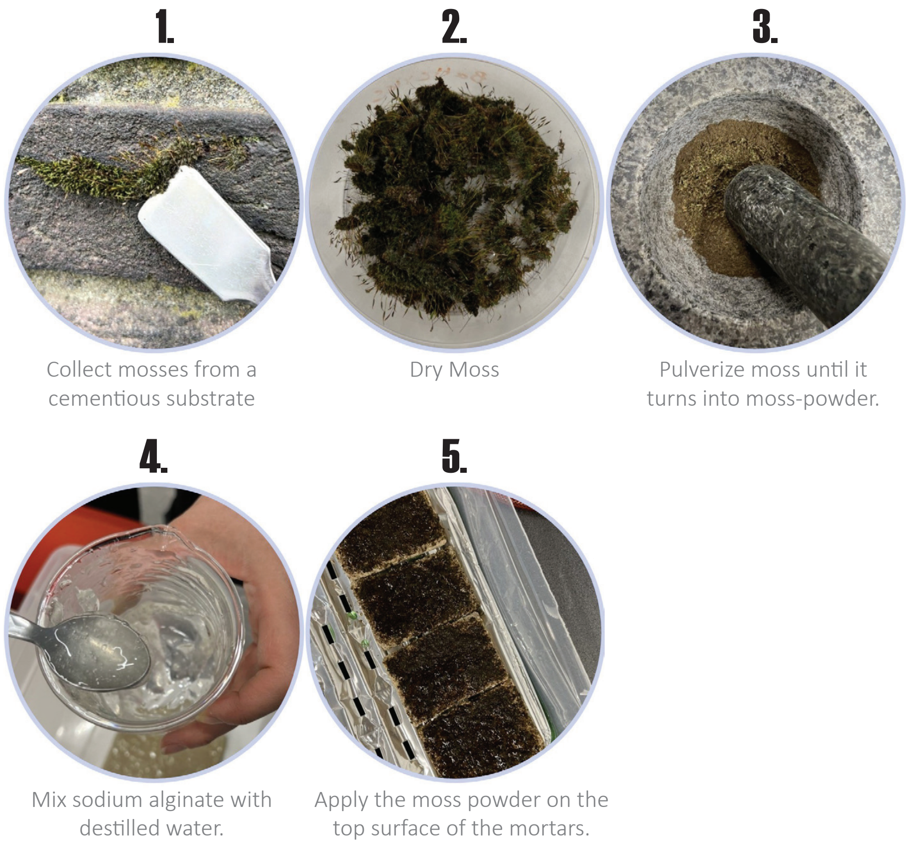


figure 78: Steps for moss growth experiment. (own source)

5.10 Results and final choice

5.10.1 Water absorption rate

Figure 78 shows that the main factor which influences mortars' water absorption rate is their grain size distribution. Mortars with coarser grain size have a faster water absorption rate. This is in accordance with the literature and we can assume that in the mortars with coarser aggregate, larger pores are created and vice versa. The type of the binder used does not significantly affect the water absorption rate. For the detailed record of all specimens' weight see Appendix .

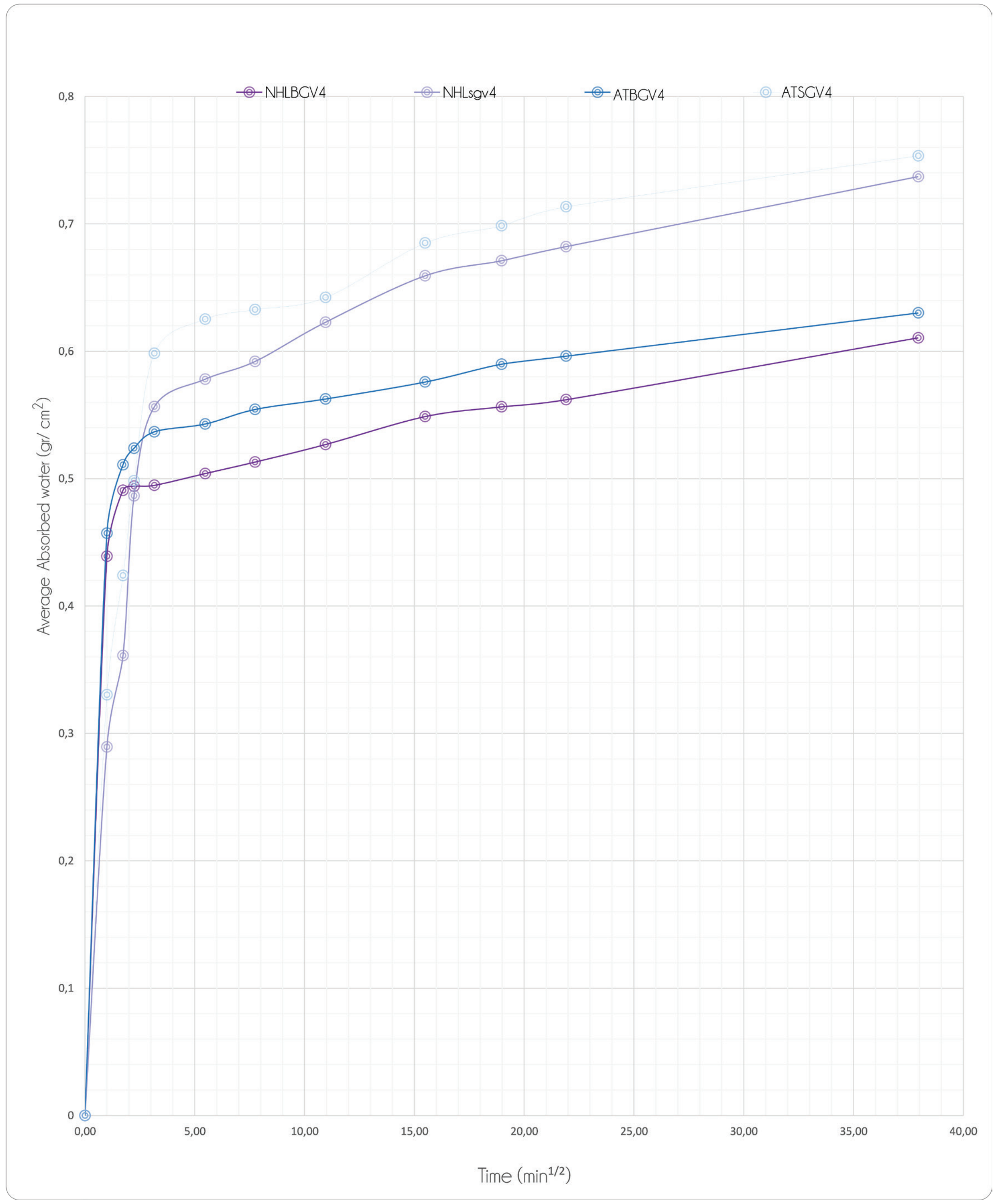


figure 78: Water absorption rate experiment results. (own source)

5.10.2 Water absorption capacity

Figure 79 indicates specimens' percentage weight gain after being immersed in water for 24 hours so they are fully saturated. Firstly, all specimens' weight gain percentage is ranged between 24,9-33,6% . This verifies that all the specimens have the capability of absorbing a considerable amount of water. This is due to the high open porosity of the mortars. The presence of highly porous vermiculite probably contributes to their overall open porosity. Another conclusion that could be made by observing all specimens' weight percentage is that the type of binder does not have any substantial impact on the water absorption capacity. Mortars made of vermiculite and fine sand grains (0,08-1mm) had the highest percentage of weight gain due to the water's absorption. The specimens with coarser grain size aggregates show a lower percentage of weight gain. This might be due to the presence of very coarse pores (not capillary active) which cannot retain water.

	dry weight (gr)	weight after 24hours in water (gr)	% weight gain
NHLBGV4			
1b	162,74	204,49	26%
1c	192,28	240,67	25,2%
2c	140,52	175,57	24,9%
	average % weight gain		25,3%
NHLsgv4			
2a	196,19	252,47	28,7%
2b	180,12	240,65	33,6%
2c	179,02	239,09	33,6%
	average % weight gain		31,9%
ATBGV4			
1a	220,51	275,61	25,0%
1b	188,13	235,42	25,1%
1c	163,85	205,8	25,6%
	average % weight gain		25,2%
ATSGV4			
2a	186,23	246,95	32,6%
2b	177,21	235,12	32,7%
2c	175,04	233,89	33,6%
	average % weight gain		33,0%

figure 79: Percentage of weight gain due to the water absorption. (own source)

5.10.3 Water evaporation rate

Figure 80 indicates the percentage of weight loss due to water evaporation. The results show that the grain size distribution affects specimens' drying. Specimens with larger aggregates evaporate water faster in comparison to the specimens with smaller aggregates. However, the differences in water retention between specimens is minor: the average percentage of weight loss is quite similar between specimens during the first 3 weeks, ranging from 21,8-24,8%. For the detailed record of all specimens' weight see Appendix x.

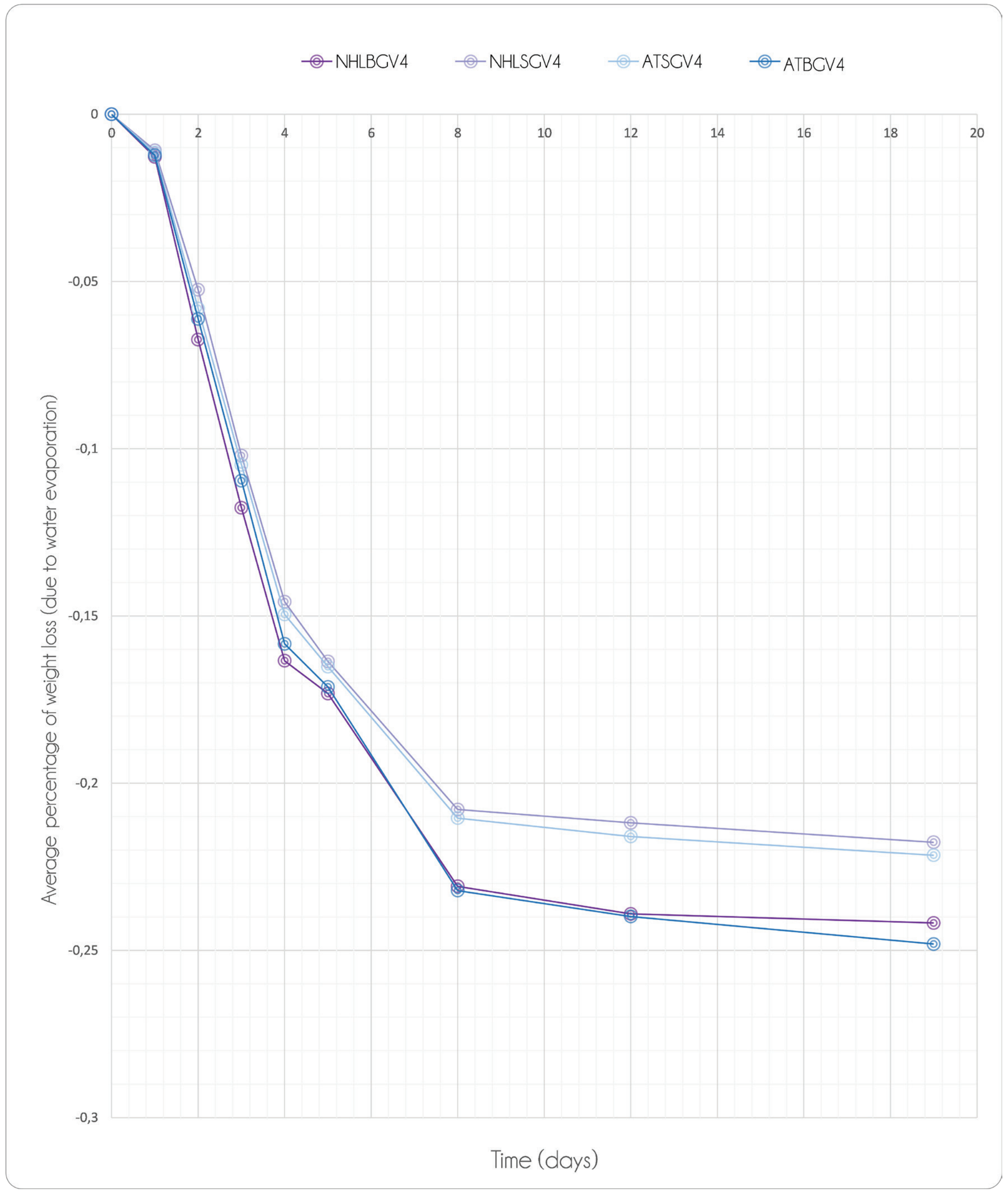


figure 80: Water evaporation rate experiment results. (own source)

5.10.4 Moss growth experiment

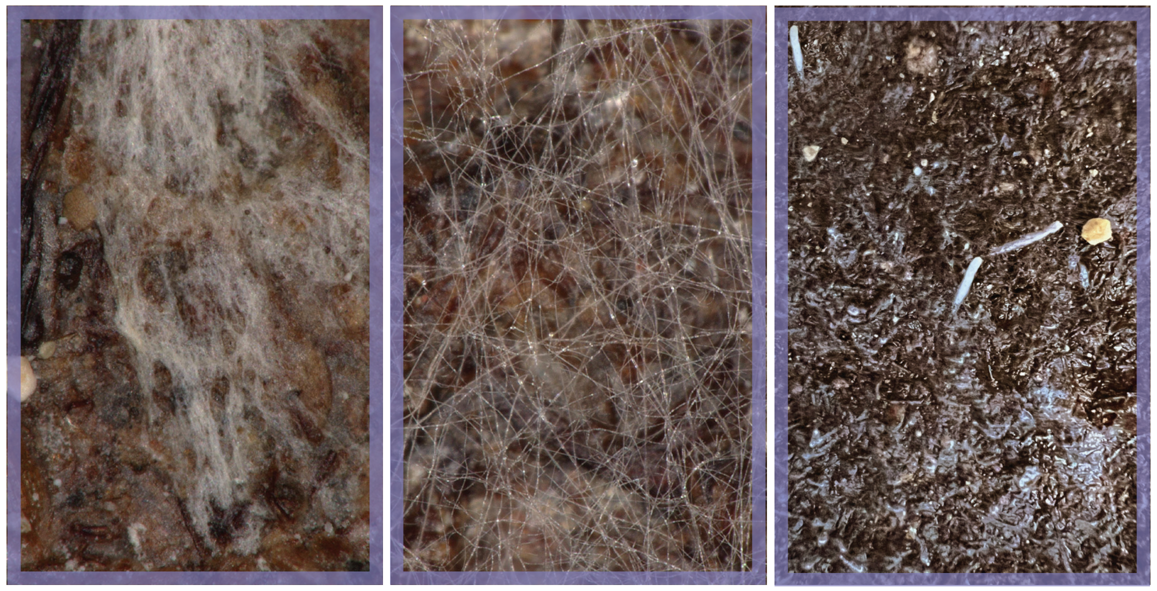
The moss growth experiment is the most challenging because it requires a considerable amount of time (estimated time for moss growth is 18-20 weeks) and specific conditions for its growth (favorable conditions are: relative humidity>75%, temperature=15 °C and indirect sunlight). On the top of that, it is really difficult to evaluate moss growth visually.

Based on the literature, the highest potential regarding bioreceptivity is most likely found in mortars with high water capacity in combination with high water retention and, in our case, between NHLSGV and ATSGV4. Additionally, according to the experiments conducted by (B.Lubelli et al., 2020), the mortars based on natural hydraulic lime had a better bioreceptivity performance than the ones based on hydrated lime and truss. Thus, it could be assumed that NHLSGV4 will have the best bioreceptivity performance.

It is remarkable to mention that during the 7 weeks of the experiment, the results meet this hypothesis. NHLSGV4, a mortar specimen based on natural hydraulic lime with the highest water absorption capacity and the highest water retention had some signs of biological growth. Undoubtedly, these factors encouraged its biocolonization since they contributed to the creation of a moist environment with nutrient availability.

More specifically, on NHLSGV4 (composed of thin grains of sand (0.08-1mm), vermiculite and natural hydraulic lime) signs of fungi growth (figure 81: a,b) have appeared in the fifth week and some small "stems" during the seventh week, which could be grass or some kind of fungi. (figure 81: c). This phenomenon is known as symbiosis, a biological interaction between two or more living organisms, when they coexist and all of them benefit from the high uptake of nutrients. *This phenomenon is the early colonizing phase by the spores and fungi before moss appears.* (K.F.Mustafa, 2020)

Even if it is unclear whether mosses are successfully growing during the first seven weeks, biological growth is evident only on NHLSGV4 and therefore it could be considered as bioreceptive. However, it is not clear if it fulfils the requirements for moss growth regarding pH, water retention, water absorption capacity etc. and to what extent its water transport behavior can influence bioreceptivity.



figures 81: (a), (b), (c) Fungi growth (a), (b) and "stems" (c) spotted on NHLSGV4. (own source)

5. Material Study

figure 82: Visual observation of the mortars every 2 weeks. (own source)

6. Bioreceptivity-oriented design

figure 83:
Concrete Printing at the Digital Construction Lab at Swinburne University of Technology.
(arunothayan, 2020)

6.1 Methodology

6.1 Methodology

Bioreceptivity is not yet integrated in the architectural design mainly because it was mistakenly equated with biodeterioration. In fact, more effort was put into the façade design and material development in order to prevent biological growth from building elements aiming an "aesthetic cleanliness". However, contemporary design of culture and aesthetics highlights the significance of bioreceptive design and questions architects and engineers about how and where buildings could be biocolonized. (Marco Cruz and Richard Beckett, 2016) In order to implement this natural phenomenon in the building industry more efficiently, new tactics should be engineered and lay the foundation for innovation. The present chapter deals with developing rational concepts of combining the topology and material studies in one design approach that would encourage bioreceptivity in a controllable way.
More specifically, moss has been chosen to be the main focus of the research for the reasons mentioned in 5.6. As it became evident from the literature review, shadow and moisture support its growth and propagation, and hence these two principles will be the main guidelines for the following design proposals. Shadow is achieved through topological manipulations, whereas a high moisture content is achieved and maintained through the use of a porous lime-based mortar capable of retaining its water content for a considerable period of time.
Moreover, two main preliminary design approaches will be examined and evaluated through a research-by-design approach in order to prototype a final design choice. Along these lines, the potential of bioreceptive materials arise and a new architectural vocabulary is being expressed.

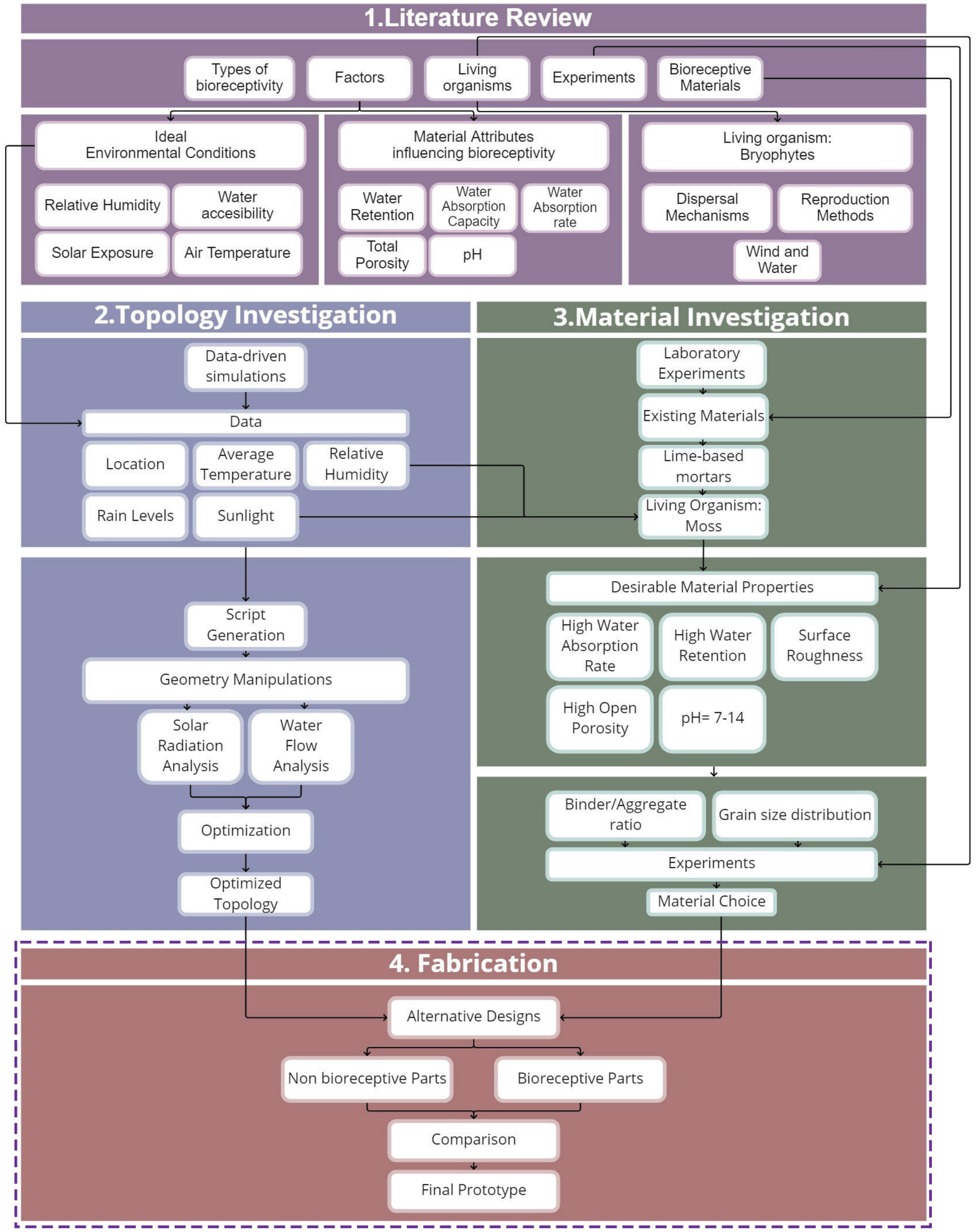


figure 84: Fabrication in relation to the other chapters of the thesis. (own source)

6.2 Design Approaches

Using as the base of the following design proposals, the most optimized topology generated in 4.5.1., offering the most optimal shaded conditions for mosses' growth, in combination with the mortar selected to be the most promising in 5.9, thanks to its properties (high water absorbing capacity and retention), two design concepts will be generated. Unfortunately, due to the limited timeframe of this thesis, the influence of the design in the bioreceptivity performance cannot be verified. Despite this, the present chapter demonstrates a tangible method of combining the aforementioned strategies in one bioreceptive wall, but also acts as a source of inspiration for future studies and experiments. The size of the wall which is used as a reference for the design conceptualization is 2,5 x 2,5 x 0,3 meters. Even though the size of the bioreceptive parts that will be integrated in the walls is arbitrary due to the scarcity of existing bioreceptivity-oriented designs, their values fluctuate between a minimum and a maximum rate. This rate is defined by the evaluation method which depends on the solar radiation analysis engineered in chapter 4. This is explained explicitly in each design proposal.

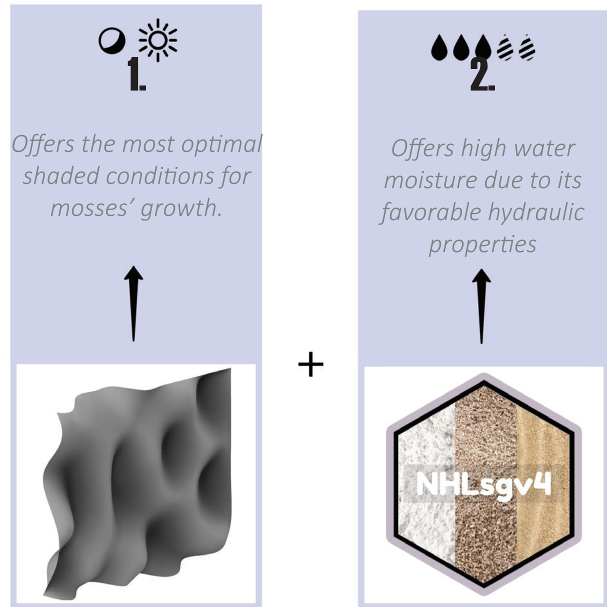


figure 85: The basis of the design proposals. (own source)

Software and material/s used for prototyping

Additive manufacturing is used for the production of the final prototypes, because it is an effective technique for producing large-scale customized components. (see 4.8) Furthermore, its availability at L.A.M.A. supports the exploration of its potential. The 3d-printer that is used for prototyping is Anycubic Mega S and the extruded material is a white PLA filament. The software used for modeling is Rhinoceros 7 and for slicing SIMPLIFY3D 4.1.

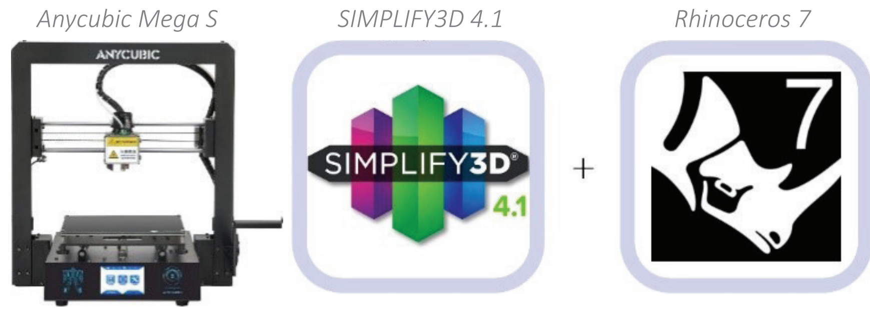


figure 86: 3-d printer and software used for modeling and fabrication.
(anycubic.com, n.d.), (simplify3d.com, n.d.), (rhino3d.com, n.d.)

The selected mortar cannot be extruded because it hardens very slowly (see chapter 5) and therefore three alternative designs will be developed in order to achieve the desirable topology. The first one uses 3d printing in order to create a complex mold and cast the material. The second proposal uses 3d-printing to create a perforated element which can cast the mortar. The last approach uses 3d-printing to create a substructure with cavities on which the mortar is poured.

According to the experiment of (B.Lubelli et al, 2020) the bioreceptive mortars that were tested, which are very similar in composition with the mortars of this research, had very low mechanical performances and could only be used as pointing mortars. As such, the main focus of the methodology lies on the attempt to integrate bioreceptive mortars in 3d-printed building elements which can offer to them structural support. The following preliminary designs do not emphasize on the material selection of the non-bioreceptive parts but on mortars' overall integration in the design. Before selecting the most realistic and efficient design approach, several small prototypes will be fabricated in order to evaluate the ease and the potential of their feasibility.

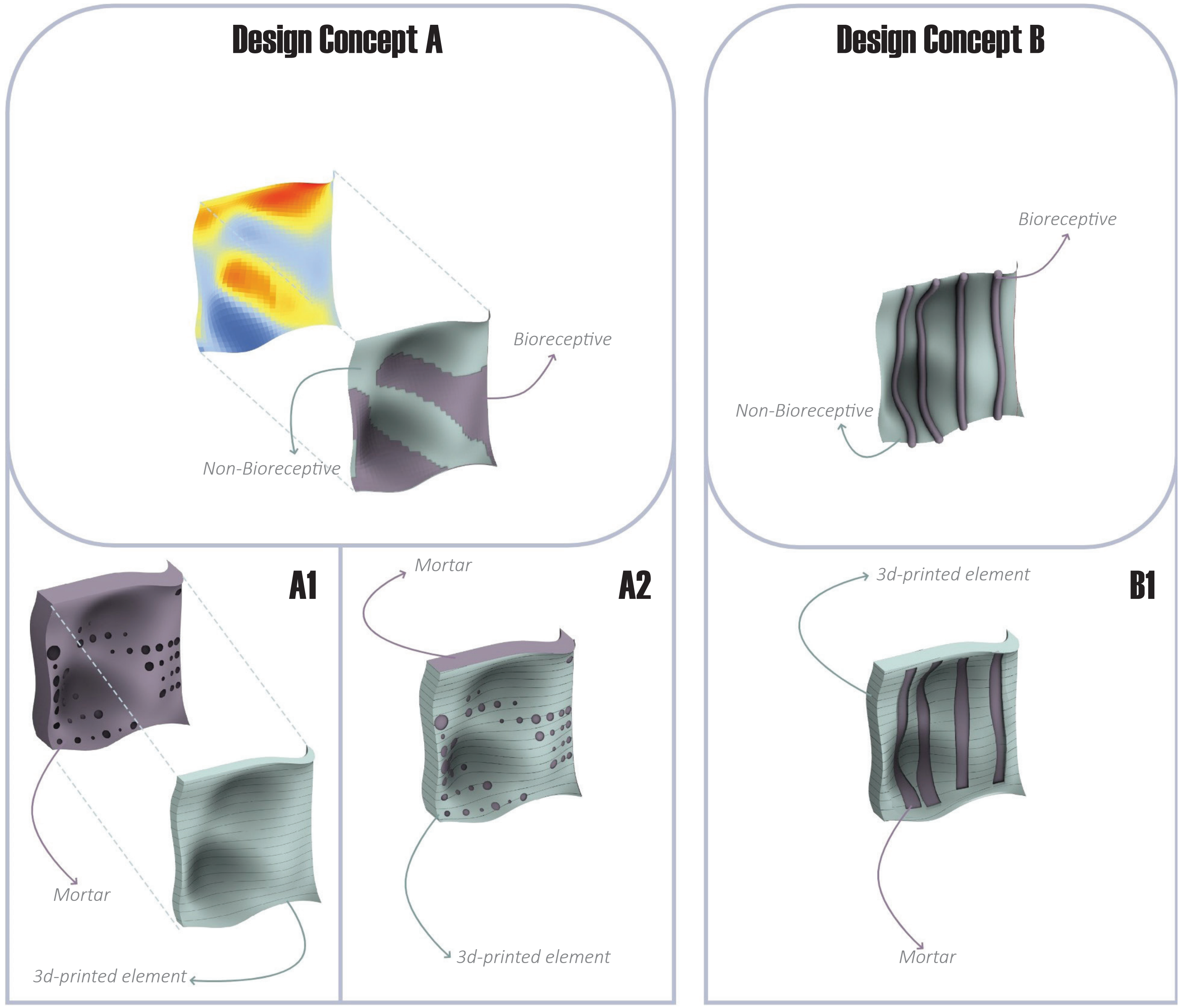


figure 87: Proposed design approaches and concepts. (own source)

6.3 Preliminary concepts

6.3.1 Design approach A

The first design proposal seeks to accommodate moss in targeted parts of a geometry by taking inspiration from the tree bark structure where they are often found. On the optimized surface, the areas with small solar exposure levels are located and small convex spaces are created in order to be colonized by mosses in the long term. The selected mortar, which is prone to bioreceptivity will be used in these parts. Features that may appear over time in the material like fissures and depressions will facilitate primary bioreceptivity. The crater-like shape of these habitats is based on the bioreceptive facade prototype that was developed by Marco Cruz and Richard Becket within the framework of BiotA Lab, a research platform. (see 2.9.2) These concave spaces can act as capturing and scaffolding mechanisms for mosses' spores through their surface roughness and texture. They also offer protection from external conditions, such as wind and solar exposure. (M.Cruz et al, 2016) Finally, they add an aesthetic value to the wall design. As seen in the figure below, the central idea is that the wall design is divided in two distinctive parts; a bioreceptive and a non bioreceptive. The bioreceptive parts' size depends on their "evaluation" (see 4.4.3, step 9): the more shadow the bigger "crater".

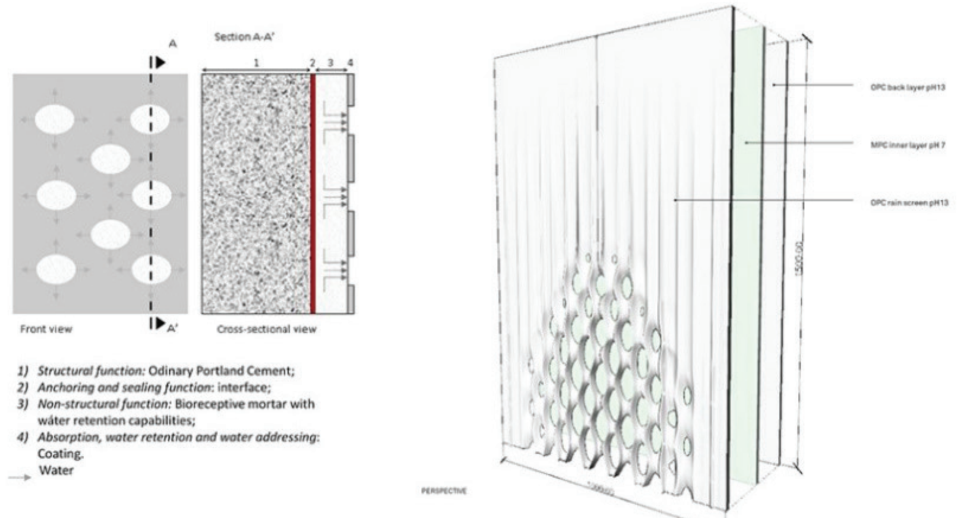


figure 88:Bioreceptive concept designed by R.Becket and M.Cruz. (M.Cruz and R.Beckett, 2016)

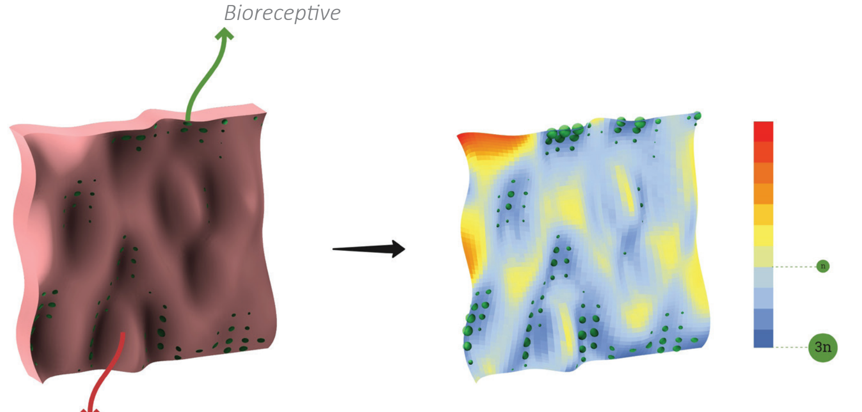


figure 89: Design approach A and its relation to solar radiation analysis (own source)

Preliminary design A1

The first preliminary design utilizes 3d printing technology for the production of a mold which later will be used for casting the material. A complex small piece (around 15x5x3cm) was 3d-printed in order to observe if the selected mortar could be used for elements' casting achieving a high level of detail. This piece was then joined with polystyrene boards in order to create a mold. The selected mortar was poured inside the mold and kept there for two days in order to cure, based on NEN-EN 1015-18. When the mortar was demolded it is noticed that it fails to reach a high resolution. None of the projecting hemispheres managed to be imprinted on the material. This is a combination of material's composition with the high complexity of the form, the tiny size of targeted imprints and the rough texture of the printable filament which has as a result the sticking of the mortar to it. Therefore, it can be concluded that the chosen mortar cannot be demolded and reach the desirable level of detail. What is more, there is a high level of uncertainty mosses might grow on parts of the geometry that are undesirable. This is because the same material is used for the whole design. It can be avoided by making the "non-bioreceptive" part smooth so mosses cannot be anchored or by applying a hydrophobic coating on the parts of the geometry that bioreceptivity needs to be avoided. However in the second case, there is a big possibility that the hydrophobic coating will affect the bioreceptive habitats. Finally, the mortar-based material has a very low structural performance and cannot be used as a building element. These first conclusions led to the creation of composite wall proposals composed of two materials: the mortar and a material with a higher mechanical performance.

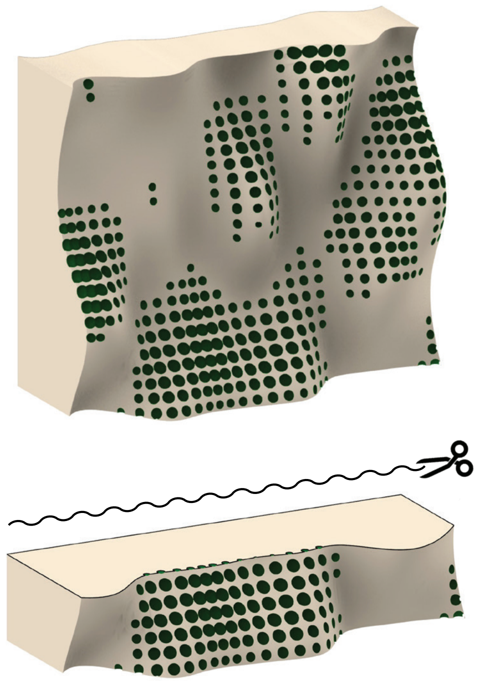


figure 91: Mold prototype for experiment. (own source)

figure 90: Preliminary design A1 and section. (own source)

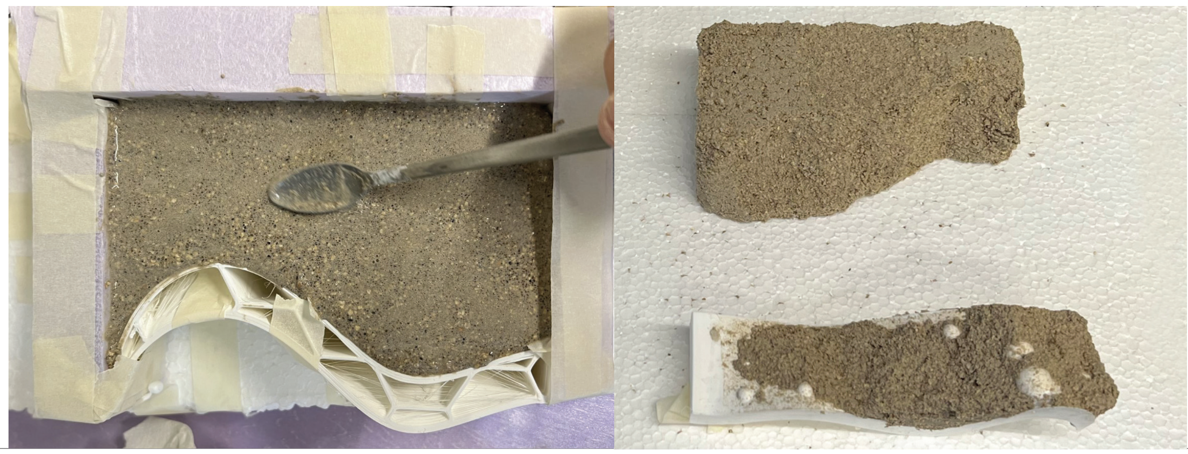


figure 92: Molding and demolding experiment . (own source)

Preliminary design A2

The second approach is also based on the aforementioned prototype which was fabricated by Marco Cruz and Richard Becket. As seen in figure 95, the bioreceptive material is placed behind a perforated surface. The perforated surface is 3d-printed using a non-bioreceptive material. In this sense, the material is protected by an outer shell, while the water is directed towards these perforations in order to provide the bioreceptive material with water content and nutrients. Following the same principle, a small prototype (around 15x5x5cm) was printed and then filled with the mortar. In terms of feasibility, the present approach is more realistic. However, the fact that the material is placed behind the outer shell does not let it perform its full potential because weathering is a beneficial condition for primary bioreceptivity, according to the literature. Additionally, only a very limited part of the bioreceptive material which is exposed through the holes can absorb water. In a nutshell, the final product is a composite wall that consists of two materials: a bioreceptive mortar and a non bioreceptive material.

Based on the existing materials that are used in the additive manufacturing, a potential non-bioreceptive extrudable material that could be used for this purpose is a mixture of recycled plastic waste and other types of biomaterials that are being used in the last decade for creating mainly outdoor furniture and temporary structures. Extrudable concrete cannot easily be used in this case because the perforated part is challenging to be achieved. In any case, the compatibility (such as adhesivity and shrinkage) between the two materials should be taken into account.

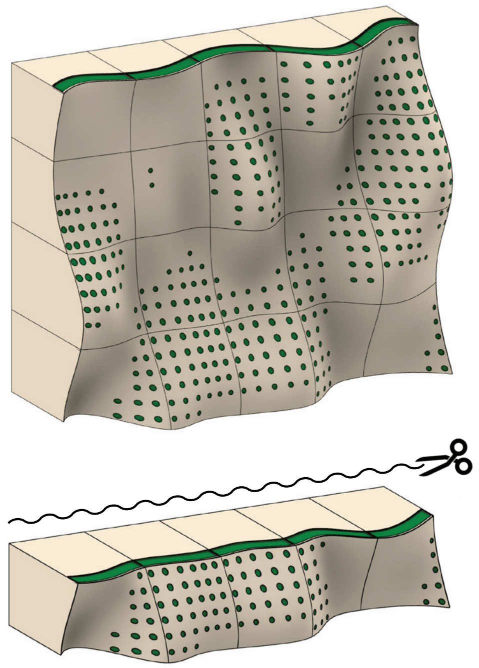


figure 94: Mold prototype for experiment. (own source)

figure 93: Preliminary design A2 and section. (own source)

figure 95: Casting material prototype. (own source)

6.3.2 Design Approach B | Preliminary design B1

The final design approach takes into account the main water flows streams on a surface, as a design guideline. By running the simplified water flow analysis (see chapter 5), with a defined resolution, the main water channels are created. These paths indicate where the bioreceptive mortar needs to be placed so it is accessible by water. By this order, cavities are created so then mortar can be poured inside. With the aim of fully exploring the potential of the data manipulation (regarding the solar radiation values) the size of the cavities is changing according to the solar exposure values. For instance, the cavities are wider where there is more self-shading because these can potentially host larger quantities of living organisms which prefer indirect sunlight, like bryophytes. Once again, the final building element is a composite wall which is composed by two materials: a bioreceptive mortar and a non-bioreceptive material. Firstly, the non-bioreceptive part is 3d-printed and the bioreceptive mortar is poured inside the cavities. Additive manufacturing is a field which still evolves, targeting in the development of more eco-friendly materials. However, based on materials which are used today, concrete is a potential material that could support this design approach. This is because it is not bioreceptive and it can already achieve the desirable design via 3d-printing. On top of that it is taken as a granted, that concrete has a good compatibility with lime-based mortars.

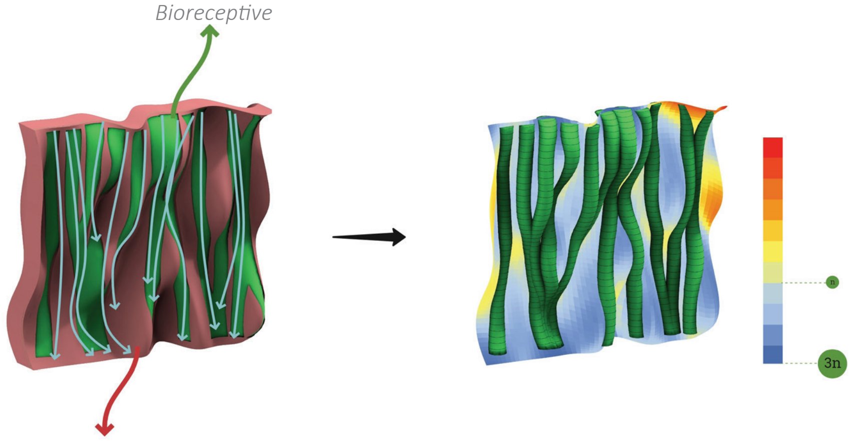


figure 96: Design approach B and its relation to water flow and solar radiation analysis (own source)

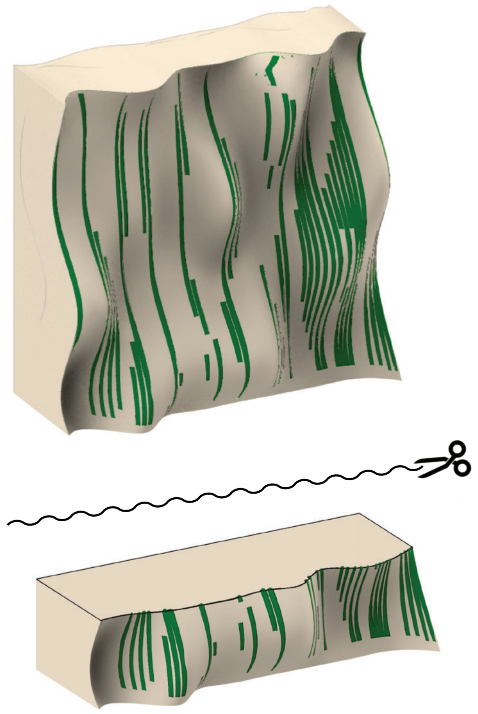


figure 97: Preliminary design B1 and section. (own source)

figure 98: : Casting the material inside the cavities (1:3 prototype) (own source)

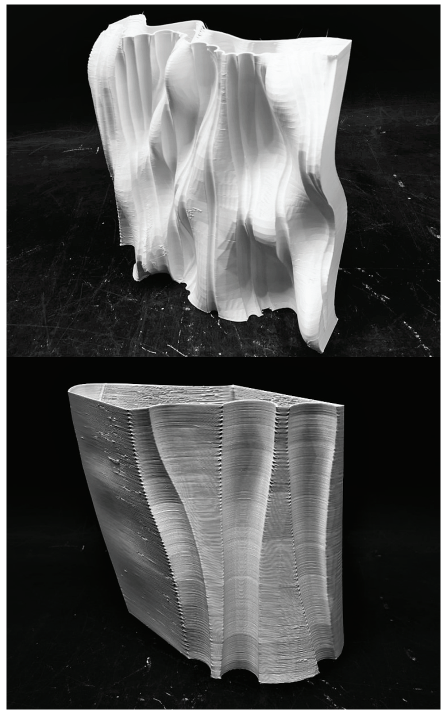


figure 99: Prototypes: scale 1:10 and 1:3 (own source)

6.4 Design Alternatives' Comparison

The following renderings were created in order to observe the architectural quality of the designs.

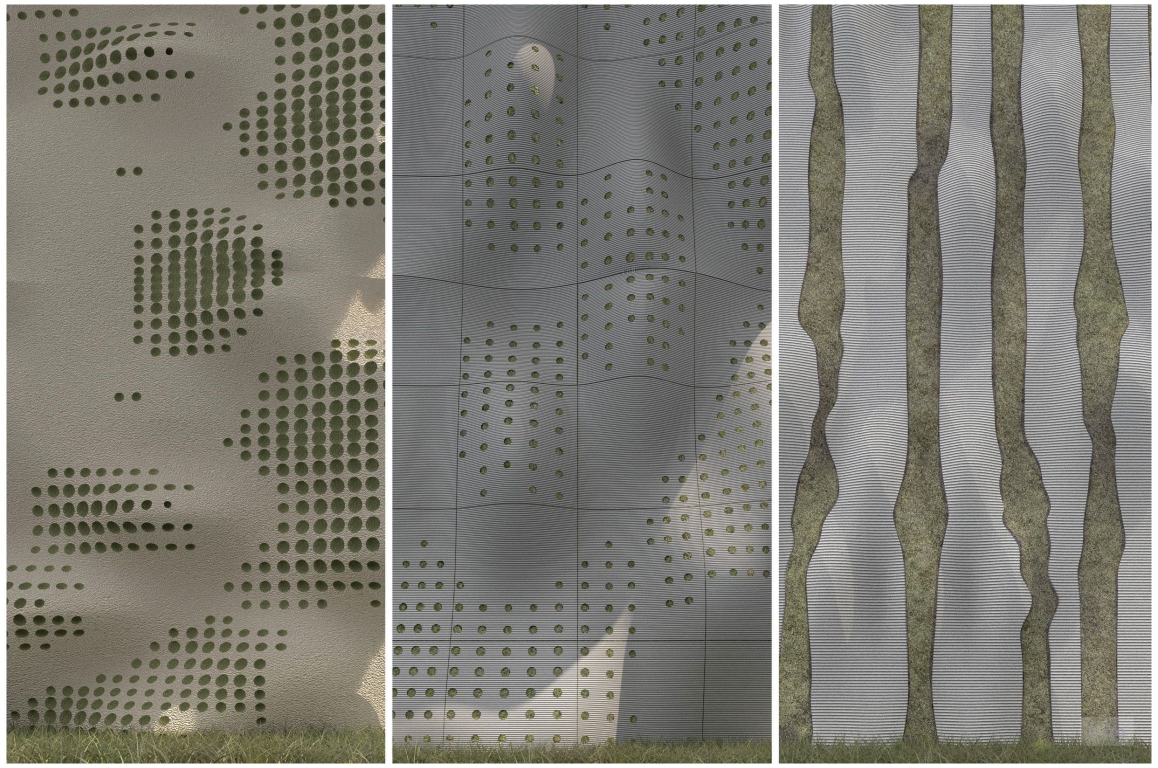
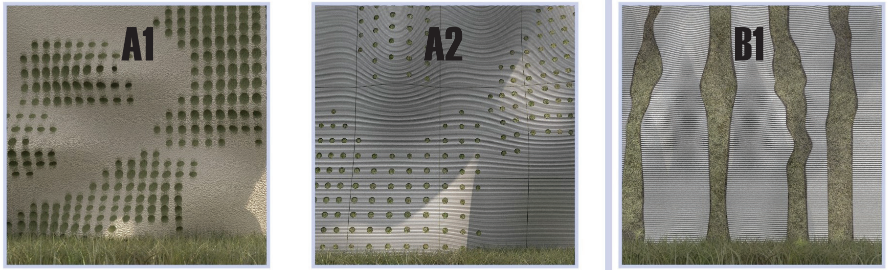


figure 100: Renderings of the three preliminary design approaches. (own source)

In order to choose between the three above-mentioned design proposals a comparison matrix is made, having as criteria the design complexity, feasibility, labor intensity, durability and time demand. The first and the last design approach are the most simple in terms of design complexity. The cavity in combination with the perforated external shell make the overall design of the second proposal much more complex. In respect of feasibility the first design proposal fails to obtain the desirable level of detail when the mortar is demolded and therefore it gets a low score. The second and the third ones are much more feasible and can reach a high level of detail through 3d-printing. In terms of labor intensity the first one is the most difficult to fabricate, especially on a bigger scale because the material needs to be molded and be cured for several days. In the other two proposals the mortar is simply poured inside the cavities of the non-bioreceptive 3d-printed elements so there is no need for demolding. In terms of durability, in the first approach the geometry is fully made of the bioreceptive mortar that was developed in chapter 4. By taking into account that the material is fully exposed and very brittle, we can suppose that it will be less durable when compared to the other two options, which protect the bioreceptive mortar inside the cavities. Finally, in terms of time demand the last design approach seems to be the most efficient in terms of fabrication, mainly because the non-bioreceptive part can be 3d-printed all at once ("in one go"), since the 3d-printing path is continuous. In the second approach there is a high time demands because the perforated part cannot be 3d-printed continuously and therefore it is the most challenging. The first approach is also quite time consuming because the molds need to be 3d-printed firstly and then the mortars need to be casted and cured. It is evident that the third design approach shows the highest potential within the present framework (design and material) and this was prototyped on a bigger scale in order to showcase its workflow and potential applications.



	A1	A2	B1
Design Complexity	5	2	4
Feasibility	1	3	5
Labor Intensity	2	3	3
Durability	1	4	4
Time Demand	1	3	3

figure 101: Comparison Matrix between design proposals. (own source)

6.5 Workflow and Applications

All the proposed design approaches have more or less potential for several architectural applications. Since the third one has more potential based on the comparison, it is selected to present how digital fabrication can transform computational data into physical objects by requesting inputs and producing outputs. The prototyping phase consists of four stages which require different technical expertise.

The first stage is addressed to the computational designer and the architect/designer because it is related to how bioreceptivity could be integrated efficiently in the design having an aesthetically pleasing value. In this project, the generative design begins having as a basis an optimized surface, which offers self-shading through its topology that was derived from an optimization process (see chapter 4). Then a simplified water flow analysis is conducted and in terms of design, the number of the cavities needs to be defined. In this step it is also essential to set the cross-section of the cavities and their size. The final design is then generated and it is put in the slicing software.

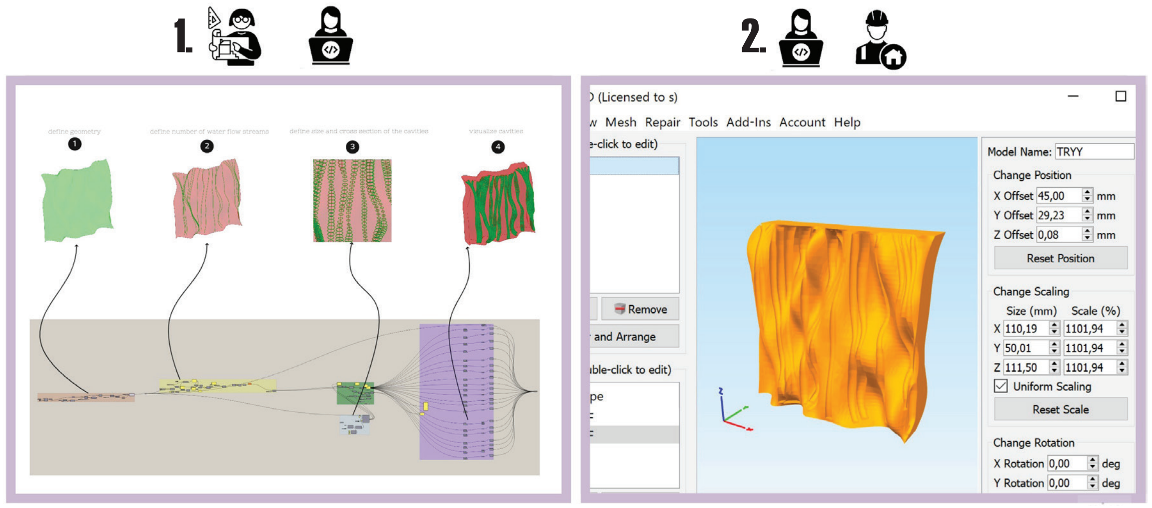


figure 102: Stage 1 and 2 of digital fabrication. (own source)

The second phase is addressed to the computational designer and the engineer in order to define multiple settings that are related to the material used and the targeted resolution, such as the height of the printed layers, the speed of printing etc.

The slicer then feeds with data the 3d-printer, which in turn prints the element. The final step deals with the placement and the curing of the bioreceptive mortar. This could be done manually or mechanically (using a mortar pouring device), depending on the scale of the project. In this order, it becomes clear how new technologies can become the extension of our ideas and offer an interaction between digital and physical space, introducing a new sphere of possibilities.

Finally, the design vision of this research is to engineer a green strategy which could support environmental sustainability by introducing bioreceptivity in the urban environment. Therefore, its applications would become more effective if it was implemented on a big scale and contributed to the creation of a green network by connecting facades, roofs, urban infrastructure and open spaces. The following renders provide an impression of how the following design could be applied in different scenarios.

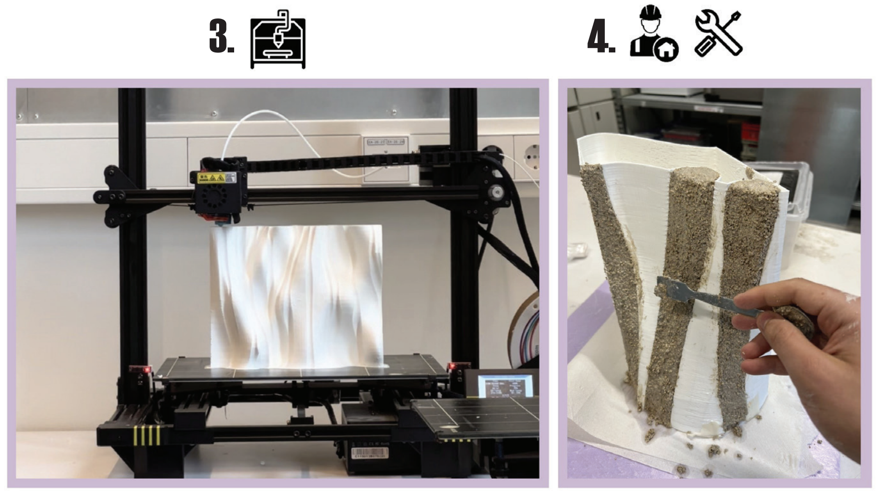


figure 103: Stage 3 and 4 of digital fabrication. (own source)

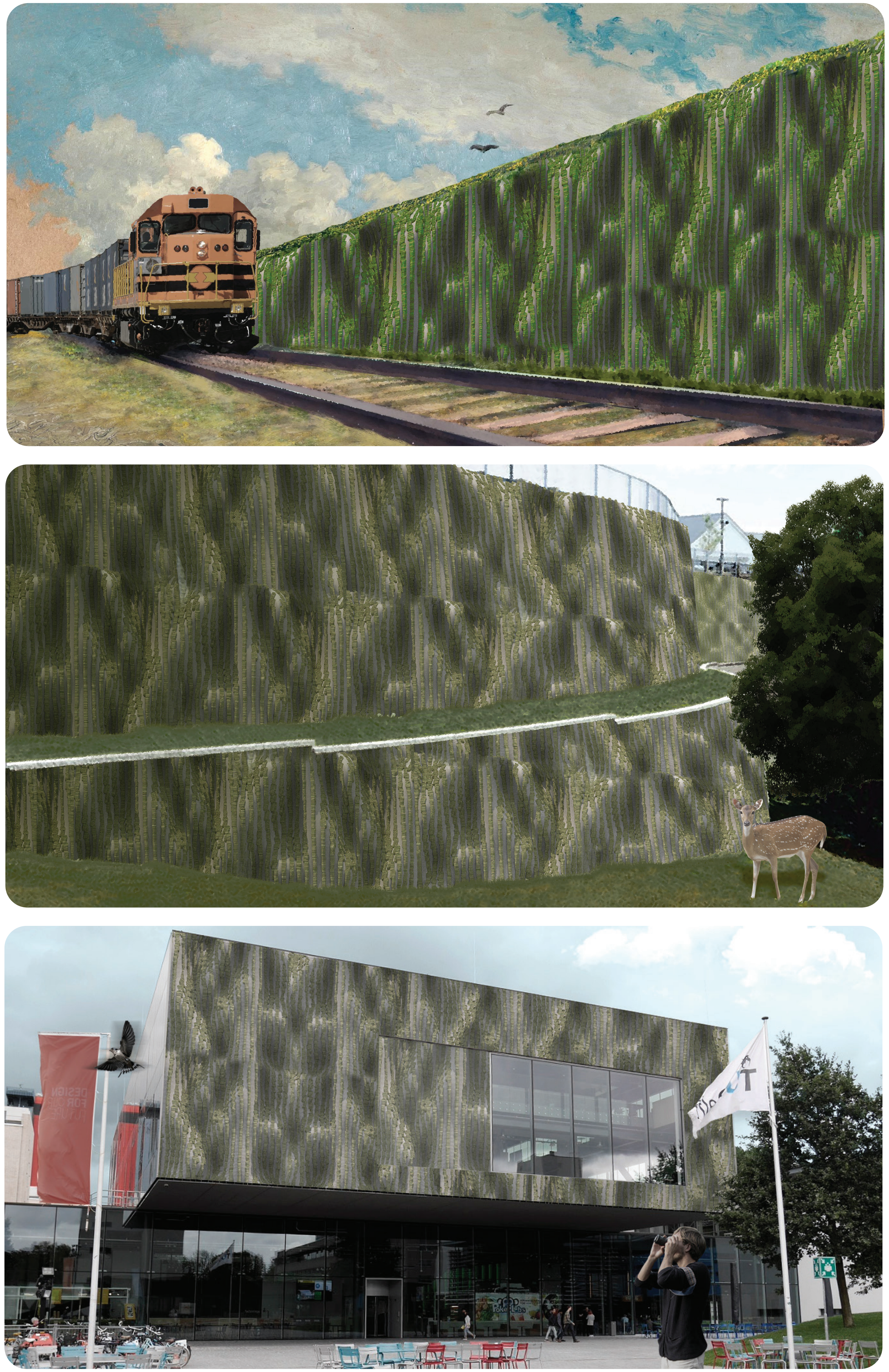


figure 104: Design Vision. (own source)

7. Conclusions

7.1 Conclusions

How can surface topology modifications improve bioreceptive performance of building envelopes, by taking into account environmental variables?

Bioreceptivity-oriented design is architectural in its application, material-driven and depends on computational methods both for simulations and fabrication. (M.Cruz and R. Beckett, 2016) This is because bioreceptivity is a multifactorial phenomenon and it requires the implementation of multidisciplinary work methods, including knowledge in computational software, engineering, material science and biology.

A material can be bioreceptive but it will not be biocolonized if the appropriate conditions do not occur. Computational performance analysis can support the identification of locations which fulfill climatic factors that encourage bioreceptivity. (like temperature and humidity) Therefore, it could act as a consulting mechanism capable of predicting if an architectural project/strategy could integrate bioreceptivity successfully in the design based on the location/climate.

Computational performance analysis and optimization can also support architects and engineers to generate, optimize, compare and evaluate different design alternatives regarding their potential of bioreceptivity from an early design phase. This is achieved by using variables that influence bioreceptivity as design principles. For instance, shadow and water benefit bryophytes because high solar exposure dries out their rhizoids and leaves, whereas high levels of moisture and water help them grow and propagate. In this sense, the orientation and the topology of the design can contribute to the creation of self-shading spaces while regulating water on them.

The topological research that was conducted through the study of a particular parametric design proved that its orientation plays the major role in the reduction of the solar radiation exposure. However, topological modifications can also significantly contribute to the decrease of the total solar radiation exposure. Therefore, there is a wide uncertainty about to what extent the topology of a design can improve bioreceptivity and needs to be tested through physical experiments.

How does the composition of lime-based mortars affect their bioreceptivity and how can this be improved?

In order to achieve a better bioreceptivity performance, specific material properties need to be targeted. Based on the literature, high water absorption capacity, high water retention, high water absorption rate and high open porosity are strongly linked with bioreceptivity. Regarding lime-based mortars, these can be achieved by modifying grain size distribution or/and binder to aggregate ratio.

Grain size distribution influences pores' size which in turn affects water transport behavior. The ratio between binder and aggregate influences the total porosity of mortars. More specifically, the use of thin and/or well-graded aggregates result in mortars with a relatively low open porosity and a high percentage of fine capillary pores. In contrast, the use of coarse and/or gap graded aggregates results in a mortar with a relatively high open porosity and a large percentage of coarse pores. In the first case, the mortar will have a slow and lower capillary absorption and a high water retention. In the second case, mortars will have a high water absorption capacity and a fast rate of capillary absorption, but a low water retention. (with the same binder to aggregate ratio) In parallel, the ratio between binder and aggregate has a strong impact on the total porosity of mortars. The use of a lower ratio of binder/aggregate leads to a higher porosity. (B.Lubelli et al, 2020)

The experiments that were conducted for this thesis validated these scientific facts. By keeping the binder to aggregate ratio stable, mortars in which thinner aggregates were used, had slower capillary absorption and a higher water retention and vice versa. Mortars made of fine sand grains had the highest percentage of weight gain due to the water's absorption. The specimens with coarser grain size aggregates showed a lower percentage of weight gain and this might be due to the presence of very coarse pores (not capillary active) which cannot retain water. In addition, binders did not significantly influence mortars' hydraulic properties.

Moreover, some conclusions were also derived regarding the relation between bioreceptivity and the tested materials/methods. Due to the small tested number of cases, the only examined type of bryophyte and the short timeframe, the following conclusions are not definitive.

Only specimen NHLSGV4 (composed of thin sand grains (0.08-1mm), vermiculite and natural hydraulic lime) can be considered as bioreceptive because signs of biocolonization were presented during the first 7 weeks. As such, natural hydraulic lime had a better bioreceptivity performance than hydrated lime with trass. However, it is not clear if its water transport behavior in combination with its chemical composition and roughness are sufficient for mosses' growth, because it is hard to observe visually their growth at this stage. Finally, a period of 7 weeks is not enough to notice moss growth and an estimated period of time would approximately be 18-20 weeks for the particular species.

How can digital fabrication support the production of customizable bioreceptive mortar elements?

The parametrization of the whole process demonstrates how generative scripts can become toolpaths and eventually lead to customized design solutions, depending on factors, like the orientation etc. In this fashion, digital fabrication and specifically additive manufacturing, a developing layer-by-layer printing process, can show the potential of its application on a large scale by offering mass customization. However, each design case is different and needs to be evaluated, regarding the cost, embodied energy, material usage and feasibility.

Applying the mortar on the parts of the topology which are less exposed to the sun and/or easily accessible by water, would theoretically benefit bioreceptivity (see 6.1 and 6.2). In order to combine the above-mentioned design approaches with the material choice, it is really important to realize that lime-based mortars have poor mechanical performances and cannot yet be 3d-printed due to their consistency. Therefore, a composite element which is composed of two different parts, a printable non-bioreceptive with a better structural performance and a bioreceptive part which would be structurally independent, would resolve these issues. The non-bioreceptive material (i.e. extrudable concrete or biomaterials) can be used to 3d-print the main structure on which special cavities are created, in which the bioreceptive mortar can be poured. In any case, the compatibility between the two parts should be taken into consideration.

As such, digital fabrication creates a multidisciplinary workflow that results in the creation of a new architectural expression by overcoming mortars' structural limitations and result in the production of customized bioreceptive mortar elements.

7.2 Limitations

Bioreceptivity is a spontaneous natural process and its initiation can take place over a long period of time making it a challenging topic to investigate. In addition to that, the constantly changing types of bioreceptivity that materials face cannot be taken into account since it is difficult to understand the exact moment when a bioreceptive material passes from one type of bioreceptivity to another.

7.3 Recommendations for future research

1. Based on the developed methodological approach a bioreceptive-oriented design can be created in order to evaluate to what extent surface topology along with water transport behavior and environmental conditions influences bioreceptivity in the long term.

2. Other ways of topology manipulation and evaluation could be tested and compared with the present one. The future researchers could simulate their proposal within a context so the shading of other elements, like building and tree, could be taken into account in the optimization.

3. A method for moss growth evaluation needs to be constructed in order to be able to compare different specimens in a more straightforward way. Also, further analyses of bryophytes' favorable conditions need to be conducted regarding their exact solar exposure limits. This can help mosses and other living organisms to be successfully integrated in the design of an element from the early phase of the design.

7.4 Reflection

The thesis involves several stages in order to develop what was learned through literature, experiments, simulations and research-by-design. Seemingly disparate subjects were investigated in order to cultivate a deep understanding of their synergies. The possible benefits of bioreceptivity and bryophytes, the support of surface topology in bioreceptivity, the underlying properties of bioreceptive materials and the introduction of a bioreceptivity-oriented design approach in the evolving industry of additive manufacturing are only some of the explored topics.

The fact that more and more scientific papers highlight the potential of bioreceptivity, in combination with the abundance of bioreceptive materials within the locality of my studies in Delft, Netherlands, have initiated this research work.

Cryptogams' absence of roots emphatically supports their integration in building elements and materials because they cannot cause biodeterioration through their roots' pressure. In order to create a successful interaction between the material and the living organisms, three are the main variables that should be considered; material properties, surface topology and environmental conditions. The majority of the existing studies focus on the material properties which boost biological growth or on the pattern-making of bioreceptive elements which supports the entrapment of biological content within their substrates. This thesis has as a starting point the identification of the requirements which are essential for an organism's growth. In order to do so, a case study is run on a specific moss species, Tortula Muralis, a popular cryptogam easily found in the Netherlands. This choice is fundamental for the research and differentiates my thesis from the existing methodologies, because even though a material can be prone to bioreceptivity it will not be biocolonized if the appropriate conditions do not occur.

Consequently, the ultimate goal of the present thesis is to engineer a strategy for designing, optimizing and producing surfaces which support bioreceptivity and express a new architectural vocabulary through bioreceptive materials. The research is examined both in digital and physical space which come as one through digital fabrication and prototyping at the very end of the process. The research starts in digital space, by identifying the environmental conditions which are in favor of bryophytes' growth. By determining several climatic variables in an advanced climate-finder, (such as high relative humidity, high rain frequency, air temperature ranging between -5 and 25°C etc.), potential locations where mosses thrive are found. This first step comes to be validated by my empirical viewpoint since several locations in the Netherlands have appeared. As a location for further investigation Amsterdam is selected, because of its proximity and thanks to the accessibility of its climatic data on the internet.

Moving on, bryophytes' survival requirements dictated the following steps. They cannot tolerate direct sunlight because it dries out their rhizoids and leaves. Instead, high levels of moisture and water can help them grow and propagate. For these reasons, the research is explored in two level. One seeks for the creation of shaded spaces which are easily accessible by water, whereas the second one attempts to identify a material which could be placed in these shaded spaces and offer a high water content for a considerable amount of time. The first case is investigated in-silico[1] and the second one in-vitro[2].

The impetus for the study in-silico originated from several structures and patterns which are often found in nature and create self-shading to tackle heat and sunlight-related issues. For instance, termites create their settlements in such a way that several shady spots are made because they cannot survive in direct sunlight. In order to make some observations but also compare several geometries, a script was set up successfully capable of evaluating the levels of sun and shadow. Solar exposure simulations are quite common in architectural projects and their contribution could support majorly bioreceptive applications. The script begins with the topology of a vertical flat surface which represents the external side of a wall. Vertical building elements consist of the largest area of building envelopes. By setting several control points and manipulating its topology and orientation in digital space, several conclusions were made. Firstly, in the case of Amsterdam (=north hemisphere), north orientation has the lowest levels of sunlight and therefore moss would probably grow in that direction. Indeed, this assumption can be considered as accurate since it is an old concept among hikers that mosses grow in the north orientation of the tree barks helping them to understand their orientation. What is more, by applying an optimization solver, it was concluded that the size of the deflections' and the number of the moved controlled points of the surface topology determines proportionally the amount of shadow that is created but also directs water towards these self-shaded spots. The same script was then applied in a dome's topology, a geometry which faces all directions in order to understand its full potential in 3-dimensional objects. Even though the script needs more advancement for a wider use and requires a multidisciplinary input from other fields, like botany, biology, engineering and material science, it can act beneficially already. For example, in the comparison of design alternatives or by identifying where bioreceptivity would more likely be efficient. The fact that the script suggests different optimized topologies in every location/orientation makes each produced element unique and that is why additive manufacturing is chosen as the means of fabrication.

Moreover, in order to produce a final design approach and a prototype, a bioreceptive material was necessary to be selected. In that fashion, lime-based mortars were chosen among others, as the most suitable material. Their high bioreceptivity performance in combination with their capability of being casted/molded, and hence be applied easily over and inside complex geometries, helped this decision. Then, based on an existing experiment that deals with bioreceptive lime-based mortars, new mixtures were made in order to evaluate if their water transport behavior could be improved and thus benefit their bioreceptivity performance. In order to observe this relation between bioreceptivity and water transport behavior, numerous experiments which required a high level of

1:"in-silico": Experiment which is performed on a computer or via computer simulation. (source: Wikipedia.org)
2:"in-vitro": Studies which are performed with microorganisms, cells, or biological molecules outside their normal biological context. (source: Wikipedia.org)

precision were conducted in the Heritage and Technology Lab at TU Delft. Even though the existing experimental proof indicates that high open porosity, high surface roughness, high water retention and high permeability support bioreceptivity, it becomes apparent that a considerable amount of time is required in order to observe clear results. In this framework, several mortars were examined in terms of moss growth and during the first five weeks signs of fungi growth were observed on a mortar due to the availability of moisture and nutrients. This phenomenon known as symbiosis is the early biocolonizing phase before moss appears. Nevertheless, it could be assumed that the developed mortars have a bioreceptive character because of their high water absorption capacity and retention in combination with their surface roughness. Mortars with smaller grain size distribution were proven to be the most promising because they had a higher water capacity and retention in comparison with the rest.

Finally, in order to showcase how these two can act synergistically by increasing the effect of bioreceptivity, three design approaches were made. This was achieved through a research-by-design experimental approach by prototyping in the Laboratory for Additive Manufacturing in Architecture at TU Delft. Their common design principle is the placement of a material prone to bioreceptivity in the self-shaded parts of a surface which are indicated by the generated script. These are not the only possible designs that can be made, but definitely they demonstrate a tangible method of combining the topology and material research expressing a new architectural vocabulary and act as a source of inspiration for future researchers. In any case, there is a growing need for a multiscientific approach in order to evaluate and improve this new concept, but also testify to what degree this approach could benefit the urban landscape.

In conclusion, conducting research on the intersection of bioreceptivity, mosses, mortars and additive manufacturing can create new design applications in the urbanscape. As designers and engineers we need to think how we can contribute to a better quality of living through the use of new materials and technologies on different scales and conditions. From my personal point of view this can be achieved by incorporating nature in the urban environment. A deep understanding of natural complex phenomena, like bioreceptivity, can help us resolve many environmental issues and lay the foundation for innovation and a more environmentally benign coexistence.

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9. Appendix

Appendix 1: Water absorption rate experiment results

WEIGHT GAIN (GR)

ABSORBED WATER PER VOLUME (GR/CM^2)

AVERAGE ABSORBED WATER PER VOLUME PER TYPE OF MORTAR (GR/CM^2)

	0min	1min	3min	5min	10min	30min	1h	2h	4h	6h	8h	24h	
NHLBGV4													
1b	162,74	193,16	196,4	196,57	196,63	197,5	198	199,57	201,14	201,71	202,01	204,5	
1c	192,28	228,12	232,35	232,51	232,55	233,25	233,66	234,72	236,13	237,1	237,7	241,87	
2c	140,52	165,7	169,03	169,36	169,4	169,75	170,68	170,91	172,45	172,55	172,83	176,32	
1b	0	0,46	0,51	0,51	0,51	0,53	0,53	0,56	0,58	0,59	0,60	0,63	
1c	0	0,47	0,53	0,53	0,53	0,54	0,55	0,56	0,58	0,59	0,60	0,66	
2c	0	0,38	0,43	0,44	0,44	0,44	0,46	0,46	0,48	0,49	0,49	0,54	
average	0	0,439	0,491	0,494	0,495	0,504	0,513	0,527	0,549	0,556	0,562	0,611	
NHLsgv4													
2a	196,19	216,00	220,22	230,04	234,13	236,2	237,1	242,15	243,93	244,78	246,07	249,68	
2b	180,12	203,12	209,12	218,31	223,02	224,2	225,4	226,02	230,43	231,34	232,19	236,04	
2c	179,02	199,69	205,21	213,81	220,3	221,8	222,76	223,93	225,81	226,65	226,98	231,56	
2a	0	0,26	0,32	0,45	0,51	0,53	0,55	0,61	0,64	0,65	0,67	0,71	
2b	0	0,31	0,39	0,51	0,57	0,59	0,61	0,61	0,67	0,68	0,70	0,75	
2c	0	0,30	0,37	0,50	0,59	0,61	0,63	0,64	0,67	0,68	0,69	0,75	
average	0	0,289	0,361	0,486	0,556	0,578	0,592	0,623	0,659	0,671	0,682	0,737	
ATBGV4													
1a	220,51	256,11	261,12	262,15	263,26	263,5	263,85	264,89	266,19	267,33	267,96	270	
1b	188,13	220,05	223,12	224,03	224,85	225,5	226,8	227,02	227,73	228,68	229	231,96	
1c	163,85	216,2	219,5	220,12	221,03	221,8	222,76	223,93	225,81	226,65	226,98	229	
1a	0	0,46	0,53	0,54	0,55	0,56	0,56	0,58	0,59	0,61	0,61	0,64	
1b	0	0,45	0,49	0,51	0,52	0,53	0,55	0,55	0,56	0,57	0,58	0,62	
1c	0	0,82	0,87	0,88	0,89	0,90	0,92	0,94	0,97	0,98	0,98	1,02	ERROR
average	0	0,457	0,511	0,524	0,537	0,543	0,554	0,563	0,576	0,590	0,596	0,630	
ATSGV4													
2a	186,23	210,17	217,02	222,21	230,03	231,52	232,03	233,13	235,9	237,01	237,19	241,16	
2b	177,21	209,88	217,37	226,5	225,36	225,41	226,2	226,66	227,3	227,75	228	228,42	
2c	175,04	200,02	207,12	213,02	220,07	222,6	223,21	223,5	227,12	228,02	230,12	232,04	
2a	0	0,34	0,43	0,50	0,61	0,63	0,64	0,65	0,69	0,71	0,71	0,77	
2b	0	0,50	0,52	0,63	0,62	0,62	0,63	0,64	0,64	0,65	0,65	0,66	ERROR
2c	0	0,32	0,42	0,49	0,59	0,62	0,63	0,63	0,68	0,69	0,72	0,74	
average	0	0,330	0,424	0,498	0,598	0,625	0,633	0,642	0,685	0,699	0,713	0,753	

Time (√min)	0,00	1,00	1,73	2,24	3,16	5,48	7,75	10,95	15,49	18,97	21,91	37,95
NHLBGV4	0	0,439	0,491	0,494	0,495	0,504	0,513	0,527	0,549	0,556	0,562	0,611
NHLsgv4	0	0,289	0,361	0,486	0,556	0,578	0,592	0,623	0,659	0,671	0,682	0,737
ATBGV4	0	0,457	0,511	0,524	0,537	0,543	0,554	0,563	0,576	0,590	0,596	0,630
ATSGV4	0	0,330	0,424	0,498	0,598	0,625	0,633	0,642	0,685	0,699	0,713	0,753

Appendix 2: Weight loss due to water evaporation results

WEIGHT GAIN (GR)

PERCENTAGE OF WEIGHT LOSS DUE TO WATER EVAPORATION (%)

AVERAGE PERCNTAGE OF WEIGHT LOSS DUE TO WATER EVAPORATION PER TYPE OF MORTAR (%)

Days	0	1	2	3	4	5	8	12	19
NHLbgv4									
1b	204,49	201,78	191,46	181,60	171,50	169,82	157,40	156,00	155,20
1c	240,67	238,10	226,90	216,45	205,87	202,61	185,64	184,56	183,22
2c	175,57	173,04	161,32	150,92	143,23	141,88	134,56	132,22	132,45
1b	0,0%	-1,3%	-6,4%	-11,2%	-16,1%	-17,0%	-23,0%	-23,7%	-24,1%
1c	0,0%	-1,1%	-5,7%	-10,1%	-14,5%	-15,8%	-22,9%	-23,3%	-23,9%
2c	0,0%	-1,4%	-8,1%	-14,0%	-18,4%	-19,2%	-23,4%	-24,7%	-24,6%
	0,0%	-1,3%	-6,7%	-11,8%	-16,3%	-17,3%	-23,1%	-23,9%	-24,2%
NHLsgv4									
2a	252,47	249,80	241,47	227,42	216,20	211,97	200,48	199,44	197,61
2b	240,65	238,30	228,37	217,95	208,15	203,40	192,52	190,74	190,15
2c	239,09	236,22	224,06	212,18	201,19	197,12	187,06	186,95	185,10
2a	0,0%	-1,1%	-4,4%	-9,9%	-14,4%	-16,0%	-20,6%	-21,0%	-21,7%
2b	0,0%	-1,0%	-5,1%	-9,4%	-13,5%	-15,5%	-20,0%	-20,7%	-21,0%
2c	0,0%	-1,2%	-6,3%	-11,3%	-15,9%	-17,6%	-21,8%	-21,8%	-22,6%
	0,0%	-1,1%	-5,2%	-10,2%	-14,6%	-16,4%	-20,8%	-21,2%	-21,8%
ATbgv4									
1a	275,61	272,4	259,17	246,8	232,38	229,8	210,3587	209,4649	207,25
1b	235,42	232,92	223,03	212,4	201,82	198	181,3907	179,064	178,01
1c	205,8	202,8	191,13	179,8	169,7	167	158,4483	156,366	153,86
1a	0,0%	-1,2%	-6,0%	-10,4%	-15,7%	-16,6%	-23,7%	-24,0%	-24,8%
1b	0,0%	-1,1%	-5,3%	-9,8%	-14,3%	-15,9%	-23,0%	-23,9%	-24,4%
1c	0,0%	-1,5%	-7,1%	-12,6%	-17,5%	-18,9%	-23,0%	-24,0%	-25,2%
	0,0%	-1,2%	-6,1%	-11,0%	-15,8%	-17,1%	-23,2%	-24,0%	-24,8%
ATsgv4									
2a	246,95	243,90	230,52	220,03	208,65	207,34	194,32	193,41	192,80
2b	235,12	232,51	222,28	212,82	203,07	197,54	183,96	183,17	182,61
2c	233,89	231,38	221,51	208,06	197,13	192,95	187,00	184,80	182,00
2a	0,0%	-1,3%	-6,7%	-10,9%	-15,5%	-16,1%	-21,3%	-21,7%	-21,9%
2b	0,0%	-1,1%	-5,4%	-9,4%	-13,6%	-15,9%	-21,7%	-22,1%	-22,3%
2c	0,0%	-1,1%	-5,3%	-11,1%	-15,8%	-17,5%	-20,1%	-21,0%	-22,2%
	0,0%	-1,1%	-5,8%	-10,5%	-15,0%	-16,5%	-21,0%	-21,6%	-22,2%

Days	0	1	2	3	4	5	8	12	19
NHLBGV4	0,0%	-1,3%	-6,7%	-11,8%	-16,3%	-17,3%	-23,1%	-23,9%	-24,2%
ATBGV4	0,0%	-1,2%	-6,1%	-11,0%	-15,8%	-17,1%	-23,2%	-24,0%	-24,8%
NHLSGV4	0,0%	-1,1%	-5,2%	-10,2%	-14,6%	-16,4%	-20,8%	-21,2%	-21,8%
ATSGV4	0,0%	-1,1%	-5,8%	-10,5%	-15,0%	-16,5%	-21,0%	-21,6%	-22,2%

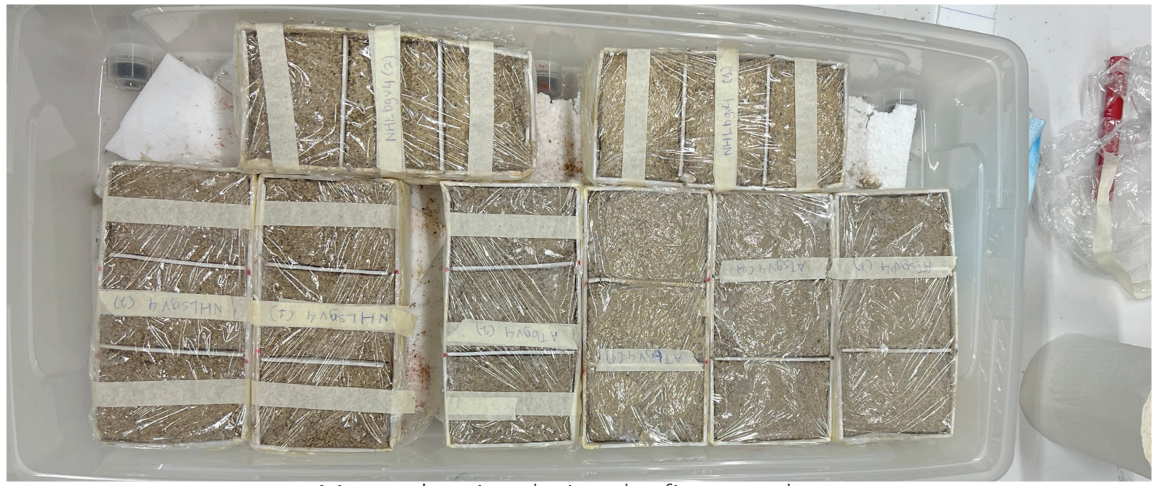
Appendix 3: Experiment set up

Mold making for mortars using polysterene boards.

Mortars’ making.

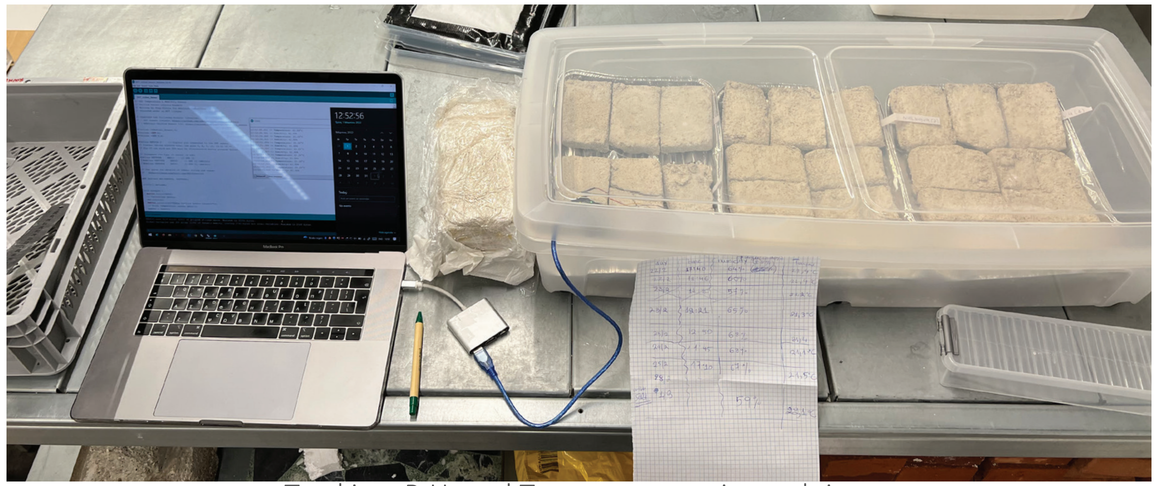
Workability test.

Appendix 3: Experiment set up



Mortars’ curing during the first two days.

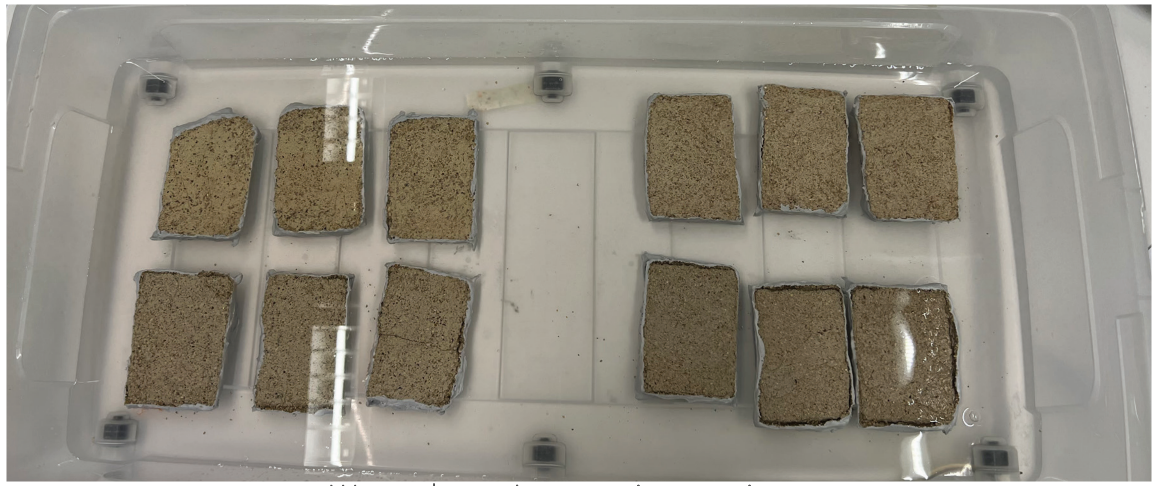
Demolding mortars.



Tracking R.H. and Temperature using arduino.

Appendix 4: Test Methods

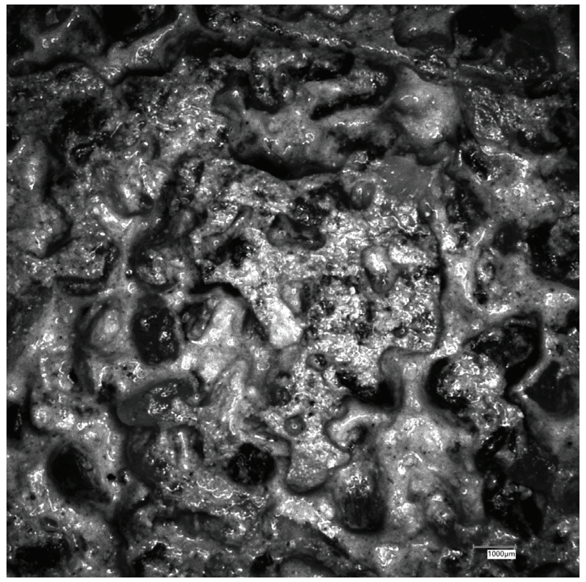
Water absorption rate experiment.



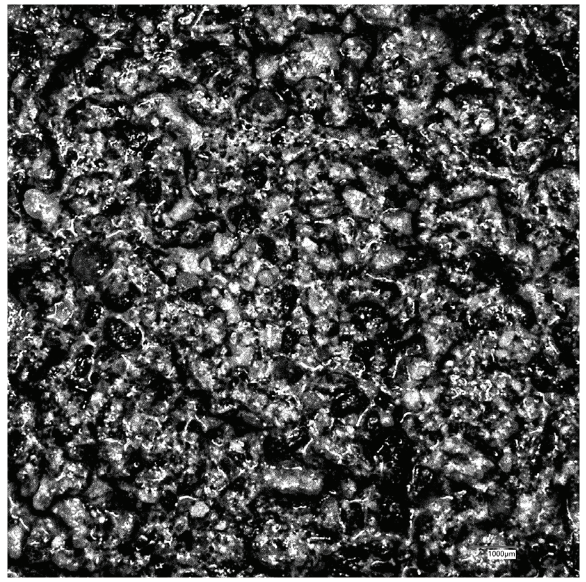
Water absorption capacity experiment.

Water evaporation rate experiment.

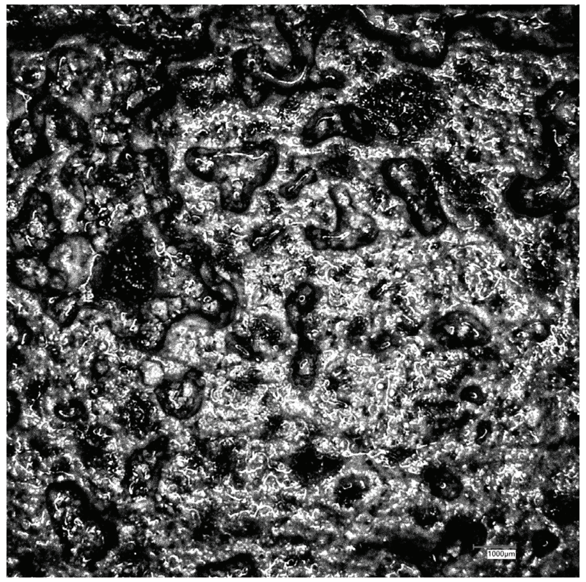
Appendix 5: Mortars under electron microscope



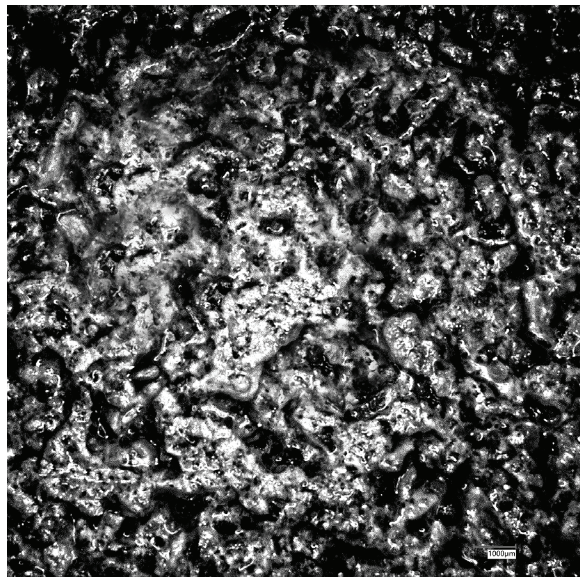
ATbgv4



ATsgv4



NHLbgv4



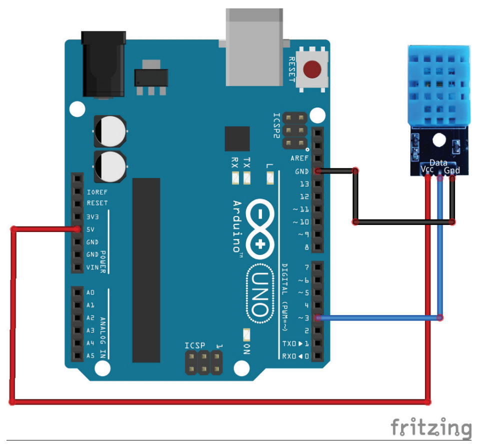
NHsgv4

Mortars' top surface roughness under electon microscope.
(pictures were captured by Georgina Giassia using KEYENCE VHX-700)

Appendix 6: Humidity and temperature sensor set up in Arduino

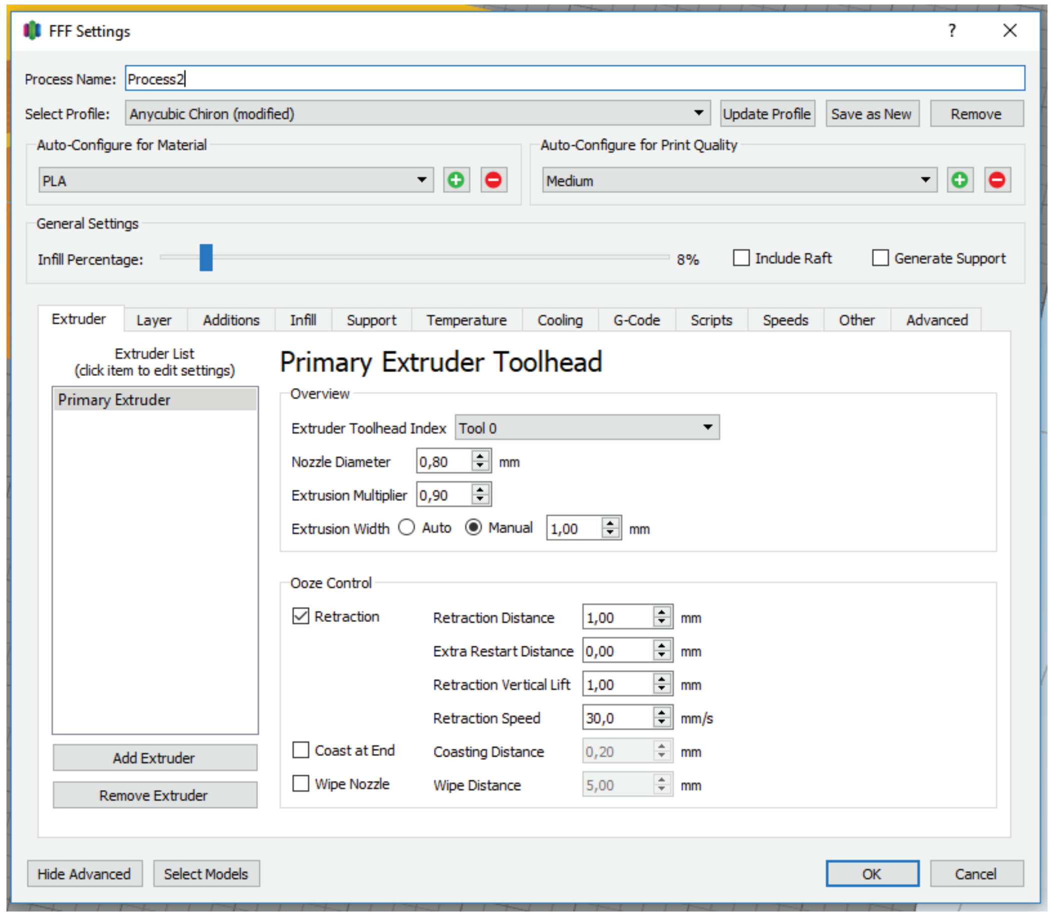
```
uint32_t delayMS;

void setup() {
  Serial.begin(9600);
  // Initialize device.
  dht.begin();
  Serial.println(F("DHTxx Unified Sensor Example"));
  // Print temperature sensor details.
  sensor_t sensor;
  dht.temperature().getSensor(&sensor);
  Serial.println(F("------------------------------------"));
  Serial.println(F("Temperature Sensor"));
  Serial.print  (F("Sensor Type: ")); Serial.println(sensor.name);
  Serial.print  (F("Driver Ver:  ")); Serial.println(sensor.version);
  Serial.print  (F("Unique ID:   ")); Serial.println(sensor.sensor_id);
  Serial.print  (F("Max Value:   ")); Serial.print(sensor.max_value); Serial.println(F("°C"));
  Serial.print  (F("Min Value:   ")); Serial.print(sensor.min_value); Serial.println(F("°C"));
  Serial.print  (F("Resolution:  ")); Serial.print(sensor.resolution); Serial.println(F("°C"));
  Serial.println(F("------------------------------------"));
  // Print humidity sensor details.
  dht.humidity().getSensor(&sensor);
  Serial.println(F("Humidity Sensor"));
  Serial.print  (F("Sensor Type: ")); Serial.println(sensor.name);
  Serial.print  (F("Driver Ver:  ")); Serial.println(sensor.version);
  Serial.print  (F("Unique ID:   ")); Serial.println(sensor.sensor_id);
  Serial.print  (F("Max Value:   ")); Serial.print(sensor.max_value); Serial.println(F("%"));
  Serial.print  (F("Min Value:   ")); Serial.print(sensor.min_value); Serial.println(F("%"));
  Serial.print  (F("Resolution:  ")); Serial.print(sensor.resolution); Serial.println(F("%"));
  Serial.println(F("------------------------------------"));
  // Set delay between sensor readings based on sensor details.
  delayMS = sensor.min_delay / 1000;
}

void loop() {
  // Delay between measurements.
  delay(delayMS);
  // Get temperature event and print its value.
  sensors_event_t event;
  dht.temperature().getEvent(&event);
  if (isnan(event.temperature)) {
    Serial.println(F("Error reading temperature!"));
  }
  else {
    Serial.print(F("Temperature: "));
    Serial.print(event.temperature);
    Serial.println(F("°C"));
  }
  // Get humidity event and print its value.
  dht.humidity().getEvent(&event);
  if (isnan(event.relative_humidity)) {
    Serial.println(F("Error reading humidity!"));
  }
  else {
    Serial.print(F("Humidity: "));
    Serial.print(event.relative_humidity);
    Serial.println(F("%"));
  }
}
```

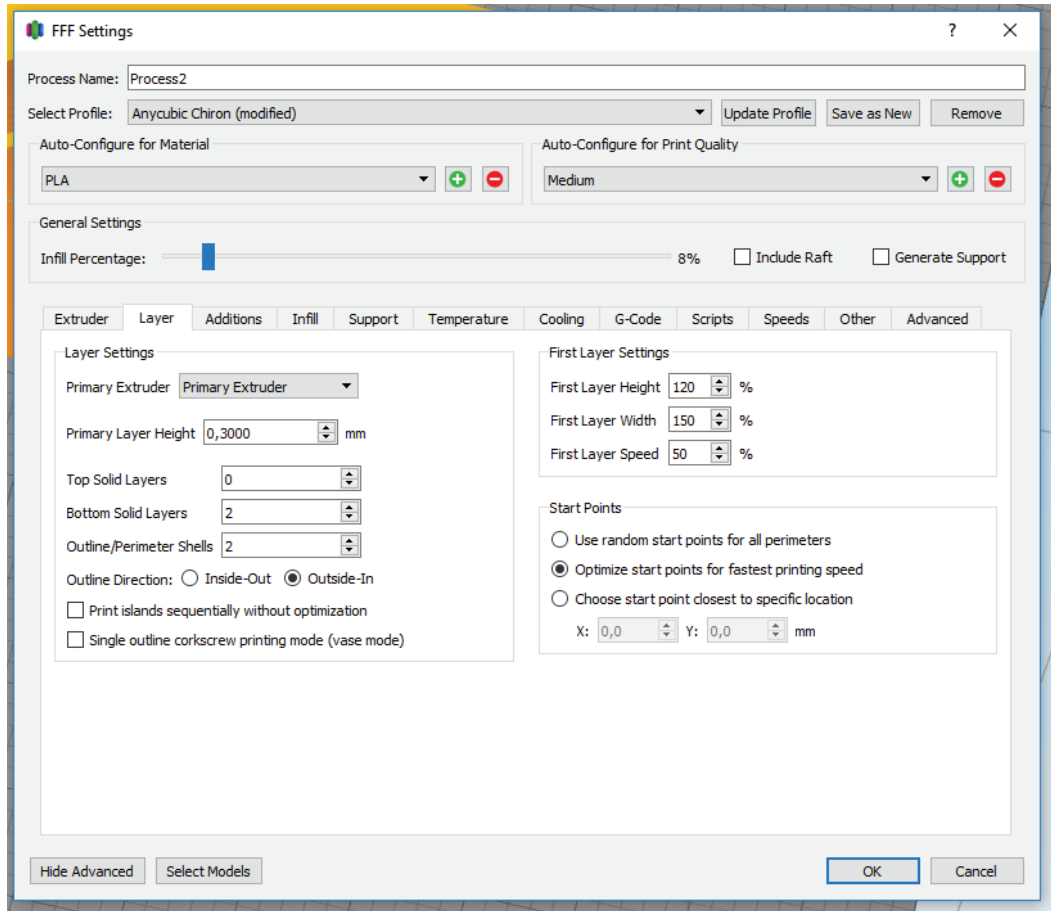
Arduino script set up (own source)



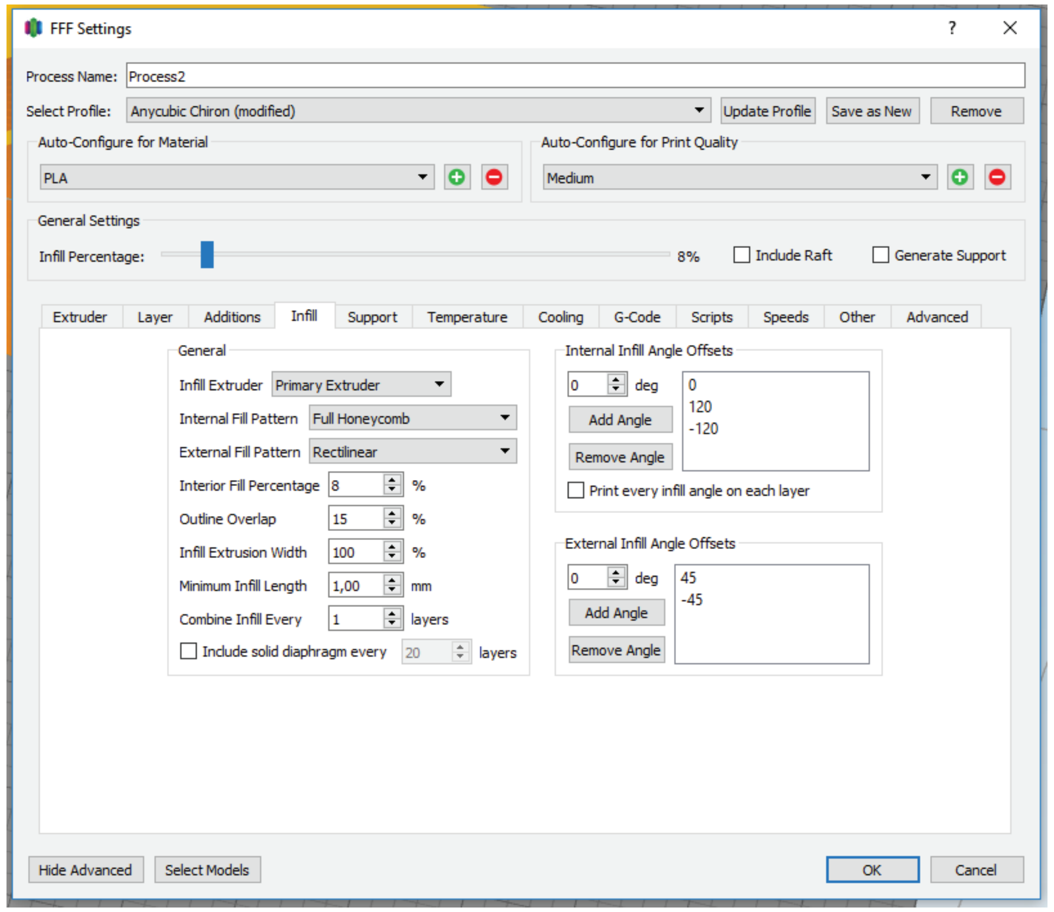
DHT11 sensor with Arduino uno (create.arduino.cc)

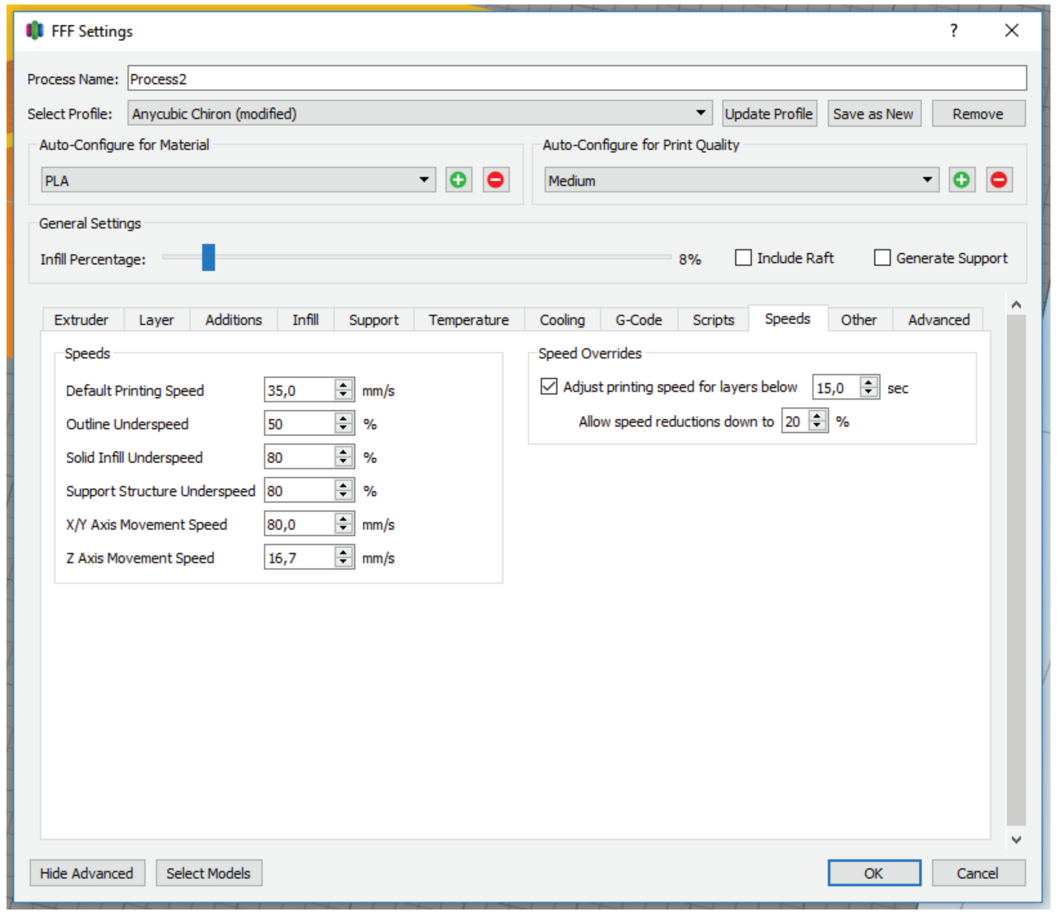
Appendix 7: Slicer set up using SIMPLIFY.3D



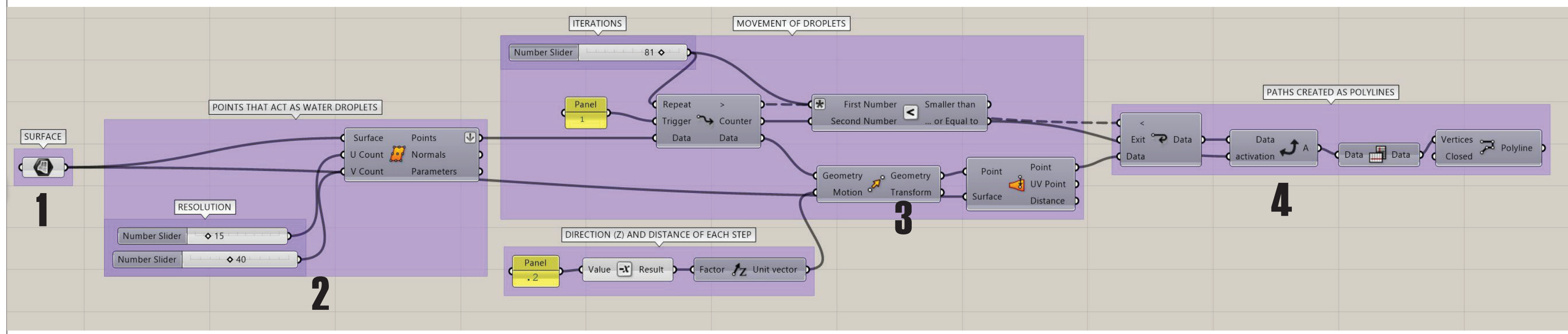


Appendix 7: Slicer set up using SIMPLIFY.3D

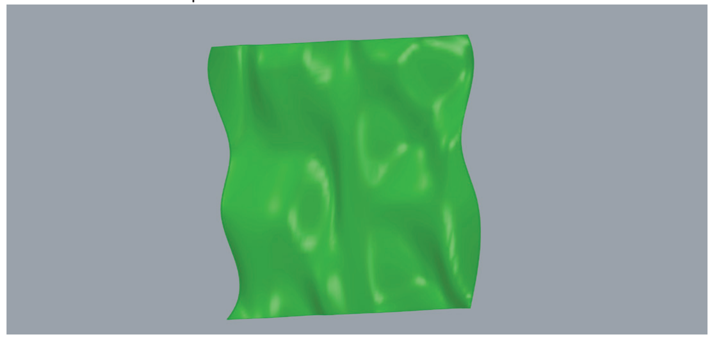




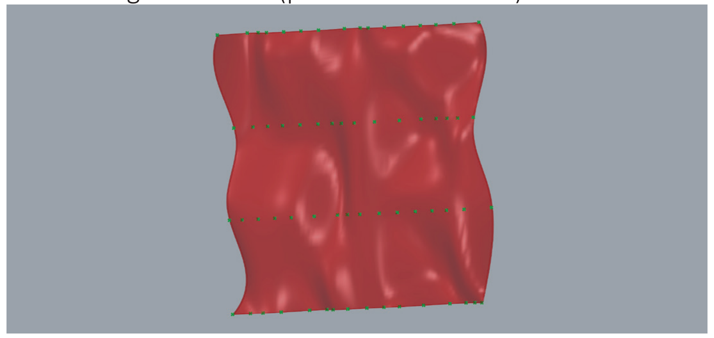
Appendix 8: Simplified water flow analysis



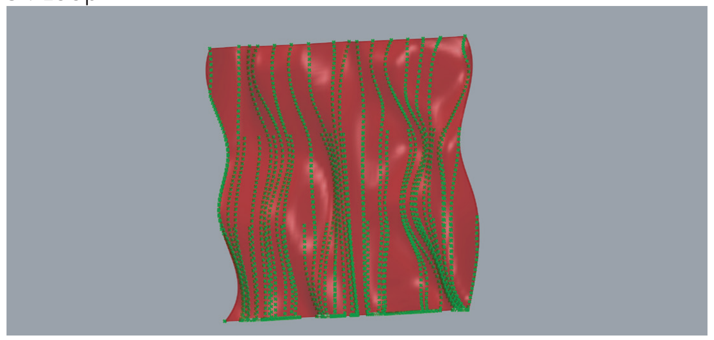
1 : Surface as input



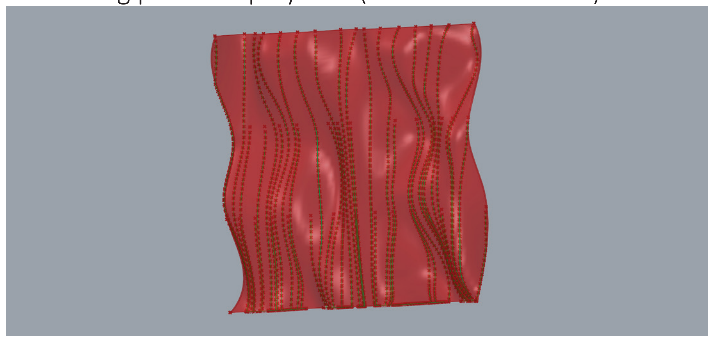
2 : Defining Resolution (points to be moved)



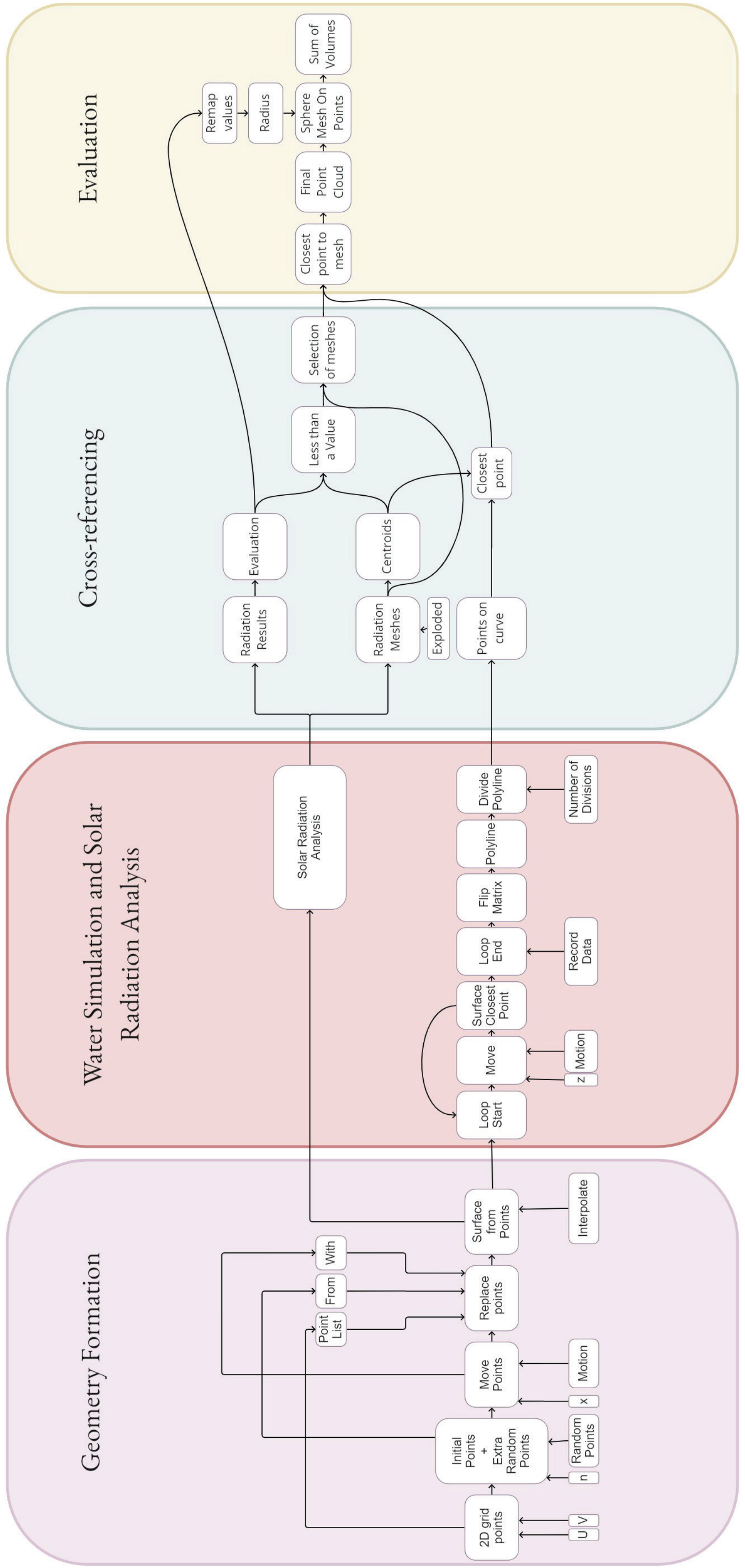
3 : Loop



4 : Turning points to polylines (water flow streams)



Appendix 9: Figure 36



Appendix 10: Figure 51