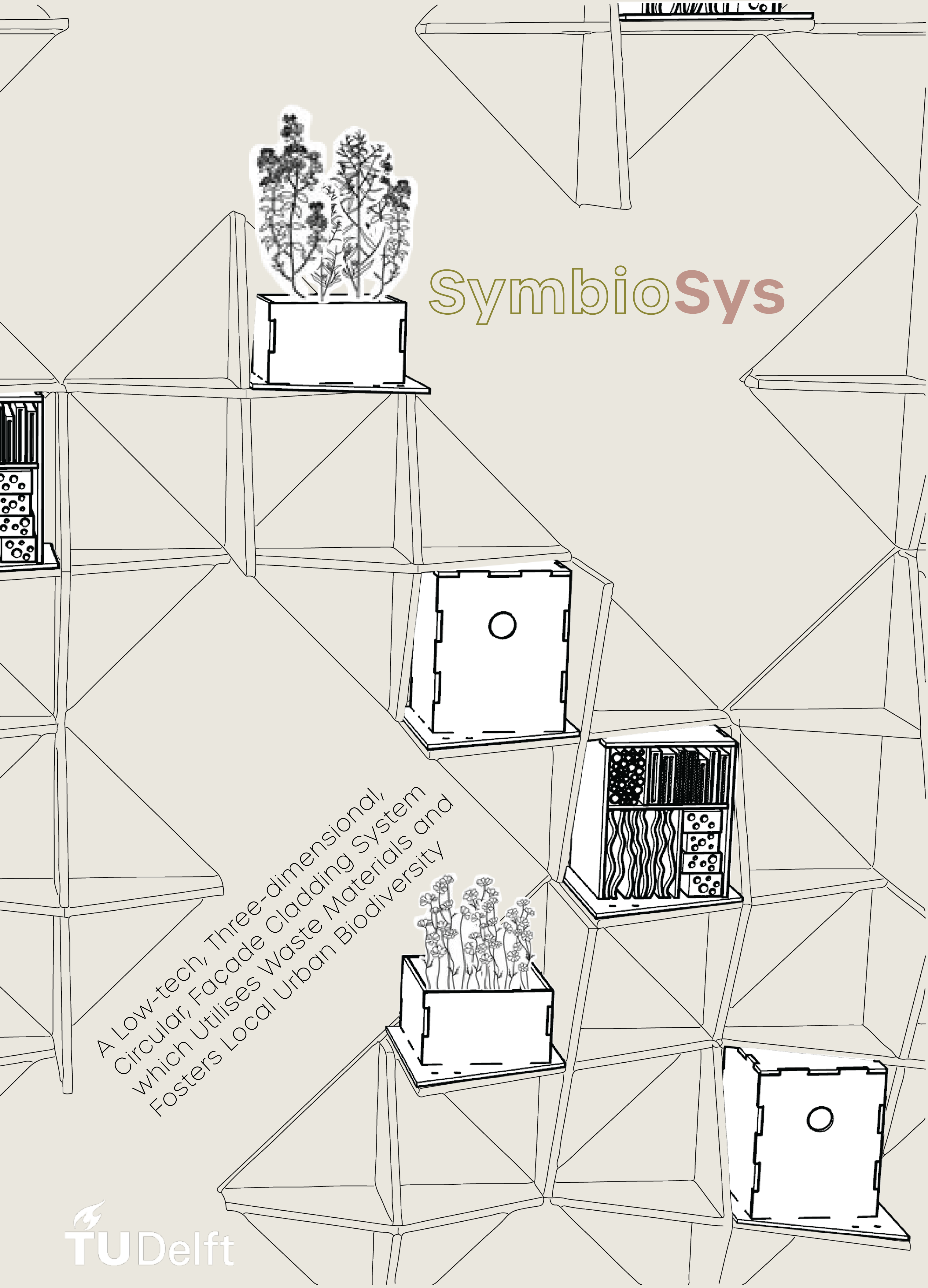
SymbioSys



A Low-tech, Three-dimensional, Circular, Façade Cladding System which Utilises Waste Materials and Fosters Local Urban Biodiversity

TU Delft

Colophon

Title
SymbioSys: A Low-tech, Three-dimensional, Circular, Façade Cladding System which Utilises Waste Materials and Fosters Local Urban Biodiversity

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Abstract

The negative effects of global climate change are experienced more clearly every day, meaning that significant alterations across all causing sectors are necessary. However, the influence of the building industry as one of the most polluting sectors, is immense, but therefore this industry also has a high potential in mitigating the greenhouse gas emissions by applying circular design principles, such as circulating products and materials, and thereby designing a more sustainable, circular and healthy living environment. Additionally, increasing the amount of nature in the built environment will also contribute to this manner, nonetheless the ongoing trend of urbanisation causes a challenging dilemma between facilitating more residences and adding extra nature to the cities. Hence, new strategies of greening cities are essential to resolve this problem, at which utilising building envelopes as hosting surfaces for fostering vegetation and fauna form a highly potential solution.

Therefore, the main objective of this thesis is to design a low-tech, three-dimensional, circular façade cladding system which utilises waste materials and fosters local biodiversity in urban areas. To properly design and develop this cladding system, research has been conducted through literature and case study review in the fields of circular design and biodiversity implementation in the façade industry and by physical and digital design experimentation and modelling.

Whereas, the research phase resulted in various potential low-tech manufacturing techniques, suitable reclaimed materials, modular and Design-for-Disassembly design principles and a selection of building-reliant flora and fauna species to implement in the design of the system, collectively facilitating the guidelines for the design phase. Finally, after an extensive design process a three-dimensional façade system derived consisting of three main modular elements, constructed from merely five unique planar components. Through the principle of rotation, a total of nine variations of the modules are generated, which facilitates not only the implementation of local biodiversity, but also creates an intriguing architectural language.

From this thesis, various conclusions have been drawn, including that in order to optimise the circular value of the design, the decision has been made to select the majority of the waste materials based on their local availability whenever the system is implemented in a certain location and at a specific timeframe. Moreover, the low-tech design strategy contributes to the involvement of the system's end-users, eventually accelerating the transitioning process and furthermore increasing people's awareness, knowledge and interest regarding circular, sustainable and nature-inclusive design subjects.

Acknowledgements

Currently being at the final end of my graduation thesis, I look back at an intense, however inspiring and joyful year, in which I was able to develop a product that I am truly proud of and moreover grow on personal levels.

Foremost, I want to express my sincerest gratitude to my mentors without whom I couldn't have achieved the result I did now. Thank you, Olga, for always being there for me and bringing along a safe, inspiring working environment. Thank you, Andy, for always sharing your honest opinion and pushing me to get the best out of myself. Thank you, Nico, for stepping in during the last stage of my project, however fully supporting my work and being able to teach me a lot in a short period of time. All of you made me learn so much and enjoy the project until the very last moment. Additionally, I want to thank Paul de Ruiter for his time assisting me in creating some 3D printed prototypes in the final weeks.

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Table of content

Abstract	***5***
Acknowledgements	***7***
00. Introduction	***11***
0.1 Background	12
0.2 Problem statement	16
0.3 Objectives	17
0.4 Research questions	19
0.5 Design questions	19
0.6 Methodology	20
0.7 Relevance	22
Section A: Circularity	***25***
01. Circular Façade Design	***27***
1.1 Introduction to circular design in the façade industry	28
1.2 Circularity case studies	30
1.3 The considered circular approaches: Modularity and Design for Disassembly	32
02. Manufacturing & Materialisation	***39***
2.1 Introduction to three-dimensional façade manufacturing techniques	40
2.2 Potential low-tech manufacturing techniques	42
2.3 Introduction to waste materials in the Netherlands	47
2.4 Selecting potential materials for the façade system	48
Section B: Biodiversity	***55***
03. Nature-inclusive design: Biodiversity on building envelopes in urban areas	***57***
3.1 Introduction to nature-inclusive design & biodiversity in urban areas	58
3.2 Nature-inclusive façade systems	60
3.3 Biodiversity case studies	62
04. The Biodiversity Map	***71***
4.1 Biodiversity parameters: criteria for selecting biodiversity species	72
4.2 Selection of species	76
Section C: The Design	***89***
05. Preliminary Design	***91***
5.1 Design inspiration: geometric origami	92
06. Conceptual Design	***99***
6.1 Design guidelines: outcomes of the literature study	100
6.2 Conceptual Design	102
07. Experimentation & testing	***107***
7.1 The Modules	108
7.2 The BioPods	116
7.3 The Connections	120
08. Final Design	***125***
8.1 The Modules	126
8.2 The BioPods	129
8.3 The connections	132
8.4 The lifecycle of the system	136
09. Design case study	***139***
9.1 Potential school buildings for the implementation of the product	140
9.2 The Matrix: case study selection	144
9.3 Design implementation on the Gabriel school	148
10. Discussion & Conclusions	***157***
10.1 Discussion	158
10.2 Conclusions	159
10.3 Limitations	161
10.4 Recommendations for further research	162
10.5 Reflection	164
11. Bibliography	***169***
11.1 References	170
12. Appendix	***177***
A. Full analysis of the potential school buildings as a design case study	178
B. Full matrix of the assessment of the potential schools regarding the species	184
C. Models from the design process	188

00

Introduction

0.1 Background

Climate change

The worldwide climate is changing and also in the Netherlands we are currently experiencing the consequences: increasing water shortages, drought and heavy rainfall with flooding as a result. In urban environments, these consequences affect not merely the durability and quality of the (green) built environment, but moreover the health and safety of all its inhabitants i.e., humans, flora and fauna (PBL, 2023).

Examining the statistics, the Netherlands reduced it greenhouse gas (GHG) emissions with almost 25 percent between 1990 and 2021. However, to reach the minimal target of 55 percent reduction in 2030 relative to 1990, a decrease of 30 percent in the remaining nine years must be achieved. This means the pace of the previous 30 years must be tripled in the coming period. Hence, fundamental changes are necessary, not just in terms of new innovative technologies and scaling-down manners which doesn't fit in a sustainable future, but also in significant behavioural changes. (PBL, 2023).

Looking at the building industry, around 37 percent of the global emissions worldwide was generated by this sector in 2021. The detailed accounting of these emissions is illustrated in figure 1, but the worldwide emissions of almost 10 percent caused by materials used for construction of buildings is something to be highlighted (United Nations Environment Programme, 2022). Additionally, the overall trend of GHG emissions caused by this sector, according to figure 2, is still lacking a reduction, which implies that the estimated target seems almost impossible to achieve by 2030.

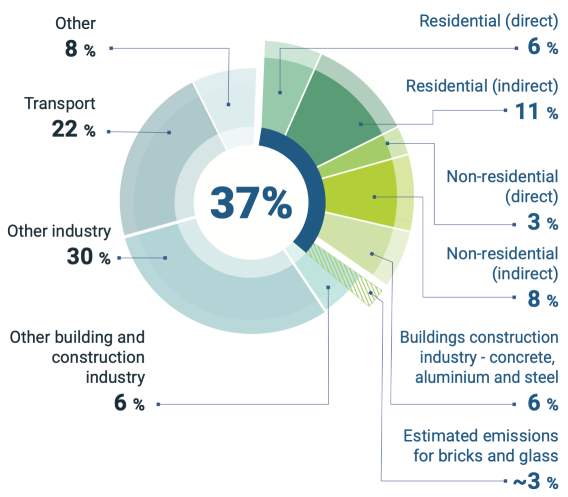


Figure 1. Global share of buildings and construction operational and process CO2 emissions in 2021 (Source: United Nations Environment Programme, 2022)

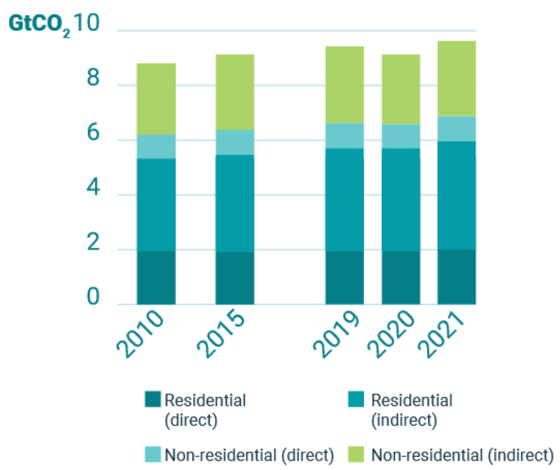


Figure 2. Global trend of CO2 emissions caused by the buildings and construction sector in 2021 (Source: United Nations Environment Programme, 2022)

From linear to circular design strategies

Transitioning from a linear to a circular economy is fundamental for fighting climate change, as this could reduce the global CO2 emissions from building materials by 38 percent in 2050 (Ellen MacArthur Foundation, n.d.-c. The Ellen MacArthur Foundation (n.d.-a) explains that the circular economy is based on three design driven, fundamental principles: (1) eliminate waste and pollution, (2) circulate products and materials (at their highest value) and (3) regenerate nature (see figure 3). However, the way we design, construct and eventually demolish our built environment is entrenched by the linear take-make-waste system and thus, rethinking these strategies is essential, to realise more value from existing assets, keep resources and building materials in the loop and prevent them from becoming waste.

Unfortunately, the transition to this circular economy in the Netherlands is still in its early phase, mainly due to the presence of several obstacles, being for instance the lack of subsidies or the current policies concerning waste materials. On the consumer side, the transition asks for significant behavioural changes, as stated earlier (PBL, 2023).

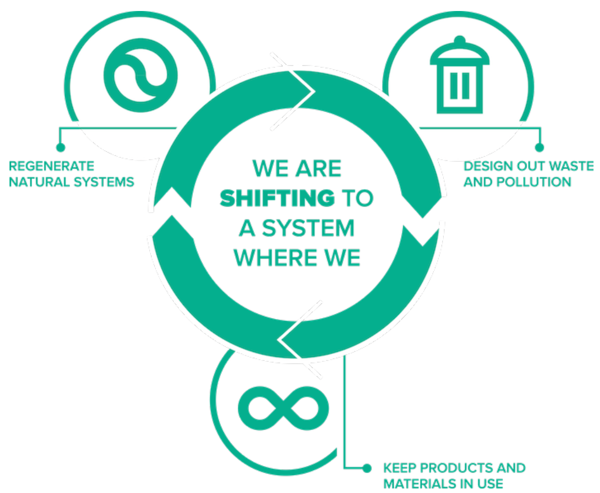


Figure 3. Principles of a circular economy (Source: Ellen MacArthur Foundation, n.d.-a)

Circular design process

From linear to circular: The European Commission (2014) claims that at the design stage of a product more than 80% of its environmental impact is determined, making it vital to incorporate the three CE principles into the design process, therefore reducing the global GHG emissions. These principles open the door to countless strategies and innovations, eventually achieving a circular and sustainable world. Examples of successfully proven strategies are designing for inner loops, moving from products to services, product's life extension, safe, circular material choices and modularity (Ellen MacArthur Foundation, n.d.-b).

(Urban) biodiversity in the Netherlands

Cities are renowned for their constant activity, encompassing construction, renovation, work, and development. Many urban centers face the challenge of densification, with increasing pressure on public spaces due to a growing population. The area devoted to green spaces diminishes as natural grass sports fields are replaced with artificial turf, and residents pave over their gardens. Improved home insulation reduces nesting and shelter opportunities for birds and bats. These trends collectively result in the shrinking of urban green spaces and the available habitat for urban wildlife (Municipality of The Hague, n.d.). For instance, of the approximately 48.000 indigenous species that thrive in cities of the Netherlands, merely 10.000 are present in the city of Amsterdam (Bouw Natuurinclusief, n.d.).

Additionally, in the period of 2013 until 2028 around 90% of the habitat types within the Netherlands exhibit conservation statuses ranging from unfavourable to inadequately unfavourable. Conversely, approximately 25% of the species designated under the Habitats Directive in the Netherlands enjoy a favourable conservation status, see figures 4 and 5 (CBS et al., 2020). In both cases, the Netherlands scores worse than the European Union average. However, the aim of the EU Biodiversity Strategy is that 30% of the protected habitat types and species listed in the Habitats Directive have a good conservation status or at least show a positive trend (EC, 2020), meaning that the improvement of the Dutch biodiversity can have significant influence in achieving this target.

Importance of urban biodiversity

Nowadays, almost 60 percent of the world population lives in urban areas and the expectation is that by 2050 this percentage has risen towards 70 percent, making urbanization an ongoing trend (World Bank, 2023). In the Netherlands, however, these numbers are even higher with over 90% of the population living in cities. These cities not only face heat stress due to the Urban Heat Island (UHI) Effect, having several negative effects on the inhabitant's health, but also increased amounts of significant stress are a common occurrence in cities, which results in higher risks of various diseases as well. Mitigating stress levels improves humans' overall health and natural, green environments and being in contact with nature decreases stress levels more quickly (Berto, 2014). Another of many beneficial factors is that a green environment encourages physical activities, reducing long-term risk of obesity. For instance, children growing-up in green areas tend to play outside 10% more often than children in grey environments.

Additionally, adding more green spaces in cities improves the green and blue structures within these urban environments. The importance of this cannot be overstated, since it provides more, larger habitats for flora and fauna species and furthermore increases the discoverability of green spaces for species. These created, resilient and extensive green-blue networks establish a robust ecosystem and thus improve the overall biodiversity of a country (Aghina et al., 2023). Hence, not merely preserving, but moreover improving urban biodiversity has fundamental benefits for all living species.

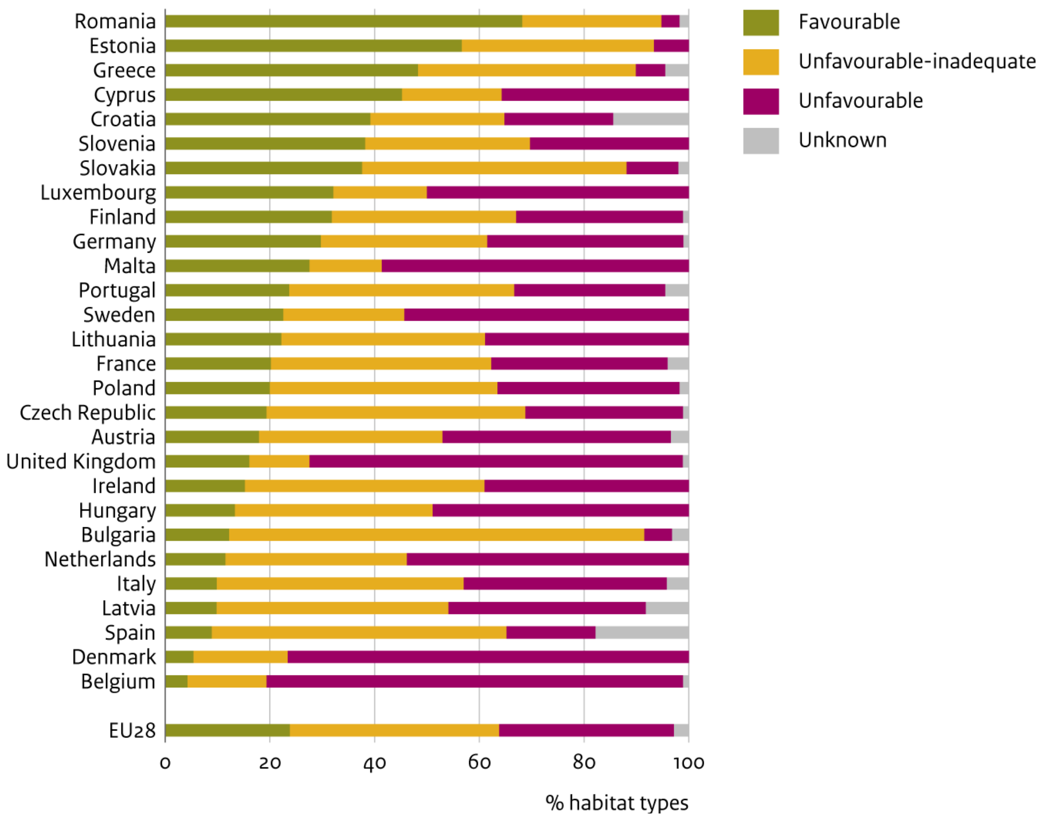


Figure 4. Conservation statuses of habitat types 2013 - 2018 (Source: CBS et al., 2020)

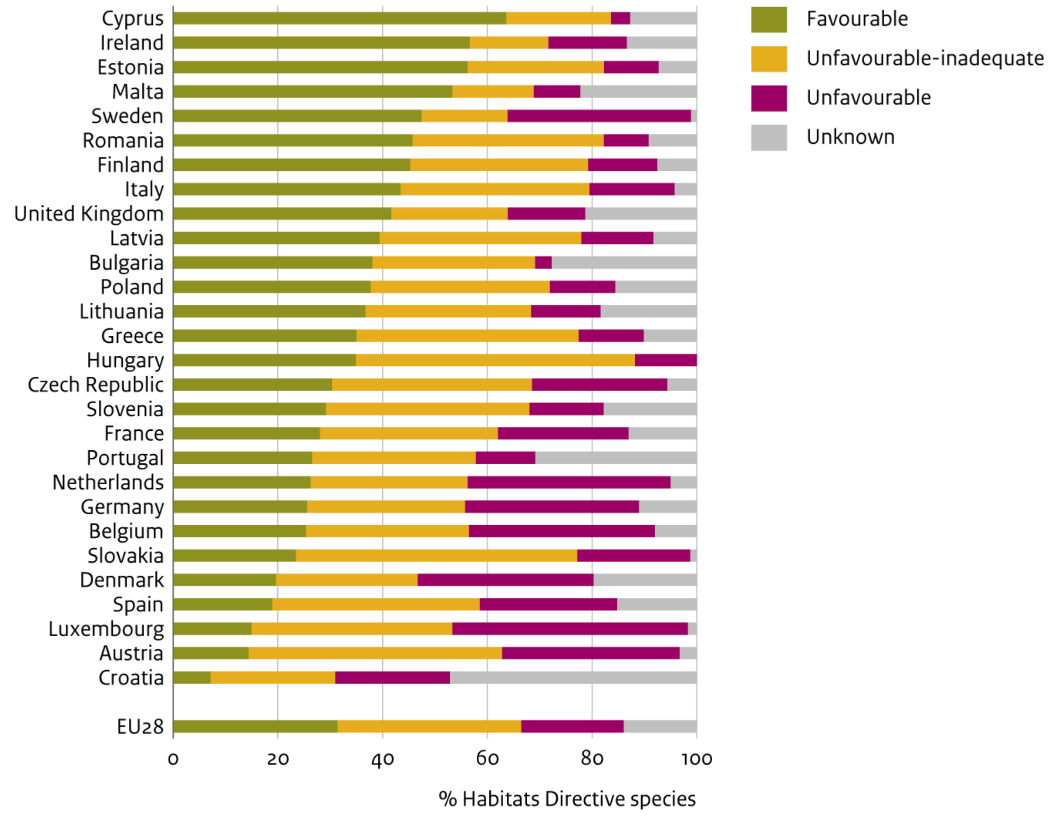


Figure 5. Conservation statuses of habitats directive species 2013 - 2018 (Source: CBS et al., 2020)

Making the transition possible

As briefly stated in the previous sections, on the road to transitioning towards a circular, greener and more biodiverse built environment many obstacles are encountered and therefore it is not something to be achieved over a short period of time. Human behavior and their ingrained (lifestyle) habits being a significant cause for this slow transition and since behavioral patterns of patterns in these habits and practices do not change, they persist (Dijkshoorn-Dekker et al., 2020). Clarifying, Wood and Neal (2009) state that habitual behavior occurs unknowingly and is triggered by the surrounding environment and habits are often not predicted by intention (De Bruijn et al., 2008).

Consequently, increasing awareness of circularity and biodiversity related topics at a young age positively affects the transition phase the world is encountering.

Explanatory, research shows that when children experience nature from up close, they develop a sense of responsibility and involvement: a nurturing attitude towards nature. Furthermore, they learn about different aspects of nature and the importance of its preservation (Van den Berg et al., 2007). Another study from the Raad van het Landelijk Gebied (2008) shows that modern-day children who learn about green surroundings at an early age, later in life more probable be concerned about the variety in nature, healthy food and landscapes. Assumingly, these results could also be achieved in circular and sustainable design related fields.

0.2 Problem statement

It is a known fact that the global climate is changing, but even the rate of its change is intensifying. Further changes in precipitation patterns, extreme events such as the increasing frequency of high temperatures as well as rising see levels are expected to occur as it is expected that by the middle of the century the global mean temperature will rise to 1.5 °C above pre-industrial levels (Masson-Delmonte et al., 2018). They state that several calculations explain that the production of global greenhouse gas (GHG) emissions must be radically lowered within the next decade if we want to escape from even further serious impacts on ecological and human systems.

Stating the obvious, rapid and drastic actions are necessary to save our planet. In decreasing the GHG emissions, changing our behaviour according to material use can have a substantial impact. Behrens (2016) states that there is a direct physical relationship between the quantity of in industrial processes used raw materials, the energy required and the GHG emissions, as he concluded from several studies that the GHG emissions are responsible for approximately 83% of material outflows by weight in 2010. These emissions are emitted during all stages of the product lifecycle, whereas the production of raw materials is accounted for around nineteen percent and the waste sector for another three percent of global GHG emissions. Shifting from a linear "take-make-waste" towards a circular economy, the CO2 emissions of Europe's largest sections of food, mobility and the built environment would decline as much as 48% by 2030 and 83% by 2050 compared to the 2012 levels (Ellen MacArthur Foundation, 2015).

Transferring to circular strategies is thus a crucial approach to fight climate change. According to the Ellen MacArthur Foundation (n.d.-a), the circular economy is based on three design driven principles: eliminating waste and pollution, circulate products and materials (at their highest value) and regenerate nature. Hence, utilizing waste and reclaimed materials for (new) products instead of the production and processing of primary materials, will contribute to mitigating the GHG emissions and meeting the Sustainable Development Goals (SDGs) of the United Nations.

Another vital role in supporting efforts to mitigate the negative impacts of climate change is appointed to our global ecosystems and biodiversity (Kapos et al., 2019). Contrarily however, climate change directly affects biodiversity, as it rapidly changes the structure and functioning of ecosystems and therefore poses a significant threat to the services that ecosystems offer (Dasgupta, 2021). Reducing the UHI-effect is one of those supporting efforts, as introducing more nature in urban environments can decline the local heat stress, considering the cooling effect of vegetation. However, cities are only expanding due to the trend of urbanisation (World Bank, 2023) and the current housing shortage in the Netherlands (PBL, 2023), which induces the dilemma of facilitating more living spaces on one hand and preserving and enhancing nature on the other hand. Looking at the surface area of building envelopes, implementing nature-inclusive solutions has a high potential in greening the urban environment, since facades contain large unused surface areas in cities. Greening facades as a potential solution for the UHI-effect, leaves enough space for humans to reside and furthermore, simultaneously improves the environmental conditions for not only humans, but all sorts of species to thrive.

0.3 Objectives

Main objective

Resulting from the problem statement, the main objective of this graduation project is defined as follows: Design a low-tech, three-dimensional, circular façade cladding system (product) utilizing waste materials and which fosters biodiversity in urban environments in the Netherlands.

As stated in the background information, children who get in contact with nature in an early state, are more likely to concern about nature related topics later in their lives. Hence, the focus for the design of this thesis lies with school environments, resulting in the low-tech aspect of the design objective. By all manners, the design should be approachable, workable and safe for children in a primary school age. They should be able to assemble the façade system and if feasible they would preferably be involved in the production of the product as well. Collectively, this encompasses the strategy of increasing awareness and interest among children regarding circular design, nature and biodiversity.

Regarding three-dimensionality, it is assumed that to develop a biodiversity enhancing façade system, three-dimensional elements are necessary in the design.

Concerning the circular aspect of the objective, a circular product can be accomplished in many ways as briefly mentioned in the background information. This graduation project, however, focusses on the circular design approaches of Modularity and Design for Disassembly (DfD).

Elaborating on the definition of façade cladding, a façade can have many functionalities as described by Klein (2013). Regarding this thesis, the main secondary functions, as Klein characterizes them, provided by this to be designed cladding system are 'keeping materials and components in working condition', 'creating reasonable production and assembly methods', 'keeping the climate within a given range', 'enabling reuse and recycling' and 'responding to urban context'.

To clarify the term waste materials as it is used here, it includes materials that are reclaimed at the end of their primary service life, discarded materials or re- or upcycled materials. As material transportation also has a significant contribution to GHG emissions, all utilised materials should have a local origin whenever possible. Lastly, since it is expected that the final product will consist of several materials, it is possible that the several aforementioned waste streams are combined in the design of the system.

Lastly, in regard to fostering biodiversity it is intended to improve the local urban ecology by attracting various fauna species to and incorporating several flora species in the system. This can be achieved through several design interventions which are to be explored in this thesis.

Sub objectives

Next to the main objective, several sub objectives are compiled to facilitate the achievement of the main objective. These sub objectives are:

- To identify low-tech, three-dimensional production techniques which are capable of processing of waste and reclaimed materials.
- To select secondary materials which are suitable for exterior façade purposes and the implementation of biodiversity, according to the design of the product.
- To design a low-tech fixing system which meet the DfD standards and is applicable to existing brick facades.
- To develop a Biodiversity Map, containing requirements of several

flora and fauna species, that guides the designers / users of the product on a particular site which species can be implemented to enhance local urban ecology.
- To select a school building in Delft as case study site and implement the design of the system on that building regarding the (ecological) local conditions.

Scope
Concerning the restricted time frame of this thesis, the scope of the project is limited and encompasses the following aspects:

Regarding the implementation of green in the system, this research primarily focusses on enhancing biodiversity in the local environment. Other benefits of vertical vegetation are briefly discussed, however aren't a part of the design guidelines for the system.

Additionally, the product will be designed for existing brick facades in the Netherlands. Brick facades are a common façade cladding in the Netherlands, also for school buildings, which is the target area of the project, and are therefore eminently suitable to form the structural foundation of the system.

Furthermore, structural calculations for their contribution to the feasibility of the system are not included in this thesis.

Moreover, as the Netherlands counts around 48.000 flora and fauna species, there is a selection made of urban reliant species based on parameters which are drawn up in the Biodiversity Section.

Lastly, although the low-tech aspect of the design plays an important role in this thesis, the decisions made related to the involvement of children regarding this aspect, are made primarily on assumptions of the capabilities of children around the age of 8 to 12 years and an extensive research concerning this subject is not a part of this thesis.

Expected outcomes
So, to conclude, the goal of this thesis is to reach the following outcomes: (1) an overview of suitable waste materials to use for the façade system or as one of its parts, (2) a fixing system for the panel which is applicable to existing brick façades and is designed according to the DfD-approach, (3) a diagram with a mapping of considered biodiversity species present the Netherlands, which serves as a design tool for the customization-aspect of the façade system, and finally (4) experimenting with and testing of the design through (digital) models and prototypes which then results in a final three-dimensional façade cladding panel that considers all the mentioned aspects.

0.4 Research questions

Main research question
The main research question of this study is as follows:

"How can a low-tech, three-dimensional, circular façade cladding system be made utilising waste materials and fostering biodiversity in urban areas of the Netherlands?"

Sub research questions
To be able to fully answer the main question of this thesis, the following sub questions are drawn up:

1. What is the influence of the considered circular approaches and strategies on the design process for this project?
2. Which low-tech manufacturing techniques are available to generate a (three-dimensional) façade cladding component?
3. What types of waste materials are suitable for a (three-dimensional) façade cladding panel or one of its components and how can they potentially be processed into a cladding component?
4. Which nature-inclusive façade systems currently exist and which of these typologies could be applied in this project?
5. Which factors are relevant for flora and fauna species to be engaged and suited for facades?
6. Which species are considered for this study and what are their requirements in order to successfully thrive in or around the system?

Background questions
To gain more knowledge for the research of this thesis some background questions are presented. These questions are not necessarily been answered in this report, but they do form part of the research and provide the author with the required information.

- What types of waste materials are suitable for the application of biodiversity in a cladding component?
- Which circular fixing systems can be made of reclaimed materials?
- What are important aspects to consider when designing one façade panel which must fulfil various options of potential biodiversity implementations, such as nesting boxes and planters?
- What are the effects of implementing biodiversity in urban areas?

0.5 Design questions

Since this thesis consists of a strong design and build component alongside the research section, a design question was formulated to guide the design process. Additionally, the outcomes of the research questions form the building blocks to answer the design question.

Main design question
Where the research questions focus more on finding the suitable materialisations of the design, the design concept regarding the considered circularity approaches and which species can thrive in building environments, how biodiversity is implemented is the focal point of the design questions, which will eventually shape the design to its final state utilizing the research guidelines. Therefore, the main design question for this project is:

"How can various biodiversity fostering functions be implemented in a three-dimensional, circular façade cladding system, designed according to low-tech design principles, aiming to foster local biodiversity in urban areas in the Netherlands?"

Sub design questions

To support the answering of the main design question, three sub questions are compiled.

1. How and where is biodiversity currently present in urban areas?
2. What are possible application methods of biodiversity in building envelopes?
3. What are the possible low-tech design solutions for the system, regarding circular design, manufacturing and maintenance, which potentially are also suitable for involving children in in these processes, hence increasing their awareness of circularity, sustainability and biodiversity related subjects?

0.6 Methodology

Now the scope of the research is defined and explained, it is important to look at how this will be achieved. In line with the thesis topic (what), the methodology (how) is segregated in the same three sections: circular design, waste materials and biodiversity. However, the findings from one division might affect the decision-making for another, so to clearly state these relations, a diagram is presented at the end of this paragraph.

The research starts with performing literature studies for all three divisions simultaneously. For circular design the research is all in relation to (three-dimensional) façade cladding. Looking at the four domains of circularity, this thesis tries to address all four of them in the design and with the literature study the aim is to gain knowledge about the circular approaches modularity and DfD and keeping this in mind, find low-tech, circular production techniques for the system.

These production techniques however should be suitable for the waste materials that are selected through literature review. From looking into waste streams in the Netherlands a few materials will be selected for the next phases of this study. As mentioned earlier on, the term waste in this thesis regards to two of the three circular principles, i.e. eliminate waste and pollution and circulating products and materials, and the primary focus lies with the R-strategies Recycle (or upcycle) and Repurpose.

For the biodiversity section of the literature study building reliant animal and insect species and various plant species from the Netherlands will be analysed. Additionally, the factors that influence biodiversity in urban areas are explored, wherefrom a set of parameters is chosen to guide the decision-making for which biodiversity species will be implemented in the design. These species then will be mapped into a diagram, the Biodiversity Map, which will serve as a design tool for the customization of the configuration of the design on a particular location.

Furthermore, analysing several case studies for the three divisions is part of the literature review and additionally the option of getting in touch with primary schools or gaining real-life flora and fauna data are considered. These approaches will help to get a better understanding of the topic and will provide inspiration, as well as focal points.

The second phase of the thesis, which will partially overlap in the time schedule and furthermore interacts with the literature study, follows the concept of Research-by-design. The outcomes of the literature study shape the guidelines of the system regarding the production and materialisation of the panel. Through experimenting and testing with sketching, physical and 3D modelling, the final design will be established. Concluding, the design will be placed in a chosen context, a primary school in Delft and according to the created Biodiversity Map a design example will be presented.

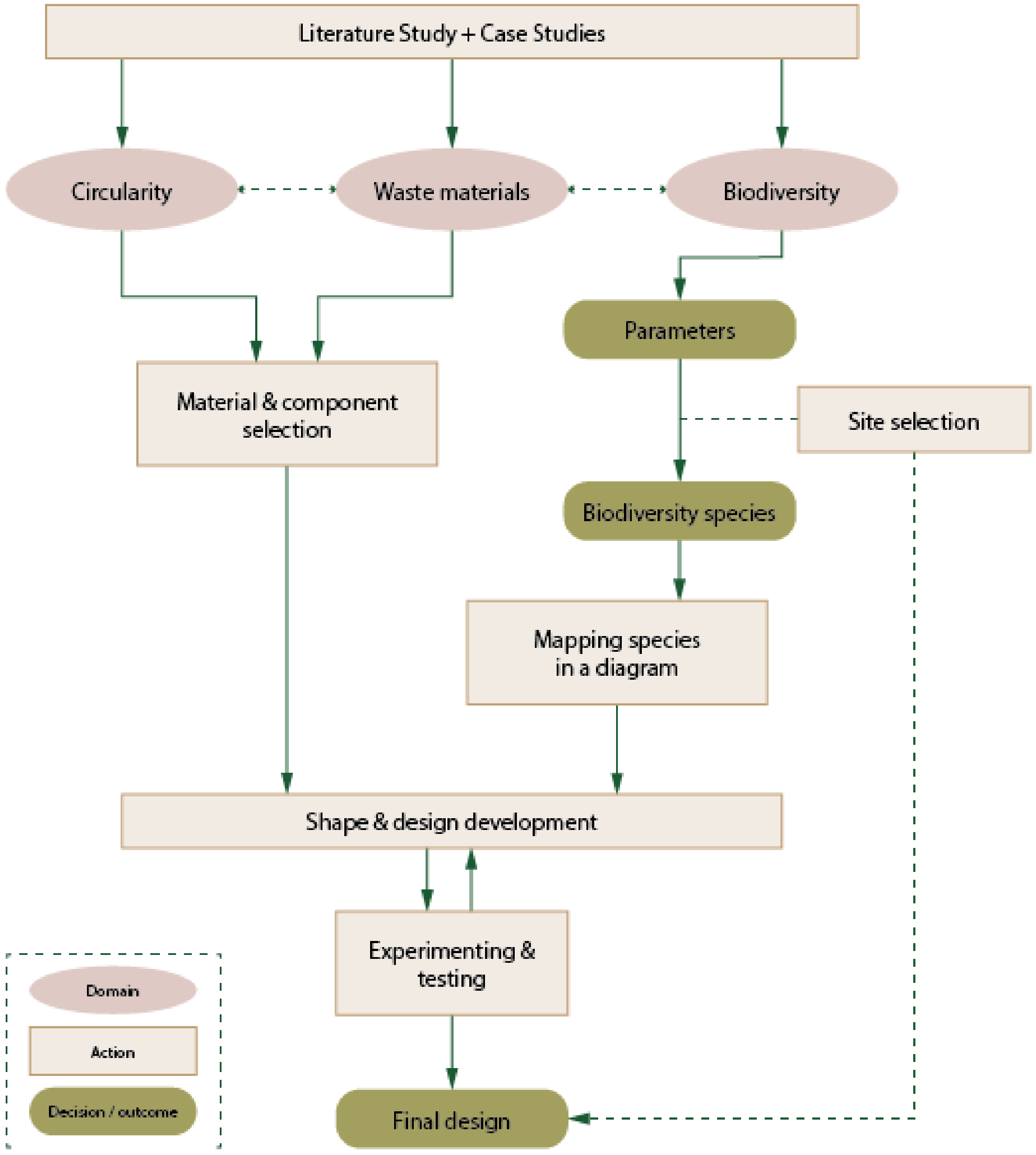


Figure 6. Methodology Diagram (own illustration).

0.7 Relevance

The design of a low-tech, circular façade system utilizing reclaimed materials and fostering local urban biodiversity in school environments can express its relevance in respect to societal and scientific themes by various manners.

Societal relevance

The circular façade system can serve as a tangible example of circular design concepts in action. It illustrates how materials can be reused and repurposed rather than discarded, reducing waste and promoting resource efficiency. Additionally, introducing children to sustainable and circular design concepts through hands-on experiences in school environments can be highly effective in fostering an understanding and appreciation for environmental stewardship from a young age. This can lead to encouraging children and their families in living a more sustainable lifestyle and thus more environmentally conscious and responsible future generations.

The use of reclaimed materials for the façade product can add unique and attractive features to urban buildings. These installations can therefore become focal points that inspire community engagement and pride, contributing to improved aesthetics and functionality of urban spaces. Moreover, as children can be involved in the design, maintenance and possibly the manufacturing of the product, it could lead to a sense of ownership and responsibility for local ecosystems which might be spread beyond the school boarders and affect and inspire local communities as well for similar interventions.

Lastly, urban areas often lack green spaces and habitat for wildlife, whereas façade cladding products that support biodiversity can help create these urban wildlife sanctuaries. Besides its contribution to a more resilient urban environment, helping to mitigate the effects of climate change, it allows children to witness these positive impacts on local ecosystems and endangered species in their own school environment.

Scientific relevance

The concept of circularity in the built environment and nature-inclusive buildings has been steadily growing interest and attention over the past years. The design of such façade systems as proposed for this thesis can contribute to the development and knowledge gaining of circular and nature-inclusive building designs. Regarding the latter, it offers the opportunity to conduct scientific research on how different species interact with the constructed habitats, which species are attracted, and how biodiversity changes over time in urban environments. Simultaneously, the local biodiversity can be monitored and the collected data can contribute to scientific research on the effectiveness of such initiatives, increasing our understanding of urban ecology.

The exploration of low-tech production and processing techniques of reclaimed materials can provide knowledge in accessible and low-cost methods of reducing the amount of waste. Demonstrating this in a school environment combined with other elements, such as ecology, biology, (circular) design and architecture, it serves children an interdisciplinary learning opportunity which can stimulate their scientific curiosity.

Finally, these small-scale façade interventions can assess the scalability and replication of such systems in different urban contexts, contributing to the creation of a more resilient green and blue infrastructure throughout cities and furthermore advocating for similar circularity and ecology related initiatives in neighbourhoods, stimulating more comprehensive policy decisions related to circular driven actions, enhancing urban biodiversity and environmental education.

A

Circularity

01

Circular Façade Design

1.1 Introduction to circular design in the façade industry

Circular principles

As described in the Introduction chapter, the CE's fundament is based on three design driven principles. In this section, these principles as defined by the Ellen MacArthur Foundation (n.d.-a) are being addressed in relation to the topic of this thesis and furthermore several inspiring case studies are analysed on how circularity is applied in those designs, providing inspiration for this project.
The first principle is all about shifting our mindset towards waste being a concept introduced by humans, meaning it is actually a result of poorly made design choices. In this manner, paying attention during the design phase to the circulation of the façade systems' products, can eliminate the concept of waste from the design.

Although strongly related to the first principle, the second one of 'circulating products and materials' is mainly about the designer being aware of the two separate material cycles and the critical demand of avoiding products which are a combination of materials belonging to the technical or biological cycle, but cannot be disconnected from each other, hence ending up as waste. The for this thesis considered circular approaches of modularity and design for disassembly form the fundamental ground for the execution of these first two principles.

Lastly, there is the principle of regenerating nature. The part of this last principle that is related to this graduation thesis, is the aspect of implementing the first two principles in the design concept, which will establish more available land, as materials are kept in cycle and thus no land space is necessary for this system. These saved land spaces, even in the smallest portions, can be returned to nature and consequently giving it space to restore its wild, native environment. Additionally, as the system is using existing, unused facades, new spaces owned by nature are created where the present local ecology can create new habitats and natural ecosystems are reinforced.

The four domains of circularity

The four domains of circularity according to Ioannou and Klein (2022) i.e., design, materialisation, manufacturing and management, are performing as design guidelines for circularity related decision-making during this project. To clearly define each domain in relation to the research and design field of this thesis, the domains are introduced hereafter. Although, this project aims to include all four the domains in the system, it is probable that the final product is not extensively or equally elaborated among all the domains.

Design
When designing a circular product, it is key to remember the architectural features of the product, internal and external. Respectively, the designer must question whether the products' parts are demountable (internal) and if the connections to the building (or another direct context) are demountable (external). Additionally, with the design of the product, the designer cannot only influence the amount of waste generated during the design process, but also optimise the quantity of materials used for the design. All these characteristics are to be considered for the design of a biodiversity fostering façade system.

Materialisation
For the materialisation of the product, several key considerations should guide the selection of materials to ensure both sustainability and longevity. Firstly, it is advisable to minimise the number of unique materials used, preferring the avoidance of critical raw materials whenever feasible. Secondly, the origin of materials should be considered, in terms of location and the technical or biological flow they belong to, favouring the latter over the first. Lastly, assessing the estimated lifetime of the product and its components is crucial in which the chosen materials should align with this expected lifespan. Implementing the mentioned aspects, it will positively affect several principles like, the products' production process and its environmental impact.

As the materialisation of the product for this thesis is a key objective to the design, in the next chapter additional research will be conducted to identify suitable reclaimed materials, while taking into account the before mentioned considerations.

Manufacturing
Regarding the third domain, an energy and resource efficient manufacturing process will contribute to a decrease in embodied energy, material consumption, waste production and its overall environmental impact. Additionally, awareness of the impact of design and material choices, can increasing the circularity of the product in terms of its production, as well as optimizing this process to the chosen design and materials, meaning that it could deviate from traditional manufacturing techniques when circular approaches and materials are applied. Finally, the circular value is affected by the required skilled labour and extensiveness of equipment necessary for the manufacturing.

Of these listed aspects, the latter is assumingly the one which is considered the most during this research since the aim to design the system according to a low technical manufacturing method and the possibility of children involving in this process. These potential low-tech methods will be explored in the next chapter of this report.

Management
The last domain of circularity is affected by al the remaining three domains, as all the earlier mentioned considerations could influence the strategy and decision-making of various stakeholders. Moreover, which companies are involved in the process can change whether the design is pursuing a linear or a circular approach. By the means of this thesis, companies providing primary materials will be irrelevant whereas those offering secondary, reclaimed materials or recycling companies are a key chain in the management process. Additionally, material choices of the product will determine whether the main users of the product, school children, will be able to manufacture the modules themselves or not, hence influencing the concerned stakeholders.

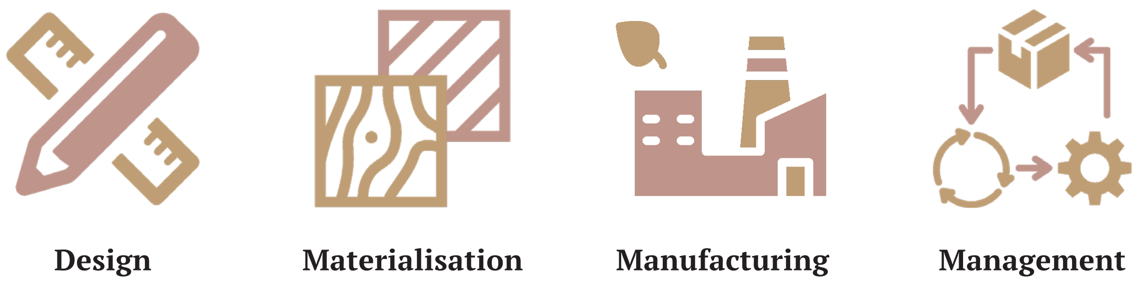


Figure 7. The four domains of circularity (own illustration)

1.2 Circularity case studies

Pretty Plastic

Pretty Plastic is a company co-founded by three designers who produce façade tiles made of 100% recycled plastic recovered from the building sector, primarily being PVC. They are easy to install with just screws, saw and an underlying layer of wood and are fully recyclable after use. As the company originates from 2015 their product is applied to several buildings since then, including the People's Pavilion of the 2017's Dutch Design Week and the Circle House project in Denmark, of which the latter is studied subsequently. Moreover, they launched their second tile design, working with a slightly different installation principle, now needing an underlying aluminium grid. Nonetheless, the installation of the tiles is just as simple as before.

This company represents an impressive example of how circular products can be designed, produced, maintained and brought back into the closed loop after use. Pretty Plastic complies with the three principles of a circular design and moreover shares their knowledge by providing free-accessible installation manuals, hence speeding up the transition phase towards a circular and sustainable future.

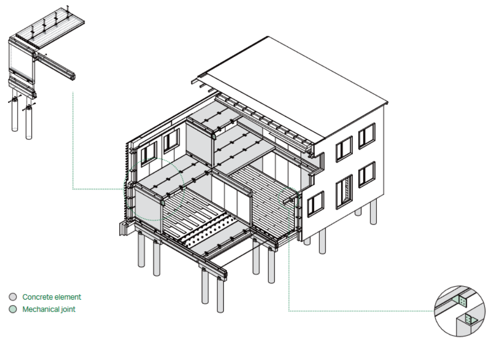
Figures 8 & 9. Pretty Plastic façade tiles "First one" (Source: Pretty Plastic, n.d.)

Figure 10. Render of the application of Pretty Plastic façade tiles "Second high" on a building (Source: Pretty Plastic, n.d.)

The Circle House project

Aside from being a social housing project consisting of 60 units, the Circle House serves as a 'knowledge hub' about circularity in architecture and construction for the building sector. A main objective of the project is that 90% of the used building materials can be reused without significant loss of value, aiming to retain their function in another building (see figure 11). Furthermore, the project contains a 1:1 mock up called the Demonstrater where all its layers, products and materials are uncovered, displayed and described. It functions as a catalogue of available solutions regarding circular building strategies, promoting the companies' circular products, like Pretty Plastic, to a wider audience and moreover educates visitors about CE principles.

Operating as a showcase and providing interested parties with information and inspiration is actually relatively similar to this project's aim of educating children and increasing their awareness of topic such as circularity. Hence, the strategy of making the considered circular solutions like connections, visible in the project is an engaging take-away point.



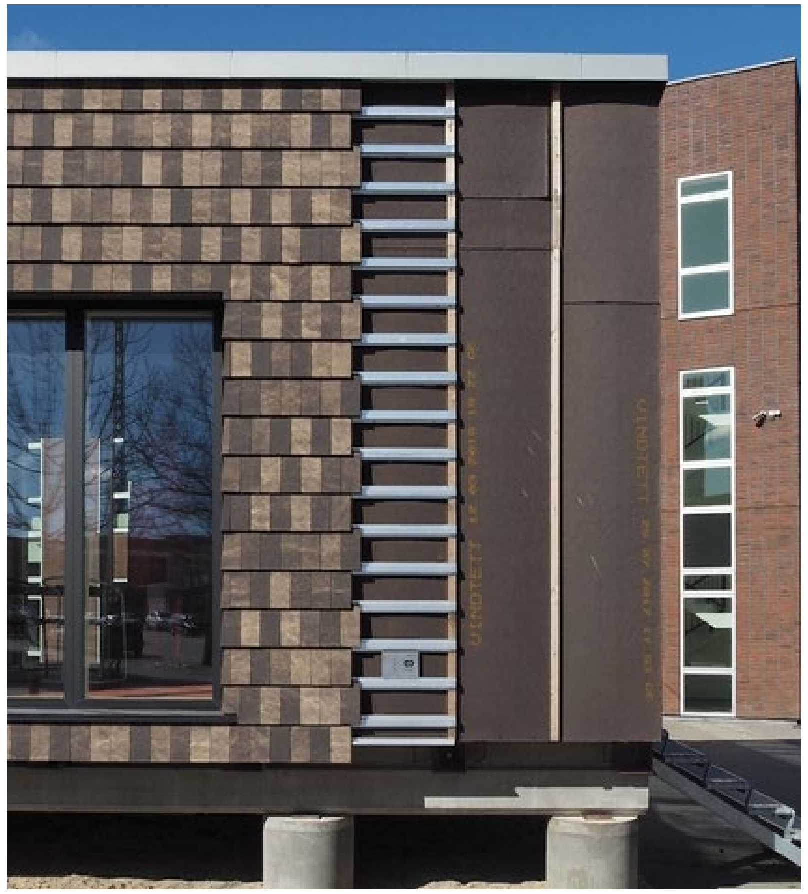


Figure 11. Building structures of the Circle House (Source: GXN 3XN, n.d.)

Figure 12. Pretty Plastic tiles on the Circle House Demonstrator (Source: GXN 3XN, n.d.)

Figure 13. The Circle House Demonstrator with visible façade layes (Source: GXN 3XN, n.d.)

1.3 The considered circular approaches: Modularity and Design for Disassembly

As stated in the Introduction Chapter and the previous paragraphs, circularity in (building) designs comes forward in many principles and several approaches. In this thesis the circularity aspect of the projects is based on the approaches Design for Disassembly (DfD) and Modularity and furthermore considers several of the R-strategies of circularity as previously presented in the Background information. To clearly state the definitions of the first to mentioned regarding this research, they are elaborated below, whereas for the latter, the considered R-strategies of this thesis are briefly appointed.

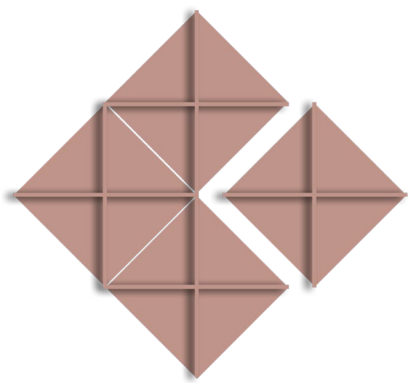


Figure 14. Modularity diagram (own illustration)

Modularity

As defined by Ioannou (n.d.) the concept of a modular system lies with the system consisting of separate, standardised elements which can be compiled and connected to each other, while they remain independent parts of the whole. One undeniable benefit following from the use of this concept of modularity, is that individual modules can be replaced or repaired without affecting the entire system (Ioannou, n.d.), thus making it easier to disassemble and consequently lowering the effort and costs of this action of replacement (Ellen MacArthur Foundation, n.d.-b).

Additionally, a system that is designed according to the modular concept includes subsystems which can create different product configurations by changing the assembly of those parts, establishing several variants of the product, while maintaining the limited number of unique parts (Ioannou, n.d.). This results in a customisable system that is able to adapt to the fluctuating and forever needs of customers and therefore forestalling the product from becoming obsolete and keeping it in the loop for longer periods of time (Ellen MacArthur Foundation, n.d.-b). However, an occurring design related challenge regarding this advantage is that once the modules are at the end of their lifespan and released from their context, they could have become outdated, hence less likely to reused in a different environment (Ioannou, n.d.).

Applying the before-mentioned strategies to the design of the façade cladding for this thesis, could elevate the design concept to a higher level. After all, it is crucial to maintain a simple, low-tech design for participation purposes of schoolchildren, while simultaneously providing spaces for divergent biodiversity species, all having their own needs and preferences, is another aim of this project. Hence, the concept of modularity and its ability to create varying configurations with a limited number of different elements, will be a key consideration during the design process.

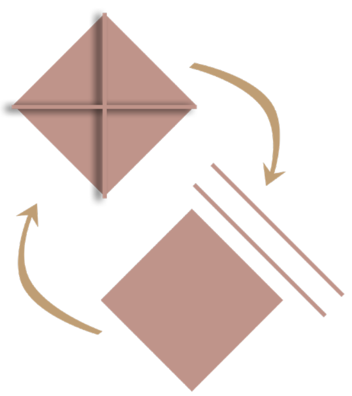


Figure 15. Design for Disassembly diagram (own illustration)

Design for Disassembly (DfD)

One approach within circular design is Design for Disassembly (DfD), by Guy and Ciarimboli (2006) defined as "the design of buildings to facilitate future change and the eventual dismantlement (in part or whole) for recovery of systems, components and materials". They state that aside from flexibility and convertibility, DfD enables addition and subtraction of whole-buildings, therefore contributing to avoid removal of buildings altogether. Agreeingly, Guldager Jensen et al. (2018) describes that this holistic design approach has the intention to make any given product easy to disassemble into all its separable components, making them fit into a closed material cycle ready to be reused, reassembled or recycled into new products of similar or higher quality.

According to Guldager Jensen et al. (2018) the key aspect to remember of DfD is that the connection must be reversible without damaging the components when two or more components are put together. Thus, dry connections like screws and nuts and bolts are preferred over nails as well as wet binders, like glue. Furthermore, they state that the connections must be easily accessible and preferably visible to ensure easier deconstruction and in terms of materiality the quality of the used materials should be able to withstand (re)use over time and prevent wear-out conditions as long as possible.

Key Principles for DfD
For the concept of DfD there are in total ten key principles and many detailed strategies (Guy & Ciarimboli, 2006), most of them regarding materials and connections. Those of most relevance for this thesis are presented and clarified here.

That there is a strong relation between the concepts of modularity and DfD already seemed to be correct, however with interchangeability being one of the DfD key principles, it can be stated with certainty. This principle means that reuse of the product will be facilitated whenever modularity, independence and standardization principles are exhibited on the used materials and systems. In the previous paragraph is already discussed how this could be considered for this design project.

Additionally, simplicity in structure and form of the design and minimizing the number of varying component types will allow an easier understanding, manufacturing, construction and deconstruction of the system and increase the quantities of similar recoverable parts. As the low technicality of the system is one of the objectives, this is certainly a feature to guide the design process. Especially since creating cladding system which is three-dimensional is highly expected due to the implementation of biodiversity, it will be key to search for this simplicity in shape and structure and avoid complex three-dimensional elements. Fewer distinctive components will also ease the building process for the children participating in this action.

The documentation of materials and methods for deconstruction and ensuring safety during the phases of construction and deconstruction are also crucial features of the DfD approach. Although something like a 'construction guide' is not opted as an outcome of this project, it will definitely be of significant value for the school that will be at least partially responsible for construction and maintenance whenever the system is to be applied to their building envelopes.

Materials
Efficient Design for Disassembly (DfD) principles entail several key considerations regarding materialisation. Firstly, minimizing the variety of materials used, helps reducing complexity and the number of separation processes during disassembly, streamlining the recycling and reusing process. Secondly, it's advisable to avoid secondary finishes like adhesives and coatings that can

obstruct connections and complicate the disassembly process, potentially leading to unnecessary material waste. Thirdly, the preference for lightweight components and materials is beneficial due to their ease of handling and reduced reliance on heavy equipment and labour. These three features are all relevant to the design of the system in this research. Considering the avoidance of secondary finishes, it will be important to select materials that can withstand external conditions. In the next chapter, this will be further explored.

Moreover, flexibility within a material type is crucial for effective renovation and reuse. This flexibility encompasses both physical adaptability and the material's capacity to fulfil multiple purposes and adapt to diverse user needs. Lastly, considering the service life of materials is vital for a strong DfD design as separating longer-lived and shorter-lived components and materials allows for a more strategic approach to disassembly, making it a fundamental concept of DfD (Guy & Ciarimboli, 2006).

Connections

It is undeniable that the design of connections is a crucial aspect of designing for disassembly, whereas the type of connection determines whether or not it can be successfully disassembled. Several connection typologies are listed in table 1 and furthermore, Morgan and Stevenson (2005) distinguish three categories: direct, indirect and infilled connectors.

Of those three categories, indirect connectors have the highest DfD potential as they are interchangeable and independent from the construction. Disassembling of direct connectors is usually more difficult, however feasible, as they interlock or overlap with components. The latter category represents connections like glued or welded ones, which are impossible to deconstruct unless the used filler is very soft, such as lime mortar. The three categories are illustrated in figure 16.

The most effective fixings are those that possess durability themselves, can withstand repeated assembly and disassembly procedures and actively contribute to preserving the structural integrity and appearance of the construction elements they join, especially during the deconstruction process. Additionally, reuse opportunities will increase and the products' lifespan will prolong when 'fixing free zones' are designated in the module and the number of notches, cuts and holes are minimized.

Summarizing, two essential principles for crafting connections that can be easily disassembled while maintaining the integrity of all components are firstly, avoiding the occurrence of connectors interpenetrating with the components whenever possible and secondly, always favour dry-jointing methods, such as bolted or screwed connections, over chemical bonding techniques (Morgan & Stevenson, 2005). The main take-away for the to be developed system of this thesis is therefore that dry-joints are prioritised and chemical connections are excluded. However, their resistance to weather conditions should be considered for the applied connections since this research concerns the design of an external façade cladding.

In addition to that, Guy and Ciarimboli (2006) describe several considerations which will optimise the disassembly process of the design. Firstly, the connections must be accessible and the process of connecting should be understandable. Regarding the design of an add-on façade system, inaccessible connections at the back of the system should be avoided or solved in an alternative manner. Considering the aim of involving children in the construction phase, the connections should essentially be simple and understandable for them to execute. Consecutively, the second consideration is to endeavour the simplest connections as possible in terms of required tools and actions. Thus,

Type of Connection	Advantages	Disadvantages
Screw	easily removable	limited reuse of both hole and screws cost
Bolt	strong can be reused a number of times	can seize up, making removal difficult cost
Nail	speed of construction cost	difficult to remove removal usually destroys a key area of element - ends
Friction	keeps construction element whole during removal	relatively undeveloped type of connection structural weakness
Mortar	can be made to variety of strengths	mostly cannot be reused, unless clay strength of mix often over-specified making it difficult to separate bonded layers
Adhesives	strong and efficient deal with awkward joints variety of strengths	virtually impossible to separate bonded layers cannot be easily recycled or reused
Rivet	speed of construction	difficult to remove without destroying a key area of element - ends

Table 1. Connections Alternatives for Deconstruction (Source: Guy & Ciarimboli, 2006)

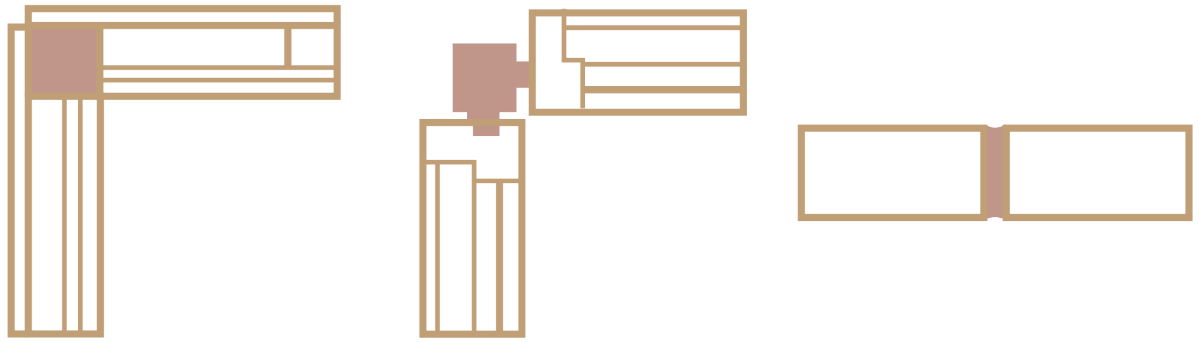


Figure 16. Direct, indirect and infilled connectors. (own illustration based on Morgan & Stevenson, 2005)

simple connections without the necessity of specialised or dangerous equipment are preferred for this thesis and the children that will assemble and maintain the product. Lastly, fewer connections mean it will reduce the labour intensity of the (dis)assembly process. Nonetheless, this might lower the products' flexibility in terms of reuse and recycling, moreover, increasing the number of materials that are still in good condition when a part of the module needs reparation, hence increasing unnecessary waste or material processing. Looking at the scale of the individual modules for this design project, most importantly the size must be manageable for children to work with, so large dimensions are unlikely to be constructed.

R strategies

As introduced earlier in this research, the R strategies (see figure 17) help a designer to conduct more circular decisions, whereas refuse will have the highest and recover the lowest impact. They function as a design tool during the whole design process, from the extraction of materials towards the destination at the end of the products' service life.

Considering this graduation project, several of the ten strategies are involved, spread amongst the three earlier mentioned stages of Smarter Use and Manufacture, Extended Lifespan and End-of-Life Application. Regarding the first stage, the strategy of **rethinking** is implemented, as the to be designed system will fulfil diverse functions simultaneously, such as serving as an educational tool for children and fostering biodiversity by various means. Collaboratively, this intensifies the products' use. In one way, **refuse** is also a considered strategy, because the aim is to use merely reclaimed materials for the design, hence refusing to consume primary materials.

The main focal point of this project however lies with the second stage in which the lifespan of the design can be extended. One of those incorporated strategies is **reuse**, whereas the concept of DfD provides as a tool to make the design suitable for reuse at a different location as well as the intention to reuse discarded products as a material source. As maintenance is an important factor in façade cladding in general, however especially in nature-inclusive façade systems, the **repair** strategy is certainly involved in the design process of the system. **Remanufacture** is a strategy that can include many processing steps like cleaning, repairing, quality control and adaptation of dimensions, which are all relevant to this design case. Additionally, remanufacture and **repurpose** are both methods employed in the development of this façade cladding system as discarded products are put into the loop of this design as a material source.

Lastly, it would be extremely valuable if a proper **recycling** strategy can be achieved for the design at the end of its service life. Next to the design's ability to easily be disassembled into its separate components, this is also dependent on the recycle potential of the materials used. This will be elaborated in the next chapter.

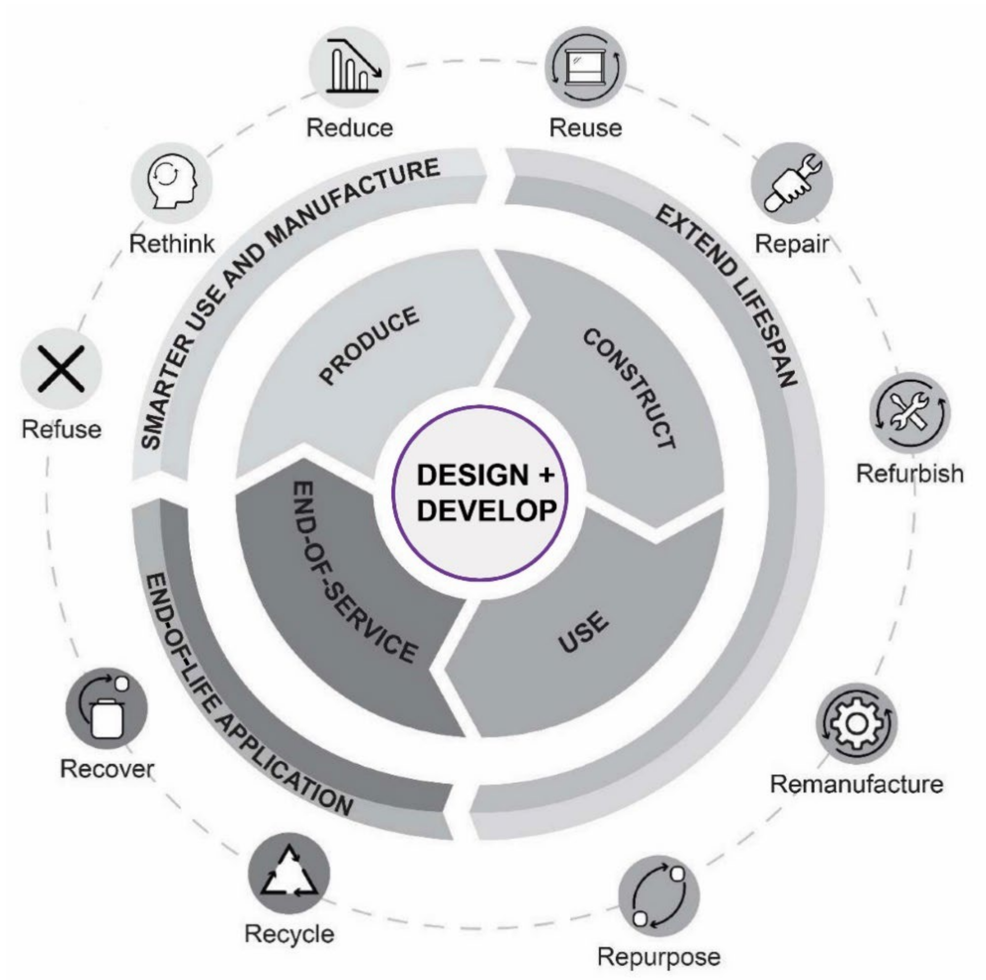


Figure 17. Distribution of R strategies amongst the three stages of Smarter Use and Manufacture, Extended Lifespan and End-of-Life Application (Source: Circularity for Educators, 2022)

02

Manufacturing & Materialisation

2.1 Introduction to three-dimensional façade manufacturing techniques

The rapid development of technology over the past decades also had its affect on the progression made regarding three-dimensional façade cladding production techniques. Several methods are briefly described here to gain understanding of those processes and their possibilities related to varying reclaimed materials.

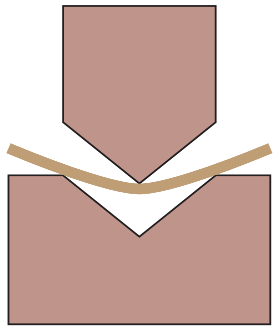


Figure 18. Bending diagram (own illustration)

Bending

The technique of bending enables architects and designers to create visually striking and unique building exteriors, adding an appealing dimension to modern architecture. Bending materials into three-dimensional shapes for facade cladding involves manipulating flat or two-dimensional materials like metal, glass, wood or plastic into curved or contoured forms, making it also possible to use reclaimed versions of these materials. Techniques include heat bending, roll bending, press braking, laminating and kerf-cutting, depending on the utilised material. Precision is vital, often requiring computer-aided design and specialized machinery and furthermore it can be considered as a labour-intensive process that may require specialised equipment.

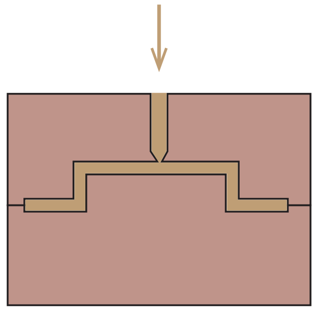


Figure 19. Moulding diagram (own illustration)

Moulding & casting

Although the processes of moulding and casting have several similarities, there are a few key differences to consider. Deciding on which technique to use, will primarily come down on the chosen material, whereas plastics are just for moulding and metals for casting, both potentially suitable for the implementation of reclaimed materials. A similarity, however, is that in both cases the melted material goes into a die or mould to generate the final shape.

In moulding, a form typically made of metal is injected with the material (injection moulding) and common types of moulding include thin wall moulding, gas-assisted moulding and, while being a production category of its own, 3D printing. Whereas the first two mentioned, the latter has relatively low costs and a wide availability and is therefore frequently used in prototyping.

With casting, the liquid material is poured into a form made of silicone rubber or a similar material (die casting) and the two primary types of this process are hot chamber casting and cold chamber casting. The latter is a typical process for metals with a high melting point, requiring the material to be melted elsewhere, whereas with hot chamber die casting, the material is heating inside the casting chamber, making it the preferred method.

Comparing the two processes, moulding is typically faster than casting and ideal for mass production. Furthermore, injection moulds allow for diverse types of materials and the technique of injection offers very accurate results. The pros of casting are that this process results in durable, high-quality products and it allows for a greater design complexity. Nonetheless, both manufacturing techniques also have their disadvantages. Injection moulds can be relatively expensive to create and the results may be less durable and of a lower quality than with casting. On the other hand, die materials for casting can be quite expensive and this process does not normally allow for the generation of large parts (Engineering Department, Pacific Research Labs, 2020).

Additive Manufacturing

Additive manufacturing (AM) is a computer-controlled process that creates three-dimensional objects by depositing materials, usually in layers and colloquially called 3D printing. Different AM technologies exist whereas with one the material is fully melted (melting) and with another the material is heated without being melted (sintering). Furthermore, there are several AM processes to be distinguished, like binder jetting, material extrusion, directed energy deposition and sheet lamination. Since this technique has a large variety of processes, it is suitable for many different materials of which plastics, metals, ceramics and biochemicals are commonly used. Moreover, the use of recycled or residual materials is often applied and the process itself reduces the material wastage. Additional benefits of AM are that complex geometries can be generated from one part in a short amount of time, which makes it ideal for prototyping. Lastly, it is a technique that is very approachable and has become available for a broad audience, as a small 3D printer is relatively cheap and some of the required software is available for free.

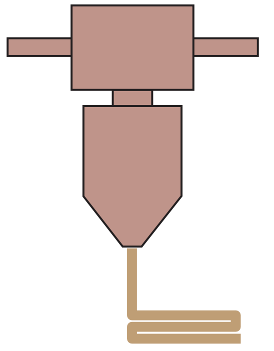


Figure 20. Additive manufacturing diagram (own illustration)

CNC routing and milling

Where in additive manufacturing a material is deposited, CNC milling uses the method of subtractive manufacturing. CNC routing and milling are precise machining techniques used to craft three-dimensional facade cladding elements from various materials like wood, metal and plastics which can also be from a

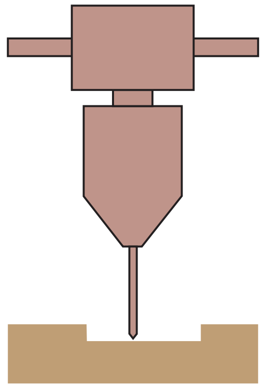


Figure 21. CNC milling diagram (own illustration)

secondary lifecycle. The process begins with a detailed 3D computer-aided design (CAD) model, followed by material setup and tool selection. A CNC program guides the machine's movements to cut and shape the material with high precision. CNC machining offers versatility, customizability and exceptional accuracy, making it suitable for intricate and customized cladding designs. However, it can be costlier and more complex than other methods, requiring skilled operators. These techniques are favoured for architectural projects that demand intricate, customized and precise cladding elements.

Vacuum forming

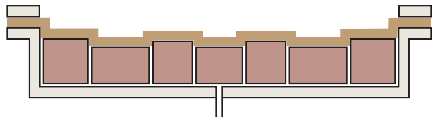


Figure 22. Vacuum forming diagram (own illustration)

Vacuum forming is a versatile and cost-effective technique used to shape flat thermoplastic sheets into three-dimensional facade cladding elements. It involves heating the (recycled) thermoplastic until it softens, then quickly pressing it over a mould with the desired shape and using a vacuum to create a tight fit against the mould's contours. Once the material cools and hardens, it retains the moulded shape. Vacuum forming is advantageous for its efficiency, cost-effectiveness and suitability for producing large quantities of light-weighted cladding components. However, it is best suited for relatively simple or shallow curved designs and creating moulds can be time-consuming and costly, making it ideal for projects where customization and complexity are not primary concerns.

2.2 Potential low-tech manufacturing techniques

Although the assumption is made that three-dimensional façade cladding is the solution to fostering biodiversity in the façade system, a more low-tech approach is preferred, it being a key aspect of the chosen design direction. Hence, the decision is made to explore the possibilities of creating three-dimensional elements with planar, thus two-dimensional components with a certain height, which better suites the low-technical approach of this thesis. Moreover, low-tech solutions fit perfectly in the field of circular design strategies and as well as being promising approaches when (young) people need to understand and work with the product, as is the case in this thesis.

In the optimal situation regarding the objective of educational purposes of the system, children can be involved in the manufacturing process of the façade modules. However, this limits the options for manufacturing techniques and furthermore requires physical space to facilitate the equipment necessary for production at the local school. Consequently, it is more realistic to presume that the façade modules will be delivered to the location as a building kit and it is designed in such a way that children can manage the assembling process. However, this still implies that complex geometries and assembling principles need to be avoided and low-tech manufacturing is favoured. Several low-tech manufacturing techniques, which have the potential to process reclaimed materials, for producing the modular elements are presented hereafter. Additionally, considering the modularity concept of the design, several construction principles are given to enable the assembling of the modular elements.

Low-tech manufacturing techniques

Sawing and cutting

Probably the most standard production technique by (non-professional) handymen is material processing through sawing and cutting. For small scale or the production of just one product, it can be done by hand, however using equipment such as sawing machines or drills increases accuracy and the production speed. Several methods include band, circle, hole and jig sawing. However, when more complex shapes are desired additional hand-labour is necessary, otherwise this technique is limited to mainly straight cuts, consequently resulting in simpler forms.

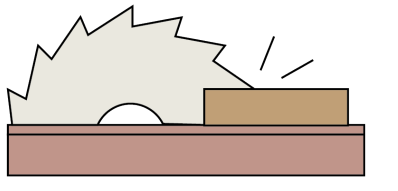


Figure 23. Circle sawing diagram (own illustration)

Undoubtedly, the most common material for sawing is any type of wood. However, the possibilities in terms of primary and secondary, reused materials are almost endless, so also several types of metal and plastics can be cut, as well as masonry or ceramics. Although, for some harder materials the cutting blade should be made from tougher materials.

Despite presumably being the most low-tech manufacturing technique, it can be very time consuming and requiring a lot of hand-labour without achieving the most accurate result. Collectively, this should be considered when deciding on an appropriate manufacturing technique for the design.

Die cutting and pressing

The principle of die cutting is simple and comparable to using a cookie cutter to cut the dough into smaller

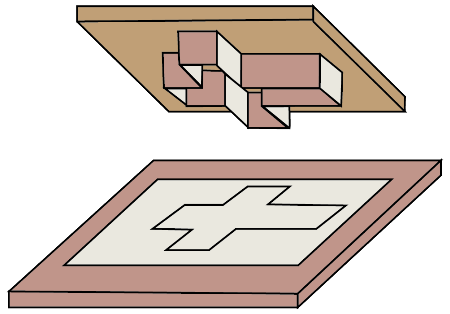


Figure 24. Die cutting diagram (own illustration)

pieces, however with this process shapes with a higher complexity can also be achieved. The die itself has sharp edges to pierce the material and modern die cutting is an automatic or semi-automatic process requiring CAD programs. Next to completely cutting through the material, other capabilities of a die cutting machine include kiss cutting, perforating and cut and crease scoring, broaching and flash cutting (IQS Directory, n.d.).

This production method can be executed with a large variety of materials, including fabrics, metals, wood, plastics, rubber, fiberglass and foam. Thus, the rigidity of the materials can differ, but the technique is also applicable to various material thicknesses and without further research, no limitations seem to occur in regard to using reclaimed materials for this process.

Although, the initial costs of die cutting are not that low, they are easily recouped by its efficiency, production speed, and excellent quality and accuracy. Concluding, die cutting is a simple and straightforward method, making it suitable for manufacturing low or high quantities and more importantly a promising low-tech way of creating façade panels.

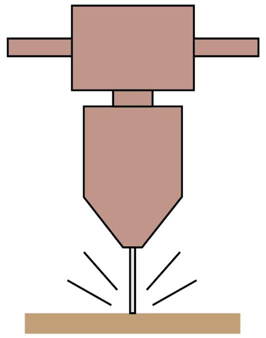


Figure 25. Laser cutting diagram (own illustration)

Laser cutting
A process with an extreme high accuracy while still preserving its low-tech label, is laser cutting. During this process, a high-intensity light, the laser, cuts through the material by heating, melting and partially evaporating it. Aside from cutting through the material, the laser can furthermore carve in the sheet, making it possible to create engravings and hatched surfaces. It is a fast and relatively cheap manufacturing method, which makes it also widely available and ideal for prototyping.

Laser cutting can be accomplished with many different materials of which MDF, plywood, acrylic, cardboard, paper, some plastics and metal are commonly used. But also, some biomaterials like leather, cork and textile can be cut with this technique. However, some materials are unsuitable for laser cutting, because of their interaction with laser energy. The option to use waste materials is feasible as long as the material itself is appropriate for the method. This would mainly come down to cutting left-over pieces that would otherwise be thrown away or recycled or for instance secondary plywood panels. The possibility of processing a material like plastic bottles into a sheet and subsequently laser cutting it, is not explored, but could potentially work out.

Although the technique's widespread possibilities regarding materials, the thickness of the material is a considerable limitation, as laser cutting is just achievable with material thicknesses of a few millimetres, naturally varying per material. This limitation must be highly considered regarding the design of this thesis, since the utilised material should maintain its rigidity despite its dimensions. However, for the experimentation and testing phase of this project, it will certainly be a useful technique.

Modular connection techniques

In paragraph 1.2 the requirements of a modular, DfD connection are already discussed and also some examples are given in Table 1 from Guy and Ciarimboli (2006) naming the primary advantages and disadvantages per type of connection. Based on the requirements regarding circularity and low technicality of the design, several types of connections are briefly explored.

As shown in the table in paragraph 1.2 both **screws** and **bolts** are easy connection types and also very similar. However, the main difference between the two is that screws fasten directly into the material's surface while bolts normally requires a nut and washer on the other side of the material. This makes the latter favourable over the first since it increases the number of times the connection can be disassembled and reassembled. Additionally, the fact that screws are fixed directly into the product limits the types of materials that are suitable for the connection compared to bolts.

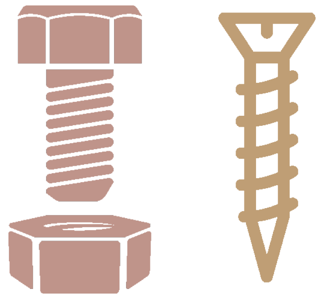


Figure 26. Srew and bolt (own illustration)

A dry connection technique that in some cases does not demand a separate connector element is **joinery**. This technique is especially suited for timber elements considering the properties of the material. However, with some minor adjustments or supporting connectors this connection method could also work for alternative materials. Timber joinery types come in many variations, but a few common examples, which are also potentially the most suited for this project, are given. Firstly, there are dowel joints, where dowel pins reinforce the connection between two pieces of wood, one of them being an end piece. This technique is often applied in furniture. Secondly, to generate corner pieces box joints and dovetail joints are highly suitable, whereas with the first the corner is created through interlocking rectangular fingers and with the latter the fingers consist of diagonal cuts. Thirdly, mortise and

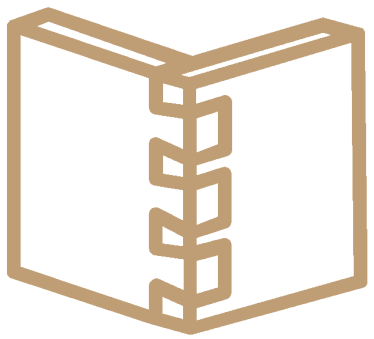


Figure 27. Joinery principle (own illustration)

tenon joints uses the principle of putting a stub ore tongue (the tenon) into a hole cut (the mortise). Within this type of joinery there are many variations, such as the mortise that does or does not pass entirely through a piece of wood or types that are enforced with wedges or other supporting pieces.

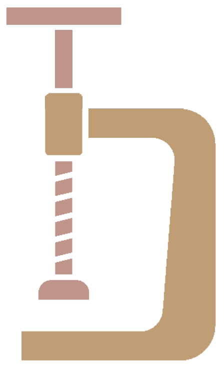


Figure 28. Clamping principle (own illustration)

A technique that in its essence might be quite similar to the principle of joinery, is **clamping**. Here, the clamp must hold the workpiece firmly against the locating elements and the cutting forces developed during the operation without causing damage. A key principle of this technique is that the system must be positioned at thick sections and a strong, supported part of the material. The clamps come in a variety of types, including screw, strap, pivoted, swinging and hinged clamps. Fundamentally, this technique requires a material which has the clamping ability itself, hence flexibility to a certain degree, or an additional element to generate the clamping mechanism, like a bolt or a spring.

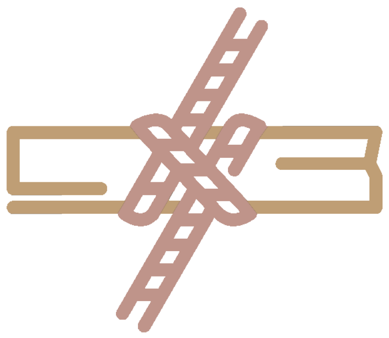


Figure 29. Knotting (own illustration)

Lastly, the method of **knotting** or **tie lashing** could be considered for attaching or securing elements to each other. It is a fast and, when executed correctly, a solid connection method, nonetheless easily reversible and therefore widely used in climbing and sailing. Where lashing is a method mainly used for securing two poles or pole like objects, the same principle can probably be achieved for larger planer elements, by creating holes in the material for the rope to go through. By all means, this approach hardly requires any modifications to the materials, could be reversed and learned easily, reckoning it as a fitting technique in terms of circularity.

Evaluating each of the explored low-tech manufacturing and modular connection techniques, they provide a solid base carrying the circular approach of this graduation project and will be further investigated during the design and experimentation phase. However, not every technique might be available or feasible within the given time frame, probably resulting in some assumptions that are to be made in the next stage.

2.3 Introduction to waste materials in the Netherlands

Industrialised countries, like the Netherlands, must use both energy and resources far more efficiently, as they want to achieve their goal of reducing the GHG emissions by 2050. Another argument for increasing material efficiency and the number of reclaimed materials that is used in the building industry, but also across other sectors, is future scarcity (Allwood et al., 2011). Key element in achieving a sustainable resource management, is waste management, as stated by Corsten et al. (2013). They distinguish several ways of how waste management can contribute to efficient resource use, including waste prevention and reuse and recycling of products and materials. Meanwhile, anaerobic digestion and incineration are ways to recover part of the materials embodied energy, however this is listed at the end of the R-strategies cycle (see figure 17) and therefore the least favourable option.

Exploring some facts, approximately 23 megatons of construction and demolition waste (CDW) is generated in the Netherlands, being almost 40% of the total waste in the country. This number is almost three times as high as all Dutch households (8,3 megatons) (Rijkswaterstaat, 2020). Although over 90% of the CD waste and around 75% of the total waste in the Netherlands is recycled, the amount which is prepared for reuse (124 kiloton) is almost negligible. The number of 75% waste recycling seems promising; However, it has to be questioned what the term ‘recycling’ means in this case.

As it is the largest waste stream in the Netherlands and furthermore part of the same industry this graduation topic is involved in, a closer look is taken on the construction and demolition waste stream. CDW primarily consists of stone-like materials which is broken by rubble crushers, whereas the rest of the stream is mixed CDW, which is sorted and separated for recycling. However, after sorting this mixed stream, various residual flows remain that are potentially landfilled or incinerated. Additionally, a part of crushed and sorted waste will end up in landfill as well. Expensive and relatively easily recycled materials such as metals are normally not or hardly found in mixed CDW and directly passed on to recyclers by demolition companies (Corsten et al., 2013).

Several other large waste streams of the Netherlands include, but are not limited to, household waste (also referred to as municipal solid waste), bulky municipal solid waste, like furniture and carpets and industrial waste, which is material that is no longer in use after the completion of a manufacturing process.

Utilizing waste materials affecting the design process

Replacing original materials with reclaimed ones does not leave the conventional process and development of the design unaltered, however, it affects the design process in several ways as described by Gorgolewski (2019) in his paper. Issues that impact the design and delivery process are availability, supply chain, ownership, detailing, codes and standards, acceptability and availability of information. Concerning the issue of material availability, this could mean that in a one location or timeframe a certain material will be available, whereas that same material in another location or time, it won’t be available, or in smaller quantities. According to a study of Sileryte et al. (2022) monitoring waste streams from the Amsterdam Metropolitan Area (AMA), the average length of a waste disposal trip is 60 km, causing 52 kg of CO_2 emissions. This results in a total amount of 167 kiloton emissions due to waste transportation starting or ending at the AMA alone. Hence, limiting the unnecessary transportation of waste materials, should be avoided whenever possible.

Furthermore, the creative ability of a designer to see presented opportunities by the available reclaimed materials and components, contributes to enlarging the potential scenarios for reuse, whereas a simple and flexible design helps to maximise these opportunities.

2.4 Selecting potential materials for the façade system

Design for Disassembly is one of the selected circular approaches for this thesis. According to Guy and Ciamrimboli (2006) DfD offers more than just ease of disassembly and adaptability; it hinges on the careful selection of materials. The primary objective of DfD is not only to streamline the recovery process but also to establish a zero-waste and closed-loop materials flow system in the construction industry. Therefore, it's crucial to emphasize that the effectiveness of the DfD concept largely relies on the initial choice of materials, prioritizing those that are reused or crafted from recycled sources.

Additionally, the Ellen MacArthur Foundation (n.d.-b) states that not all materials are fit for a CE, as some of them contain chemicals that are hazardous to humans or the environment. Therefore, choosing safe and circular materials, one of the successfully proven circular design approaches as stated in the Introduction, will ensure that the created products and services are appropriate within a circular economy. Although this approach is not one of the main considered ones for this project, it is still wise to keep the material health into account during the design phase.

Selection criteria

As mentioned in the previous paragraph, material availability could highly differ over time and location, resulting in the decision that for this thesis not one particular will be selected for the design. However, a selection of several potential materials is made and according to the circular principles that are considered for this thesis – Design for Disassembly and Modularity – it is favourable that these waste materials should fulfil certain requirements related to these principles which were mentioned earlier in this research. The ones related to materiality are shortly repeated, being:

- Minimize the different types of materials to reduce the project's complexity and amount of separation processes.
- Avoid secondary finishes to materials that might cover connections, making it more difficult to locate them.
- Minimize the number of unique components for the design, so the quantities of similar recoverable components increase.
- Minimize the number of fasteners and connectors to gain more speed of assembly and disassembly.
- Design joints and connectors that are suited to withstand repeated assembly and disassembly, which allows adaptation of the design and connectors to be reused.
- Use lightweight materials and components that are readily handled for human labour and specifically are convenient for children to work with.

Furthermore, as the materials fill fulfil a role in an exterior façade cladding element, the materials should contain several other characteristics. Firstly, and probably most importantly, the materials should be weather resistant as this contributes to the overall durability and sustainability of the system. This includes for instance being watertight and vapor, heat and corrosion resistant. Additionally, as well as the reflectivity of windows can cause birds crashing into them with all the consequences this entails, this should also be considered for the materialisation of the system, so transparent materials might not be the most appropriate. Although it is likely that this problem wouldn't be as large as with windows, considering the underlaying layer of the existing façade. Aside from being safe for birds and other species, the overall safety of the material functioning as an external façade system has to be considered. Especially since the system will be applied in a school environment, meaning children will be and play around the hosting façade, so avoiding sharp edges or components will decrease the risk of accidents. Taking into account these selection criteria, an overview of the potential materials for the system is presented hereafter.

Potential waste materials

Aside from the standard companies that offer new building materials, many (online) shops and companies exist that offer second hand materials retrieved after their first use. Examples of these sources, varying in size, include Opalis.eu, bouwkringloop.nl, gebruiktebouwmaterialen.com and tweedehandsmaterialen.nl. Additionally, Marktplaats.nl, the national website for second hand materials in the Netherlands offered by private individuals, could also offer suitable, large quantities of second-hand materials. Furthermore, local initiatives exist, like Buurman, a circular construction market that receives their second-hand materials from local organisations and people.

Other sources for waste or discarded materials are, like discussed in the previous paragraph, the waste streams coming from households or companies. The largest among these waste streams are plastics, paper/cardboard, textile, glass and of course residual waste.

Hereafter, some materials are briefly discussed regarding their properties, potential as a secondary material and possibilities of functioning as a part of the to be developed modular and DfD design concept or one of its connectors or fixing items. However, it is likely that during the design stage of this project several other potential materials are encountered.

Figure 30. Reclaimed timber

(Thermally-modified) timber
Initially, timber has a high potential being applied in the design of this project, as it is a sustainable, renewable material choice and already commonly used in the building and façade industry. Aside from its natural strength, it helps to regulate temperature and humidity. However, to be applicable as an external façade material, timber often needs to be (thermally) treated. These processes are essential to enhance the wood's durability, weather resistance, and longevity when exposed to outdoor environments, hence increasing its lifespan and thus circular value. However, some preservatives and treatments can contain chemicals that are harmful to the environment en human health and thus choosing eco-friendly treatments, such as heat treatment, acetylation, water-based coatings or linseed oil and beeswax, is essential. Alternatively, reclaimed timber elements that are already treated chemically can be selected for the design, to maximise

the lifespan of those elements and thus preventing those chemicals from releasing during for instance incineration processes as long as possible.

Regarding manufacturing processes, timber is suitable for low-tech methods like die cutting, where it can be shaped and moulded into specific patterns and designs. Also, laser cutting can be applied, although it is less common for timber due to its combustible nature and the limitation in thickness of the material. Other techniques such as CNC routing and traditional woodworking are typically employed to craft intricate and customized timber cladding elements.

Figure 31. Recycled plastic

Plastics
In terms of sustainability, plastic's reputation is mixed. While some plastics are recyclable, many are not, leading to concerns about environmental impact. However, the reuse and repurposing potential of plastic as an external facade material is growing. The material is lightweight and versatile and properties related to façade applications include resistance to corrosion, its ease of maintenance and the ability to be moulded into various three-dimensional shapes, like briefly mentioned in the manufacturing processes paragraph.

Aside from processing and recycling plastics into forms for façade panels, requiring a more intensive process, the repurposing or upcycling of certain plastic products is also highly considerable for this project. For instance, plastic bottles or containers can be used as planters, thereby contributing to the purpose of enhancing the local urban biodiversity with the design.

Figure 32. Reclaimed HPL

High-Pressure Laminate (HPL) panels
High-Pressure Laminate (HPL) is a versatile material often employed for external facades due to its impressive properties. HPL is composed of layers of kraft paper saturated with phenolic resin and finished with a decorative layer, all compressed and heated under high pressure. This results in a durable and weather-resistant cladding material. HPL is known for its exceptional properties, including resistance to UV radiation, moisture, and impact, making it an ideal choice for exterior facades.

What adds to the appeal of HPL is its sustainability potential. While not inherently biodegradable, HPL is recyclable and can be reprocessed into new sheets or other products, reducing waste. Additionally, its robustness allows for a longer lifespan, contributing to the reduction of construction waste. Lastly, HPL can be processed by both low-tech and high-tech manufacturing techniques, making it a versatile material for various applications and also a potential material for this project.

Figure 33. Reclaimed limestone

Limestone
Limestone is a timeless and enduring type of natural stone and its properties encompass a remarkable resilience against the elements, including resistance to harsh weather conditions, UV radiation, and pollutants. Furthermore, its potential for reuse and repurposing aligns seamlessly with sustainable design and construction practices. Salvaged limestone from old buildings or construction sites can be given a new life, preserving the material's character while reducing waste. Limestone can be cut, reshaped, and adapted for various architectural elements and landscaping features.

In terms of manufacturing techniques, low-tech processes which are appropriate for this material involve mainly sawing and carving, as these methods harness the stone's natural strength and beauty.

Figure 34. Reclaimed ceramic tiles

Ceramics
Exploring the properties of ceramics, the material is quite similar to natural stone, being weather resistant and UV radiation and corrosion proof. Its low-tech manufacturing potential, however, is actually somewhat lower than limestone, due to its hardness and brittleness. Therefore, ceramics are shaped and prepared using specialized equipment such as diamond saws, grinders, and waterjet cutters, often requiring skilled artisans to handle the material with precision. However, modern, alternative techniques such as 3D printing are used nowadays for (secondary) production of the tiles.

Figure 35. Reclaimed concrete plywood

Concrete plywood
As composite material, concrete plywood blends the robustness of concrete with the flexibility of wood, making it a notable choice for external facades. Its properties include exceptional strength, resistance to weathering, and fire retardancy, making it suitable for robust and long-lasting facade construction. This material combines the visual appeal of wood with the durability of concrete, offering architects diverse design possibilities.

Furthermore, the material exhibits commendable reuse and repurposing potential, as salvaged concrete plywood panels can be given a second life. However, concrete plywood is not typically suitable for low-tech manufacturing processes like die cutting or laser cutting. Due to its composite nature and reinforced concrete layer, working with concrete plywood typically requires heavy-duty equipment such as diamond saws or other specialized machinery. These tools ensure the precise and safe shaping of the material, often necessitating the expertise of skilled artisans to handle concrete plywood for external facades.

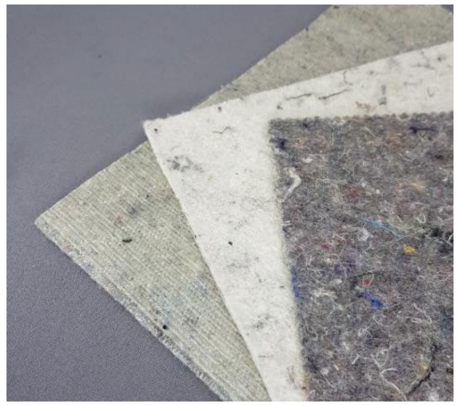


Figure 36. Recycled textiles

Textiles
Textile materials are available in a wide range of textures, colours, and patterns, allowing for creative and expressive designs. Moreover, textiles are lightweight and flexible, offering an opportunity to add movement and depth to architectural exteriors. However, in the recycling process, many obstacles can be encountered, such as the contamination of the material with other, non-textile components or the fact that recycling textiles is often not cost-effective. Additionally, as textiles come in various forms, like natural fibres, synthetic fibres, blends and coatings, they all require a different recycling process, increasing its overall complexity.

In the cases that textile does get a second life, it is often as insulation material, acoustic panels or interior applications. Other than operating as sun shading or a thin flexible façade layer, hardly any examples exist of textile utilised as an external façade cladding. Hence, textile may not be the most obvious choice for the design of this thesis, however some forms may have potential for the biodiversity implementation of the design. Wool, for example, is known for its remarkable, including natural insulation, weather and flame resistance. Furthermore, wool has natural moisture-wicking properties, making it remarkably suitable for planters. It can absorb and release moisture, helping to maintain optimal soil moisture levels for plant growth. This reduces the risk of overwatering and root rot, a common issue with plastic or ceramic planters that don't offer the same moisture-regulating benefits. Furthermore, it is a non-toxic material and could also serve as insulation to plant roots.

In the Netherlands, every year almost 1.5 million kilograms of sheep wool ends up in landfill. Circular startups as the Dutch Wool Collective (in Dutch: Hollands Wol Collectief) buy wool from farmers for a fair price, process it into semi-finished products and sell it to companies that can give the material a second life (Hollands Wol Collectief, n.d.).

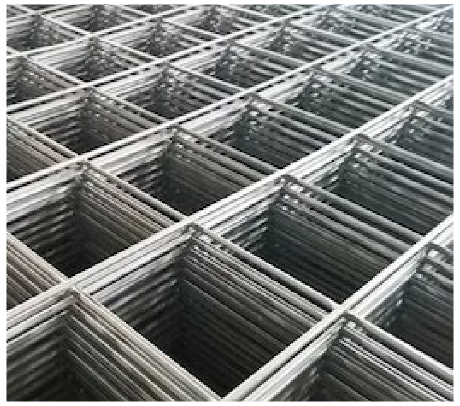


Figure 37. Reclaimed wire fence

Wire fence / netting
Although this material might not be suitable to generate the main elements of the design, it can serve other functions within the system. Firstly, it can provide some structural stiffness to more flexible materials, such as textiles. Furthermore, second-hand wire fences normally are still in a good condition regarding its structural properties and is therefore a potential solution for attaching the designed façade panels onto the hosting façade. Simultaneously, it could serve as a climbing guide for potential vegetation of the system.

The fact that the material does not require a complex or any remanufacturing process at all to find its new implementation as described above, it would make it a sustainable choice with a high circular value, which even fits in the approach of DfD.

B

Biodiversity

03

Nature-inclusive design: Biodiversity on building envelopes in urban areas

3.1 Introduction to nature-inclusive design & biodiversity in urban areas

What is nature-inclusive design?

As briefly addressed in the Introduction the importance of biodiversity cannot be overstated. Aghina et al. (2023) describe biodiversity as the amount of divergent flora and fauna species present in a specific area. The more variety and stratification in vegetation, the higher the number of species that benefit from this. A large diversity in species not only assures their resilience, but also the social resilience of humans, like health and wellbeing (Dijkshoorn-Dekker et al., 2020).

With nature-inclusive building design the urban environment is designed in such a way that, without losing safety or comfort for the users, animals and vegetation regain a place in the system (Aghina et al., 2023). The Board of Government Advisors (College van Rijksadviseurs) (2023) append to this that nature-inclusive building purifies the air, soil and water and prevents damage of ecological values to vegetation, animals and natural elements caused by building activities. They stress that nature-inclusive design is not completed when a building is delivered, as the building becomes a part of the nature-rich habitat that requires ecological management to continue reinforcing the local biodiversity.

Importantly, nature-inclusive measures are more effective when they are optimally connected to and actively integrated in the local ecological systems (Wageningen University & Research [WUR], 2020; Rijksdienst voor Ondernemend Nederland [RVO], 2022; Aghina et al., 2023). Furthermore, these newly created habitats must be well integrated into the urban fabric to make sure the species are able to locate the habitat and will successfully flourish in their new green-blue area. So, under the precondition that they are tailored to urban locations, the interventions can be relatively straightforward and affordable, however the WUR (2020) distinguished four 'ambition levels' for nature-inclusive building (see table 2). Examples of simple interventions are adding more native vegetation for nutrition or as hiding and resting places and places of residence for birds and bats. On the more eco-technical side, wadis and green roofs and facades are common interventions for nature-inclusive design in urban areas (WUR, 2020; Aghina et al., 2023).

Challenges in nature-inclusive design

Although, nature-inclusive interventions can be straightforward and there is an ongoing transition in the building sector in terms of building nature-inclusively, as more architects and developers incorporate this in their designs, Dijkshoorn-Dekker er al. (2020) conclude from several studies that it is still subordinate to other (economical) preconditions and often not processed until the final stages of the design phase. In a survey conducted among the Dutch real estate industry to determine the current role nature-inclusive construction plays in the real estate industry, results show that the main obstruction for the respondents is 'the lack of willingness of customers to pay for nature-inclusive building'. Additionally, 'maintenance and management of the added vegetation' and 'the influence of municipal regulations and procedures' are called as constraining factors (Van Haaster-De Winter et al., 2020). The WUR (2020) confirms this in their own research and notices that in some cases it is easier to adjust the nature-inclusive ambitions and remove initiated green elements than to find a solution for these obstructions.

Business as usual	Urban areas comply with the legal obligations in terms of nature and environment. There is no specific consideration for greenery and biodiversity.
The first steps	Generic nature-inclusive interventions, that globally stimulate biodiversity, are considered during the design process. Certain examples are green roof or façade elements, nesting opportunities for birds and bats and a variety of (native) vegetation species. With these interventions, the specific characteristics of the accounted natural environment are not considered, which results in kind of stand-alone green elements in the area. All the vegetation is shredded and connecting components are missing.
Intensifying	The connection between the nature and its surroundings is clearly present. The taken actions on and around buildings are fitting the existing landscape, vegetation and fauna of that specific place. This ensures that plants and animals more easily find their way through the city and that building blocks are part of the local ecosystem.
Complete integration	Buildings and nature form a coherent system. Nature attached to and around buildings is fully adapted to the soil type, hydrology and history of the location and fully integrated to its natural environment. The greenery is no longer shredded, but part of a continuous and coherent entity where green-blue spaces and buildings complement each other. It's a space not only for flora and fauna to survive, procreate and grow, but also humans like to abide in these environments (WUR, 2020).

Table 2. Ambition levels of nature-inclusive design (WUR, 2020).

Urban nature's effect on a large scale

Birds, much like humans, don't exist in isolation. To foster healthy bird populations, it is crucial to establish a green-blue network that connects regions via roadside verges and waterways. These networks encompass clean water and a diverse array of native trees and plants under eco-friendly management practices. Parks and green spaces entirely enclosed by urban development tend to support fewer bird species compared to green areas that link with other regions and the surrounding countryside. Green solutions, often referred to as ecosystem services, can address various urban challenges, including street trees and versatile rooftop spaces or nature-inclusive façade systems. (Vogelbescherming Nederland, n.d.).

3.2 Nature-inclusive façade systems

The potential of facades to increase biodiversity and the amount of green in the city, is not a new strategy. In fact, the earliest form of vertical greening goes back to about 2000 years ago where in the Mediterranean region the with vines covered facades provided shade and transpirative cooling. However, it was not until the 1980s when the idea of green facades and their contribution to the ecological enhancement of cities peaked (Köhler, 2008). Since the goal of this thesis is to develop a biodiversity fostering façade system which is constructed from circular principles, the basic green façade typologies are distinguished and assessed on the requirements to potentially work as a circular system.

Different typologies

Ottelé (2014) divides the green wall technologies in two main categories (figure 38), where the distinction is based on the systems that are rooted into the ground (green facades) and the ones that are based on hydroponic systems i.e., rooted in artificial substrates or potting soil (living wall systems (LWS)). Within these two groups the separation is made between direct greening, meaning the façade functions as a guide for the greening system to grow upwards, and indirect greening, where the greening system and the façade are separated by an air cavity, which is illustrated in the same figure. The air cavity of indirect greening systems can be established by supporting systems, spacers, planter boxers or modular substrate structures.

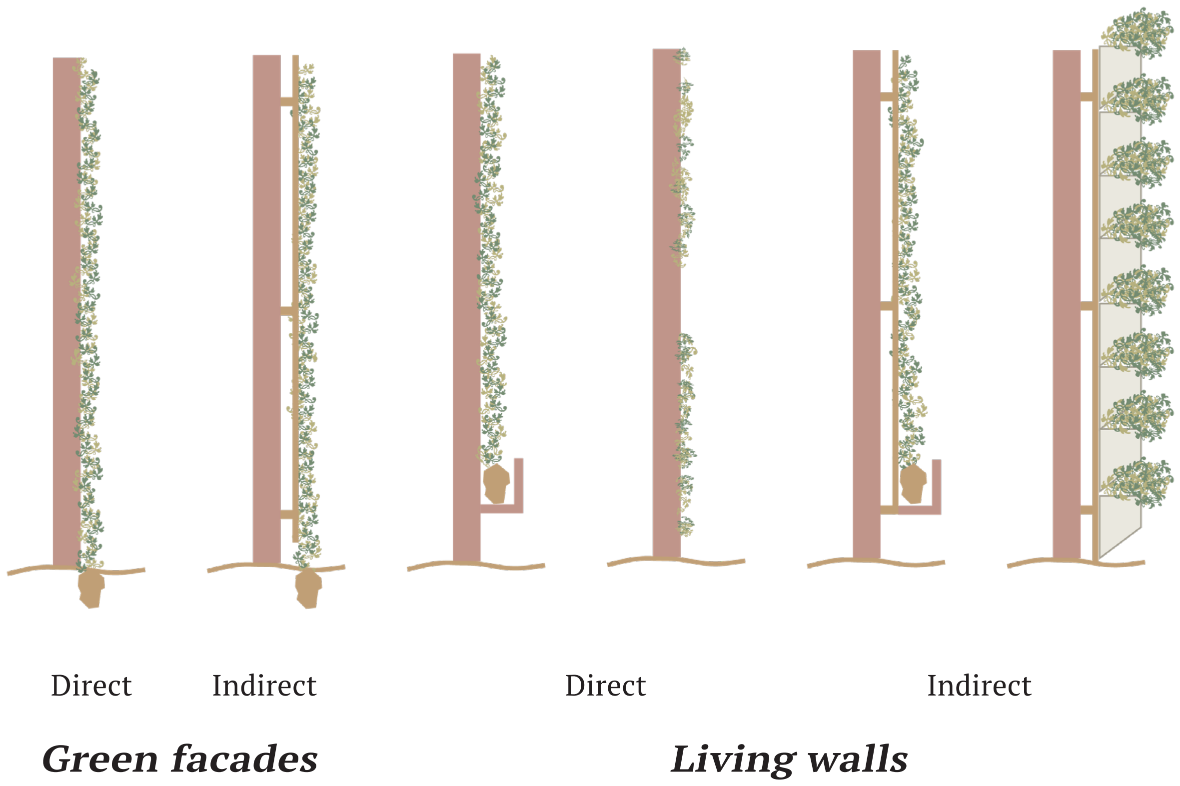


Figure 38. Distinction between green wall principles and related concepts according to Ottelé (2014) (own illustration).

Based on the categorization of vertical green systems the green facades systems (direct and indirect) show the less potential for a circular system in this thesis than the LWS, as building a modular and DfD system will be harder when the vegetation is spread over the whole façade and thus different modular elements. Moreover, separating the vegetation from the façade panels at their end of life in case of recycling is a time-consuming process. Direct greening systems within the LWS section have some potential when the vegetation stays within the borders of one modular element. Mosses are in this case a better fit than climbers, because they require less maintenance in terms of growing speed, nonetheless the material separation process remains a disadvantage regarding circular potential.

Hence, the indirect living wall concepts theoretically show the most potential as a circular system. Additional factors are however that a LWS is dependent on an irrigation system and additional nutrients to the substrate (Ottelé, 2014). Furthermore, it requires more maintenance than a green façade system and likewise the costs per square meter are much higher. Despite these disadvantages, the LWS concepts allow for a greater variety of plant species and offer more possible functionalities than the green façade systems, which are positive factors for this research. Nonetheless, during the design phase the potential of the other vertical green systems will also be briefly investigated.

Benefits of nature-inclusive façade systems

Firstly, they are capable of cooling the direct environment in two different ways, thereby reducing Urban Heat Island Effect. Research shows that walls behind green surfaces will absorb less heat energy from the sun and green walls use the process of evapotranspiration, cooling the heated air through evaporation of water, helping to regulate humidity and temperature (Wong et al., 2010; Enzi et al., 2017). This air-cooling capability caused by evapotranspiration is one of the four mechanisms which increase the thermal insulation of buildings because of the added vegetation (Rath & Kießl, 1989; Peck et al., 1999; Pérez et al., 2011). The other three mechanisms include firstly, thermal insulation, predominantly caused by LWS concepts, that is provided by vegetation, substrates and configurations, secondly, a dense plant foliage captures an air layer, meaning that the plant will function as a buffer that keeps wind from moving along the building surface, considering the fact of wind being able to decrease energy efficiency by 50%, and thirdly, the mechanism that heat is prevented from reaching the building skin in summer, while in winter the internal heat is blocked from escaping, is reflecting or absorbed.

Additionally, Pfoser (2013) states that vertical vegetation reduces noise pollution between 1 and 10 dB. And not just noise pollution, but also other pollutants, such as particulate matter, CO2 and NOx, are filtered out, therefore improving the overall local air quality (Minke & Witter, 1982; Enzi et al., 2017). Moreover, green walls can manage surface water flooding during (heavy) rainfall (Envi et al., 2017).

Other, less technical, benefits of vegetation on facades are its function as external shading elements and thereby also reducing other costs (Pfoser, 2013) and, as already briefly mentioned in the previous paragraph, its contribution to creating a functional, interlinked green and blue infrastructure network inside cities connecting to the surrounding rural areas (Hansen et al., 2016).

Lastly, green walls provide many health and scientific benefits, such as improving mental and physical health, humans' connection with nature and being a learning tool for next generations to learn about urban nature and biodiversity (Envi et al., 2017). Additionally, it enhances productivity at work and reduces absence from work due to illness, ergo it contributes to healthier and happier citizens and a better quality of life (Envi et al., 2017).

3.3 Biodiversity case studies

Hotel Bus Stop – Studio NAB, 2019

A concept designed by Studio NAB has reinterpreted an ordinary bus stop into a hub for biodiversity that operates as a hotel for birds and insects of all sorts. Studio NAB designed the bus stop to such it serves five different purposes: (1) promoting the presence of pollinating insects; (2) bringing humans of all ages closer to nature, hence promoting environmental awareness and education; (3) showcasing architecture constructed from recycled materials, like stainless steel, wood and cardboard; (4) introducing urban vegetation and by the utilization of a vegetated roof and exposed plant wall improving air quality; and finally, (5) providing “green jobs” for maintenance around the bus stops (Wang, 2019). An overview of all the precise functions the bus stop includes, is shown in the figure hereafter.

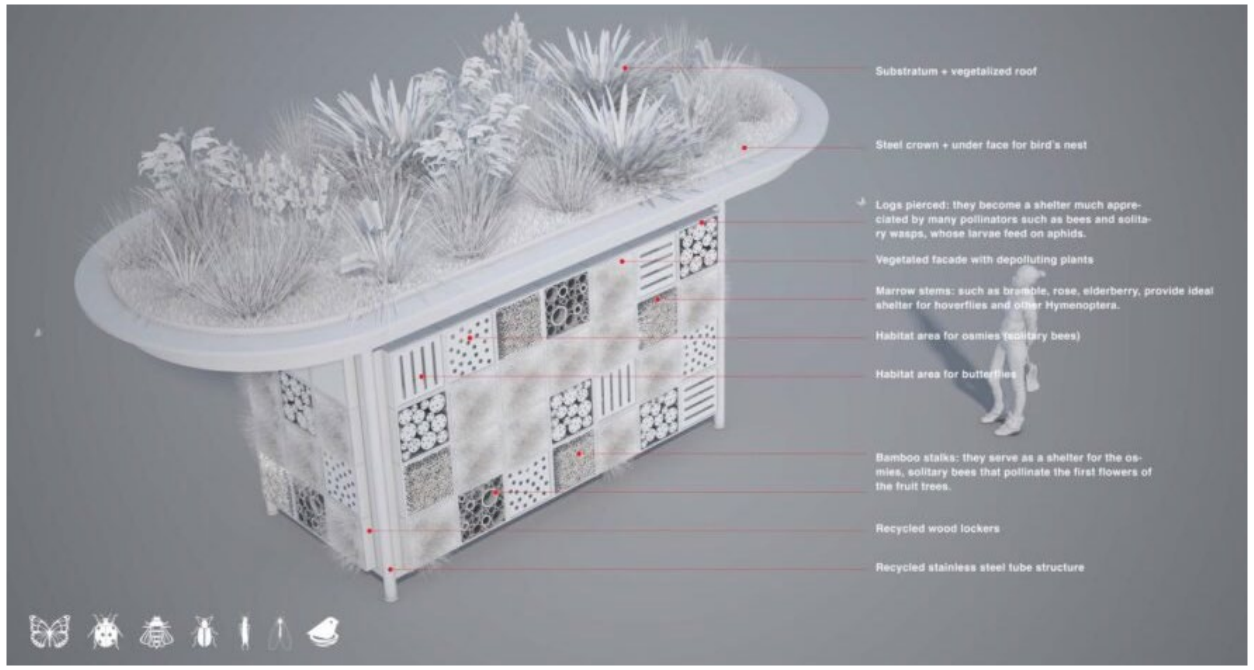


Figure 39. Functions of insect hotel bus stop, render image (Source: Studio NAB, 2019)

Although not much (technical) information is available about this project, it is certainly an inspirational resource for this thesis in terms of biodiversity and circularity. By the look of the renders, the bus stop seems, aside from the use of reclaimed materials, also circular in terms of construction. Assuming that the ‘recycled wood lockers’ are modular elements, the structure could be easily disassembled if necessary. In terms of biodiversity, this concept includes many distinctive forms of attracting species, which are also interrelated and takes cleverly advantage of the primary function of a standard bus stop, as people will regardless connect with the present nature as opposed to actively seeking the nature themselves.

Figure. 40. Overview of insect hotel bus stop, render image (Source: Studio NAB, 2019)

Figure. 41. Inside of insect hotel bus stop, render image (Source: Studio NAB, 2019)

Triodos Bank, the Netherlands – RAU Architects

This sustainable building is the new head office of the sustainable Dutch bank Triodos since 2019 and won several awards, including the Nature Inclusive Building and Design award 2019. The architect positioned the building utmost carefully in the landscape as such it became a part of it. The construction does not exceed the trees and moreover the shape of the building respects the flying routes of bats (RAU Architects, 2019). Additionally, the green roof attracts insects and other species and integrated nesting boxes provides spaces for bats and birds (DERIX-group, 2019). From a circular perspective, the entire structure is composed of just five standard elements, which form a fully dismountable, CO2 free, unique energy office (RAU Architects, 2019).

The concept of ‘form following nature’ is a very inspirational aspect of the design.

Figure 42 and 43. Exterior and interior of the Triodos Bank (Source: RAU Architects, 2019)

Figure 44. Top view of the Triodos Bank (Source: RAU Architects, 2019)

Bird and Bee Friendly Façade – COOKFOX and Buro Happold

This three-dimensional biophilic screen wall consists of standardized stacking modules filtering sunlight and providing a customizable array of terra cotta units where micro-habitat pods for bees, birds and plants can be inserted suited for that local native ecology. In Figure XX is visible that the arrow-shaped design involves one square module, which orientation varies based on its intended use. Thus, the upward facing arrow funnels water and provides space for plants to grow, while the downward facing module protects the reed of bee hotels from water. The horizonal oriented modules give the birds access to their nesting pods (COOKFOX & Buro Happold, 2022).

The multifunctionality of the green façade system which is accomplished by utilizing just one element is an inspiring concept regarding to the aim of this thesis. Not merely the changing orientation of the module, but also the shape generates this performance. It is a system where the design genuinely follows from the functions provided by nature, which makes it a great example of a nature-inclusive design project.

Figure 45. Mock-up of the façade (Source: COOKFOX & Buro Happold, 2022)

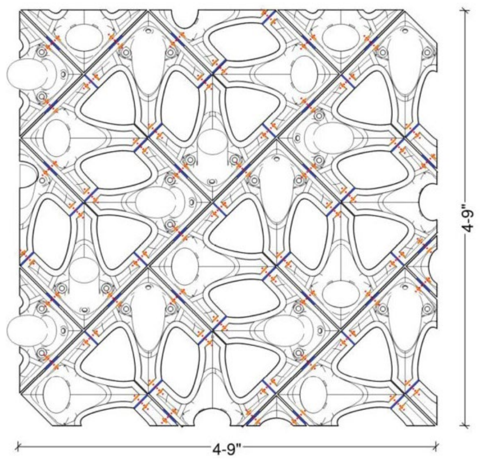
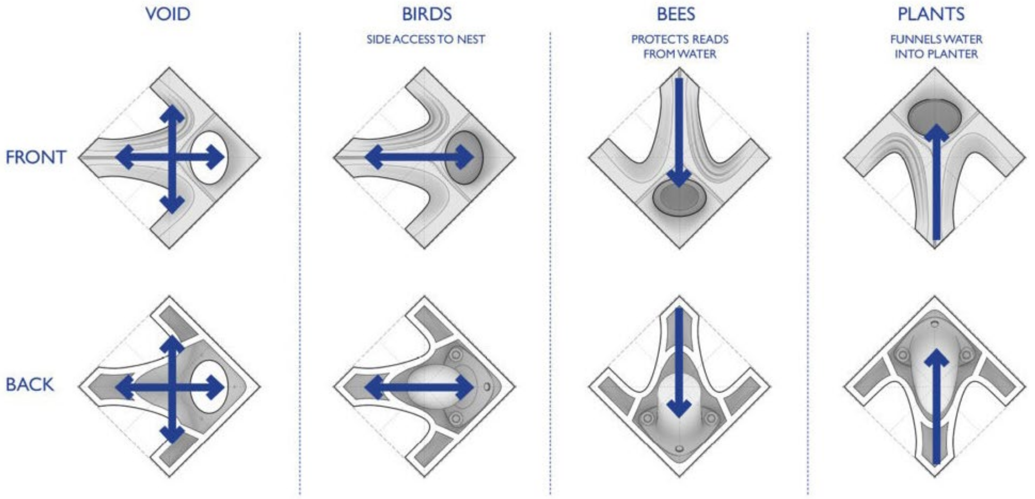
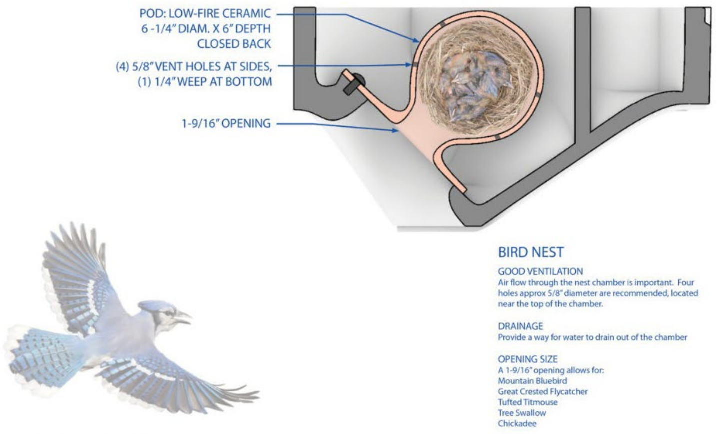
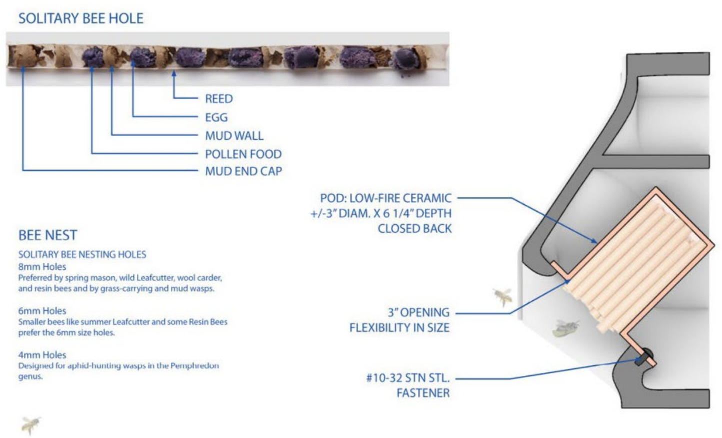


Figure 46. Structural analysis of the façade (Source: COOKFOX & Buro Happold, 2022)







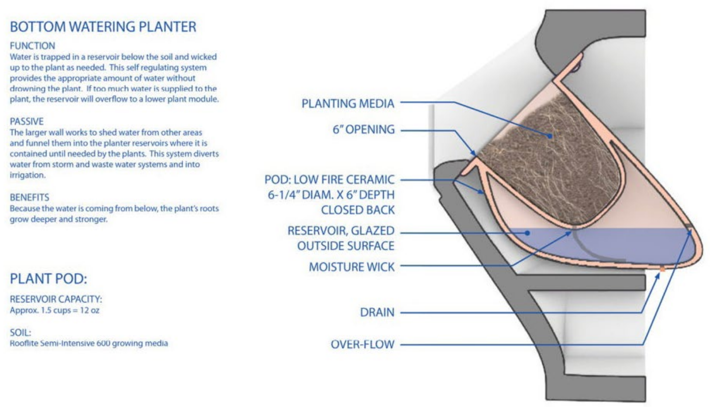


Figure 47. Module and Pod orientation (Source: COOKFOX & Buro Happold, 2022)

Figure 48. Module program 1: Birds (Source: COOKFOX & Buro Happold, 2022)

Figure 49. Module program 2: Solitary bees (Source: COOKFOX & Buro Happold, 2022)

Figure 50. Module program 3: Plants (Source: COOKFOX & Buro Happold, 2022)

Biosphere - BIG

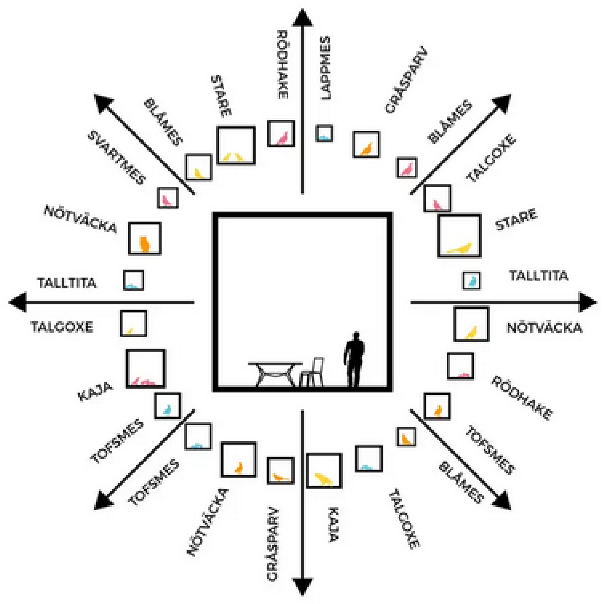
Another reference project where the local ecology is the driver behind the architectural expression is Biosphere, a Treehotel in Swedish Lapland, designed by the Danish architecture firm BIG. With the mission to decrease the downward spiral of the bird population in the region, BIG designed the Biosphere cabin with 350 bird houses. These bird houses are varying in sizes and expanded outwards regarding the bird species and frequencies in the area. Accordingly, light can still enter the Treehotel and outwards views are maintained. Guests of the room are given the opportunity to experience the birdlife in close proximity, through wrapping the hotel room in an ecological habitat. The designer hopes that by this matter, visiting people are inspired to install bird nests near their home as well (BIG & Öhman, 2019).

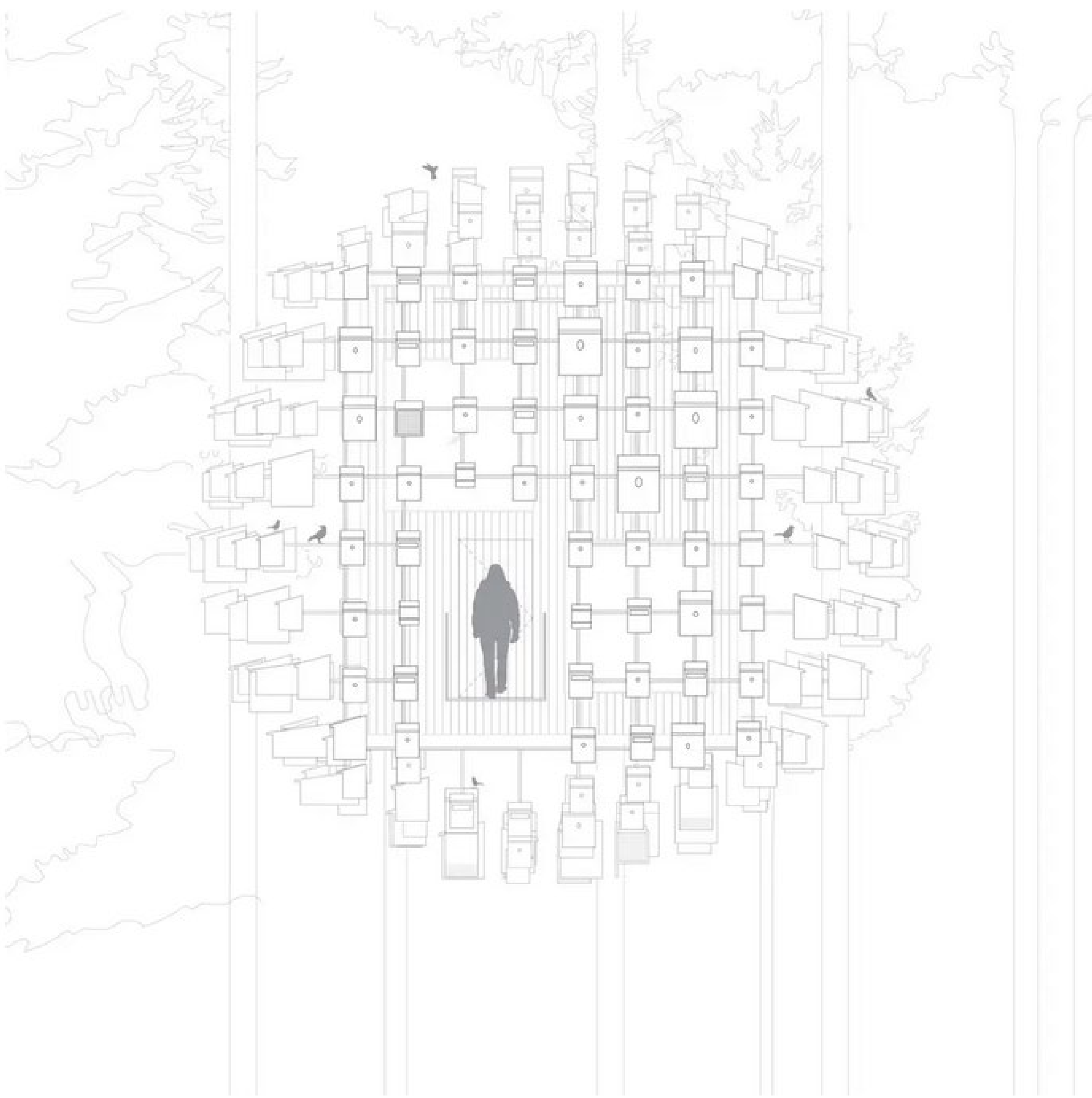
Although it is unlikely that all the bird houses will eventually be engaged by birds, simultaneously or not, the concept and architectural expression of this design is a strong statement of nature-inclusive design.

Figure 51 and 52. Close up images of the Biosphere where the connection between the façade and bird houses is visible. (Source: BIG, 2019)

Figure 53. Biosphere Threehotel (Source: BIG, 2019)

Figure 54 and 55. Orientation of bird houses in Biosphere (Source: BIG, 2019)





04

The Biodiversity Map

4.1 Biodiversity parameters: criteria for selecting biodiversity species

With the building envelope of a school building as a canvas for this project, there are three criteria established for selecting the biodiversity species: (1) the species are building reliant and able to thrive in urban conditions, (2) the vegetation species preferrably have a native origin and (3) they could contribute to the educational purposes and DIY-strategy of this thesis. The essence of each criterion is declared in this paragraph.

Building reliant species in the Netherlands

As described by Gunnell et al. (2013) the term 'building reliant species' is defined as animal species that have come dependent on buildings for their survival due to the widespread urbanisation and these species adapting accordingly to share our built structures with us. They acknowledge however, that there are many organisms, for example plants and invertebrates, which (could) make use of buildings. Hence, for this thesis also the species that could thrive on building envelopes or benefit from the interventions taken on the façade are included in the term 'building reliant species' and are contemplated when the selection for the system is made. In figure 59 an overview of some building reliant species and where on and in buildings they can reside, is illustrated based on a figure made by Aghina et al. (2023). This also indicates that not every orientation or building height is a proper fit for the distinctive species.

Native vegetation species

According to Given and Meurk (2000) the overall genetic diversity of ecosystems and its ability to adapt to future changes is reduces by the diminishment in population of common native species. Furthermore, they state that local species richness can be increased by focussing on and primarily planting these indigenous species, whereas they also enhance the changes for maintaining the global biodiversity. Native vegetation is thus the favourable choice when adding new planting to an area, as they are better adaptable to local conditions than non-native species and they provide local fauna in their food supply (Aghina et al., 2023). Consequently, when growing at the convenient location and in the ideal soil they are more resilient and request less maintenance and caring (IVN Nederland, 2023).
However, other studies show that within urban environments, non-native plant species can serve as a valuable addition to the native flora, effectively enhancing biodiversity. This, in turn, extends the flowering season, consequently expanding the food supply for insects, birds, and mammals in urban areas (Salisbury et al., 2015). Therefore, the aim is to use native vegetation species, however, in cases that alien species also provide significant benefits when implemented in a certain location, they are also considered for the system.

Educational and DIY possibilities

Although this third criterion might not have the largest influence on the selection on the consideration of the species for this project, it is nevertheless one to be mentioned. Increasing the awareness among children about circularity and biodiversity can be achieved by facilitating lessons or workshops about various topics and species regardless of which particular forms of vegetation are present or which bird species are attracted. Subjects could be building your own bird house for the façade system, gardening your own herbs or an interactive lecture about the insects that are hosting the vegetated system. In the Netherlands, several green organisations like 'IVN Natuureducatie' and 'NatuurWijs' offer learning materials in divergent topics concerning nature education and might be willing to create lectures about nature-inclusive façade systems.

Fig 56, 57 and 58. Biodiversity parameters (own illustrations)

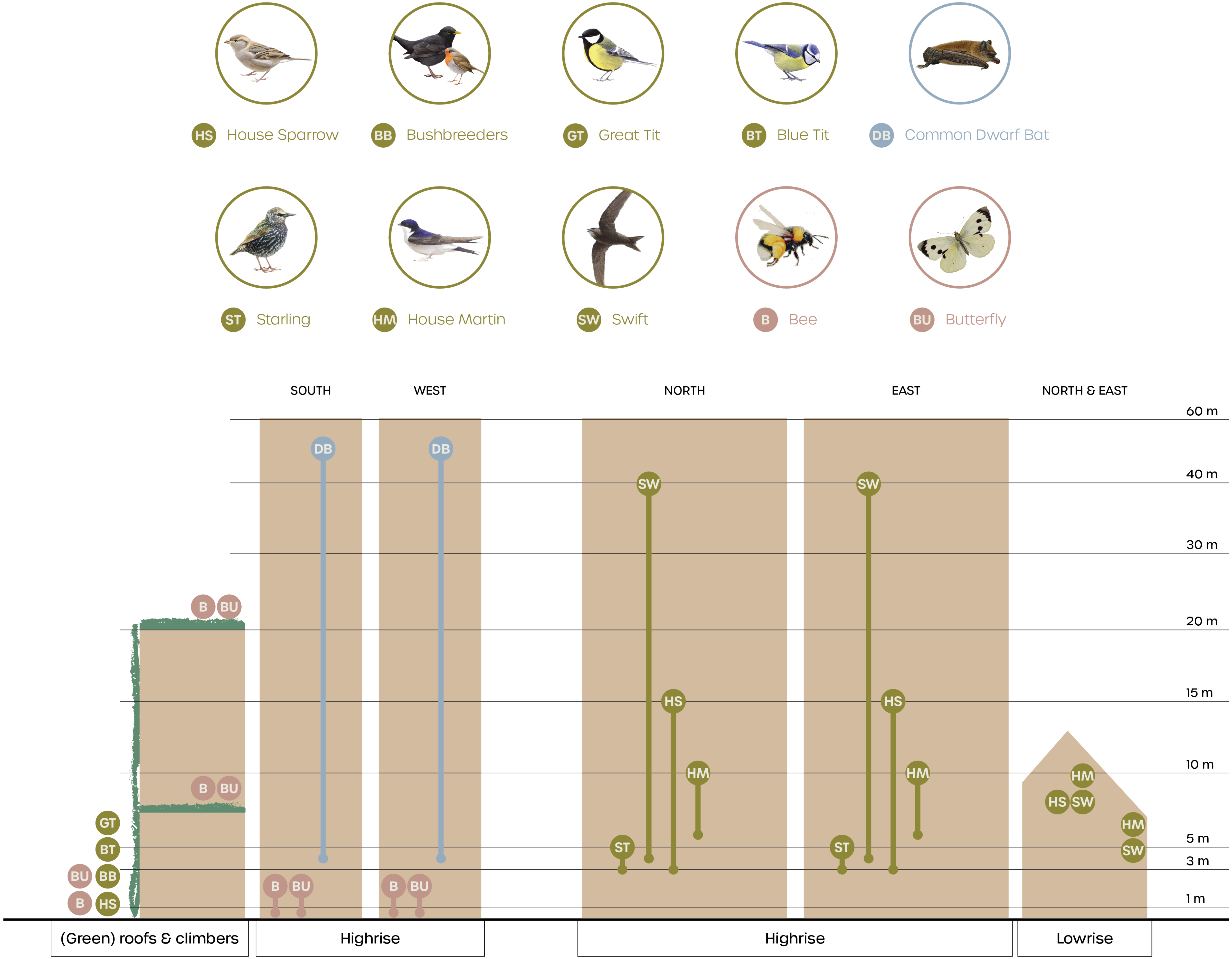


Figure 59. Overview of where on and in buildings some species can thrive, based on Aghina et al. (2023) (own illustration)

4.2 Selection of species

Since the number of existing species to enhance biodiversity is too large for this design project a selection is composed mainly based on the three criteria mentioned in the previous paragraph. Four groups are defined to implement in the design of the system: birds, bats, insects and vegetation. With each selected species, come corresponding requirements which need to be present in or near their new habitat for them to successfully thrive at that site.

Ecologists in the Netherlands make use of the 'Vs' requirements for the target species to validate a certain habitat. In Dutch these Vs are defined as 'voortplanting', 'verblijfplaats', 'voedsel', 'veiligheid', 'verbinding' and 'variatie', translated to respectively procreation, residence, nutrition, safety, connection and diversity. It is necessary that the Vs of a certain species, must be present in or close by to a habitat before the species can successfully thrive there (Aghina et al., 2023). Therefore, for all species considered in this project their Vs are researched and listed, so the particular location of the system can be validated as suitable for them or not. As there is no predefined site for the designed system of this thesis, consequently, the final design of the system on one location will not include each of the hereafter mentioned species. In practice, the façade system will, partially due to this approach, be different in each site where it is installed and is therefore optimally adapted to the local urban ecosystem, which implies the highest possible success rate of the system.

Within each group of species, a table is presented listing an overview of the requirements based on the Vs of the bird, bat, insect and plant species analysed in this project. The requirements are further divided in parameters that affect the design of the façade system (colour coded in green), those that are dependent on the target location (colour coded in orange) and parameters that fit into both categories (colour coded in blue).
Lastly, it has to be mentioned that a great variety of species fostered by the façade system, results in a more resilient environment whereas species of different sorts are interdependent and rely on each other's presence to survive.

Bats

On a global scale, bats play an indispensable role in our ecosystem, as they are responsible for the dispersion of seeds, aiding in pollination, and acting as natural pest controllers in forests, agriculture, and the broader environment. Alarmingly, approximately one-fourth of the 1200 bat species worldwide, which equals a fifth of the total mammal species, are currently facing the looming threat of extinction. As an example, in the UK the dwindling bat populations can be predominantly attributed to human-induced factors, including the depletion of their feeding habitats, the use of pesticides and intensive farming practices that diminish insect populations and construction and development activities that disrupt their roosting sites (Gunnell et al., 2013).

Unlike other creatures, bats do not construct their own nests; Instead, they utilise existing spaces for roosting. These roosting sites must offer the appropriate climatic conditions, ensure darkness and remain free from disturbances to be considered suitable by bats. Roosts come in various sizes, with some accommodating only a single bat while others host hundreds. Bats typically alternate between different roosting locations throughout the year, often returning to the same roosts within buildings, which may have served as their homes for generations (Gunnell et al., 2013). Favourable roosting spaces are cavities in building envelopes or slitted spaces in roofs or basements. The alternation between varying roosting locations is related to the different functions and required conditions of the roosts throughout the seasons, such as hibernating spaces in winter and maternity roosts between May and August (Aghina et al., 2023).

Since temperature plays a crucial role in the selection of roosting sites for bats, one of the key factors that render buildings attractive to bats is their ability to maintain a stable microclimate (Gunnel et al., 2013). However, some bat species, like the common dwarf bat, reside in human-built roosting boxes as well. Along with the rest of the required conditions for these bats to thrive, the requisite dimensions of such roosting boxes are presented in table 3. According to Aghina et al. (2023) until now there are no successful cases of human-built roosts accommodated by bat species like the small dwarf bat, common big-eared bat and parti-coloured bat in the Netherlands, hence only the common dwarf bat is considered for this project. Bat boxes for these species could be integrated in the design of the façade system under precondition of all the requirements being present at the site location.

Common Dwarf Bat

Common Dwarf Bat
Procreation
Built-in flat (5cm) boxes with a minimum size of 20x50cm
Boxes at a height between 4 and 50m
Opening on the bottom with a width of 16-20mm and underneath that a raw surface or landing board of >30 cm
Multiple boxes on different heights and wind directions
Connection (other populations)
Water lines and tree lanes
Nutrition
Insect-rich planting
Water area with musquitos
Safety
No artificial light at place of residence and non-lit areas
Residence
Several small cavities

Table 3. Requirements Bat species (own illustration)

Birds

Each bird species needs assurance in somewhere safe to nest, year-round food availability and multiple shelter locations, however it is dependent on the species what its foraging range is and how much influence as humans we have on their survival. For instance, ensuring the right habitat for species that forage close to the nest, such as house sparrows and starlings, is achievable, while contrarily for species that forage over much wider areas and feed in flight, like swifts, swallows and house martins, there is often little influence in obtaining habitat requirements far away from the created nesting location. Therefore, the most important intervention for those species when interfering in their habitats is the protection of existing nests as well as the provision of new nesting places (Gunnell et al., 2013).

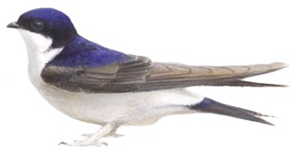
According to the organisation of Bird protection Netherlands (in Dutch: Vogelbescherming Nederland) (n.d.) there are twenty typical urban birds in the Netherlands, each having deviant preferences and requirements regarding the five Vs. In their guide Aghina et al. (2023) discusses approximately ten urban species of which only the peregrine is not selected for this project considering it being a predator for smaller bird species and its demand to have a nesting location at the minimum of 25 meters, although preferably a height between 80 and 120 meters. The rest of the urban species ask for requirements that are more feasible in average school building environments (see table 4).

Considering the design of a façade system in this case, possible actions to attract these urban birds to host on or around the systems include adding food providing vegetation or other nutrition resources, water baths, nesting materials, nesting locations in the shape of façade vegetation or nesting boxes or (dense) climbers ensuring hiding spots.



House Sparrow	**Bush breeders, e.g. Robin & Blackbird**	**Starling**
Procreation (nesting boxes)	**Procreation**	**Procreation**
Minimum of 5 nesting boxes, each minimum 50 cm apart Nesting boxes at a height between 3 and 10 m Nesting boxes close to the gutter and far away from windows Opening on N, E or NE Minimum size 12,5x12,5x12,5 cm and opening d=34mm	Dense, evergreen (thorny) bushes or façade greenery like climbing plants	Minimum of 5 nesting boxes clustered Nesting boxes at a height between 2 and 5 m Minimum size 16x16x30 cm and an opening of 45 mm Opening preferably on NE, or N or E
Connection (other populations)	**Connection (other populations)**	**Connection (other populations)**
Other house sparrow populations nearby	x	No colony breeder, but prefers other starlings nearby
Nutrition	**Nutrition**	**Nutrition**
Plants (e.g. seeds, grains, flower buds, berries) Insects (like aphid) Bread, peanuts and fat balls	Nectar-rich and berry-bearing planting	Lawns (grass fields) for insects and their larvae within 500 m Berry-bearing planting
Safety	**Safety**	**Safety**
Climbing plants and thorny bushes of minimum 3 m high	Thorny bushes and dense, evergreen hedges	x
Residence	**Residence**	**Residence**
Evergreen bushes to sleep Grass within 100 m Water (clean and shallow) within 100 m Sand within 100 m No big/high trees	Dense, evergreen (thorny) bushes or façade greenery like climbing plants	Nesting boxes and tree cavities

Table 4. Bird species requirements (own illustration)



	Great Tit & Blue Tit	**Swift**	**House Martin**
Procreation	They breed inside nesting boxes, tree cavities or sheds Nesting boxes at 2 m height and minimum 10 m apart in case of 1 specie. Combination of species: 3 m apart Min. size Great tit: 12x12x32cm and opening 32mm Min. size Blue tit: 12x12x28cm and opening 28mm Opening on N, E or NE	Minimum of 5 (built-in) nesting boxes, each min. 80 cm apart Nesting boxes at a height between 6 and 40 m Min. size 25x15x13 cm and oval opening of 70x35mm, max. 20mm from the bottom of the box Opening on N, E or NE In front and underneath box should be a free space of >3m	Minimum 5 nesting bowls clustered per project Nesting bowls at a height between 4 and 10 m Nesting bowls have a specific, hanging half bowl shape Opening on NE In front and underneath bowl should be a free space of >3m
Connection (other populations)	Territorial birds, so therefore minimum of 10m between the nesting boxes	Water and lawns nearby	Water and lawns nearby
Nutrition	Nectar-rich and berry-bearing planting Insects (like caterpillars) Beechnuts and other seeds Fat balls	Insect-rich (herb) lawns within 500 m Water-rich area within 500 m	Plants for insects in a water-rich area
Safety	Thorny bushes and hedges	In front and underneath box should be a free space of >3m	In front and underneath bowl should be a free space of >3m
Residence	Ascending, evergreen bushes Big tree (like a beech, oak or hawthorn) with a dense foliage	Minimum 5 nesting boxes clustered in one place	White cantilevers near roof edges

Table 4 (continued). Bird species requirements (own illustration)

Insects

This group of species can be split into two categories: the first of them being actively appealing bees and butterflies to the site of the façade system and secondly, passively attracting a wide range of other insects by incorporating plants in the system to accumulate the food stock for the bird population of that area. Despite the passive approach of the latter, specific actions could be considered to increase the appearance of insects on the façade. Catering to invertebrates seeking shade, shelter and increased humidity, one can consider climbing plants such as ferns on north-facing walls. The foliage of these north-facing, or other orientated, climbing plants also offers additional support to various invertebrates, including spiders, while the accumulation of leaf litter can attract woodlice, snails, and more (Gunnell et al., 2013).

Bees and butterflies are a key link in the food chain as they maintain 60% of the cross-pollination of humans' fruit and vegetables. Unlike the high humidity favouring insects however, they prefer their place of residence on sunny facades facing the south or west, although butterfly hotels on the shady side of a building could function as a hibernation spot for them (Aghina et al., 2023). When dealing with an older wall with soft mortar, varieties of e.g. bees, wasps and beetles can use holes and crevices in the façade as their microsystem (Gunnell et al., 2013), nonetheless, human-built insect hotels on or integrated in newer facades, or in this case a modular system, act as a sufficient substitution. In table 5 is illustrated which conditions are necessary for well-functioning insect hotels as well as the potential actions to be taken to improve the appealing of invertebrates in general.

	Bees & Butterflies
Procreation	Each specie needs certain host plants. This differs per specie.
Connection (other populations)	x
Nutrition	Nectar and pollen plants (flowers and herbs) Trees with a blooming period from early spring till fall
Safety	Variety in vegetation with different structures
Residence	Insect stones, sand, dead wood, small cavities in stems or stacked stones Butterfly hotels and bee bricks with opening on S, SW or W Min. size butterfly hotel: 13x15x23cm Min. size bee bricks: 6x10x21cm Min. 50 openings in bee bricks with sizes between 1 and 9 mm

Table 5. Insect species requirements (own image)

Vegetation

In the previous Chapter the many benefits of implementing a vegetated façade in an urban environment are already presented as well as the importance of utilizing native over exotic vegetation whenever beneficial in the previous paragraph. Considering the completed research about green facades, this thesis will make use of two typologies of vertical vegetation as shown in figure 38, i.e., indirect green facades and indirect living wall systems with modular vegetation elements. For those green wall typologies, four categories of vegetation are selected for implementation in the system: small climbers, succulents, perennials without irrigation needs and perennials with irrigation needs. The first mentioned will be applied in the form of an indirect green façade system and the other three will be applied according to the indirect, modular LWS typology. For each category, some examples of suitable vegetation are given based on some general requirements regarding vertical green and, if applicable, some category specific demands.

General vertical vegetation requirements

Every plant species has its own preferences and requirements to optimise their ability to flourish. However, it would take an extensive amount of time to thoroughly explore this, which therefore not falls within the scope of this research. Nonetheless, some general subjects to consider for vertical vegetation are addressed, that would facilitate the decision-making of selecting the particular species for the specific locations that would be chosen for the implementation of the design.

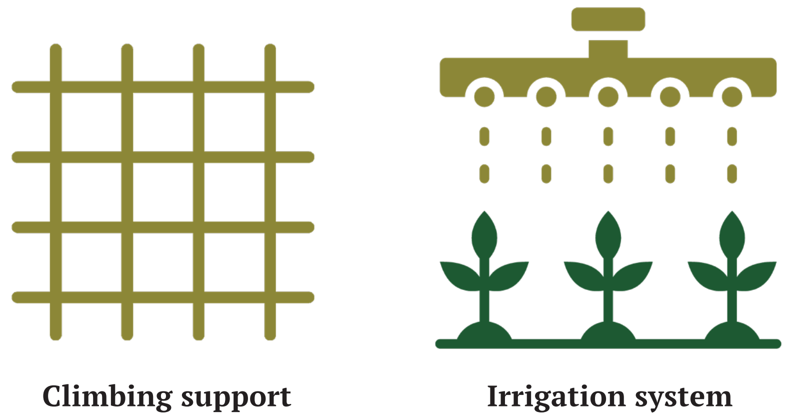
Firstly, it is obvious that vertical vegetation growing on facades has minor rooting space compared to the ones that are rooted into the ground. Similarly, considering the modular concept of the design, it is likely to occur that the plants also have limited growing space in terms of height. Both these considerations result in the fact that the implemented vegetation will mostly have a small, limited size and must not require substantial growing space, above or below the soil.

Furthermore, the plant's preferences regarding exposure to sun and wind has to be investigated and will determine the optimal orientations for the plant to grow. In general, plants that prefer a sunny location, require at least five sun hours per day and (semi-) shade favouring plants request less than five hours of sun. Which species eventually will be the right fit, completely depends on the location of the system and more specifically, the orientation of the facades the design is applied on.

Lastly, conducive to enhancing the local biodiversity with the system, it would be strongly recommended to achieve an ensemble of applied plant species that collaboratively provide a year-round growing and flowering period. This is beneficial for several fauna species, which not merely are dependent on the presence of flora during spring or summer, but also, sometimes to a greater extent, rely on food providing vegetation during the colder months of the year. Hence, when selecting suitable vegetation for the system, this aspect should be highly considered.

Figure 60. Three general vegetation requirements (own illustration)

Figure 61. Vegetation type specific requirements for climbers and irrigation demanding perennials (own illustration)



Climbers

Façade vegetation in the shape of climbers and creepers is the second typology for this project. Despite the disadvantages given in the previous Chapter regarding to chances of a lower circular value of the system, these could be mitigated when the climbers are maintained as a deliberate growth of vegetation surrounding the modular elements instead of growing over them. Advantageously, contemplating this as a part of the system, it could have significant benefits in terms of fostering biodiversity in the area by for example attracting insects and offering food, hiding spots and nesting possibilities for birds. However, it is favourable for these types of façade vegetation to be planted directly into the earth at the base of the façade as roots have more space to grow and the climber can benefit from the natural conditions of the soil. Placing them in pots at the bottom of the façade is a costly en fragile solution due to intensive care and maintenance (Hermy et al., 2005), so when putting the climbers directly into the earth is not an option at that particular site, this typology should not be considered.

Alongside considering the given requirements, a few extra conditions are to be dealt with increasing their potential for the system. First of all, the climbers need to be supported by a climbing frame, as the climbing species that grow directly onto the façade cause several disadvantages regarding the modularity of the system. Furthermore, although not defined by a small volume of rooting space, the size and proliferation of the species must be limited in order to minimise the chance on damaging the modules.

Conforming to the requirements, some potential examples of climbers for implementation in the cladding system are presented.

Species	***1. Clematis Tibetana Subsp. Tangutica***
Origin	*Non-native*
Site	*Sun & Semi-shade*
Blooming Period	*July - September*
Height	*400 - 500 cm*
Winter Hardiness	*Excellent*

Species	***2. Clematis "Pixie"***
Origin	*Non-native*
Site	*Sun & Semi-shade*
Blooming Period	*April - May*
Height	*80 - 100 cm*
Winter Hardiness	*Medium*

Figure 62 - 66. Five potential climbers for the façade system (Source: De Tuinen van Appeltern, n.d.)
Table 6. Specifications of the potential climbers (Source: De Tuinen van Appeltern, n.d.)

Species	***3. Clematis Montana***
Origin	*Non-native*
Site	*Sun & Semi-shade*
Blooming Period	*May - June*
Height	*500 - 700 cm*
Winter Hardiness	*Good*

Species	***4. Clematis Viticella "Rubra"***
Origin	*Non-native*
Site	*Sun, Semi-shade & Shade*
Blooming Period	*July - September*
Height	*300 - 400 cm*
Winter Hardiness	*Good*

Species	***5. Clematis Vitalba***
Origin	*Native*
Site	*Sun, Semi-shade & Shade*
Blooming Period	*July - September*
Height	*700 - 900 cm*
Winter Hardiness	*Excellent*

Succulents (Crassulaceae)

Succulents are species capable of storing water in their roots, stems or leaves, meaning that they can successfully thrive in dry soils and will survive longer periods of drought more easily. They are commonly applied to green roofs and are therefore also suitable as vertical vegetation in facades. However, not many native Dutch species exist, but fortunately the species that are also show potential for implementation in the cladding system for this project.

Species	***1. Hylotelephium Telephium***
Origin	*Native*
Site	*Dry & Damp*
Blooming Period	*August - October*
Height	*30 - 40 cm*
Winter Hardiness	*Extremely Excellent*

Species	***2. Sedum Acre***
Origin	*Native*
Site	*Damp & Marshy*
Blooming Period	*June - July*
Height	*10 cm*
Winter Hardiness	*Excellent*

Species	***3. Sedum Hybridum***
Origin	*Non-native*
Site	*Sun & Semi-shade*
Blooming Period	*June - July*
Height	*10 - 15 cm*
Winter Hardiness	*Medium*

Species	***4. Sedum Spathulifolium***
Origin	*Non-native*
Site	*Sun*
Blooming Period	*May - June*
Height	*3 - 10 cm*
Winter Hardiness	*Unknown*

Figure 67 - 71. Five potential succulents for the façade system (Source: De Tuinen van Appeltern, n.d.)
Table 7. Specifications of the potential succulents (Source: De Tuinen van Appeltern, n.d.)

Species	*5. Sempervivum*
Origin	*Non-native*
Site	*Dry*
Blooming Period	*July - August*
Height	*10 - 20 cm*
Winter Hardiness	*Excellent*

Perennials (no required irrigation system)

The last two categories, both being perennials, are discussed simultaneously, as the only difference made for these species regarding their implementation in the design, is whether they need an irrigation system for more consistent watering or not. Perennials are species that lives at least two years and blossoms at least once during his lifetime. The primary functions the vegetation in these categories can fulfil regarding this thesis, are providing nectar for polluting insects, food for bird species in forms of berries, seeds and associated insects and perform as educational purpose for the school children as herbs and small sized vegetables or as research objects for a nature-related workshop.

As described above, the primary functions of vegetation in the design of the system are mostly related to serving other species. Therefore, comparable to the other categories, no specific selection is made for the plant species as this will be mostly dependent on the other species that are to be fostered with the implementation of the façade, alongside the local conditions of the selected site. Nonetheless, in this category, some examples are presented as well.

Species	*1. Stachys Byzantina*
Origin	*Non-native*
Site	*Sun & Semi-shade*
Blooming Period	*July - August*
Height	*20 - 50 cm*
Winter Hardiness	*Excellent*

Species	*2. Coreopsis*
Origin	*Non-native*
Site	*Sun & Semi-shade*
Blooming Period	*June - October*
Height	*30 - 40 cm*
Winter Hardiness	*Excellent*

Species	*3. Lavendula Augustifolia*
Origin	*Non-native*
Site	*Sun & Semi-shade*
Blooming Period	*June - August*
Height	*30 - 50 cm*
Winter Hardiness	*Good*

Figure 72 - 75. Four potential perennials for the façade system (Source: De Tuinen van Appeltern, n.d.)

Table 8. Specifications of the potential perennials (Source: De Tuinen van Appeltern, n.d.)

Species	*4. Centaurea Montana*
Origin	*Native*
Site	*Sun & Semi-shade*
Blooming Period	*June - August*
Height	*40 - 50 cm*
Winter Hardiness	*Excellent*

Perennials with irrigation system

To avoid complex systems and thereby preserving the low-tech principle of the design, it is recommended to concentrate the species requiring consistent watering in the configuration of the design and not widely spread them over the façade, resulting in an unnecessary complex network of water pipes. The irrigation system can essentially be executed quite simple and low-tech, meaning that the small water pipes are located behind the modular elements and they can access the planter through small holes in the module. The pipelines are connected to an (outdoor) tap, which supply a drip system, whenever opened manually.

Species	*1. Bergenia Cordifolia*
Origin	*Non-native*
Site	*Semi-shade & Shade*
Blooming Period	*April - May*
Height	*25 - 30 cm*
Winter Hardiness	*Extremely Excellent*

Species	*2. Geranium*
Origin	*Non-native*
Site	*Sun*
Blooming Period	*June - August*
Height	*30 - 50 cm*
Winter Hardiness	*Medium*

Species	*3. Thymus Vulgaris*
Origin	*Native*
Site	*Sun*
Blooming Period	*June - July*
Height	*25 - 30 cm*
Winter Hardiness	*Medium*

Species	*4. Persicaria Bistorta*
Origin	*Native*
Site	*Sun & Semi-shade*
Blooming Period	*May - June*
Height	*30 - 50 cm*
Winter Hardiness	*Good*

Figure 76 - 79. Four potential perennials requiring an irrigation system (Source: De Tuinen van Appeltern, n.d.)

Table 9. Specifications of the potential perennials requiring irrigation (Source: De Tuinen van Appeltern, n.d.)

C

The Design

05

Preliminary Design

5.1 Design inspiration: geometric origami

Designing a three-dimensional structure is part of the main goal of this thesis. Additionally, multiple functions need to be implemented in the façade elements while a modular, adjustable design remains. Therefore, it is favourable to limit the number of different designs for the panels in the total system, or preferably design one element which is suitable for all the façade functions.

At first some hand drawings were made based on own ideas and thoughts, see figure 80 and 81.

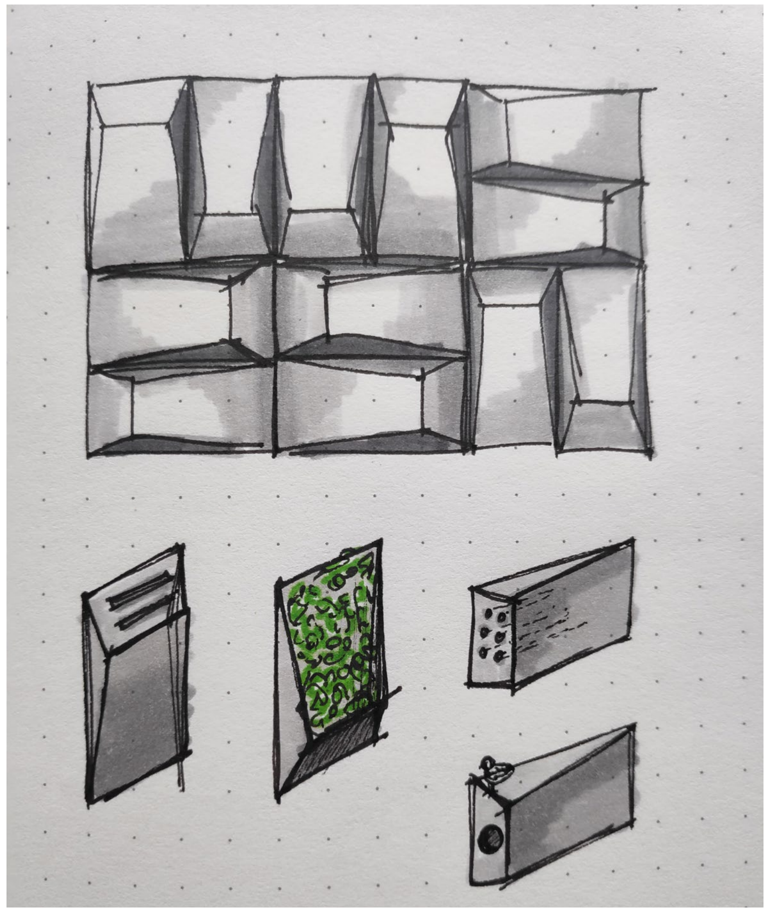
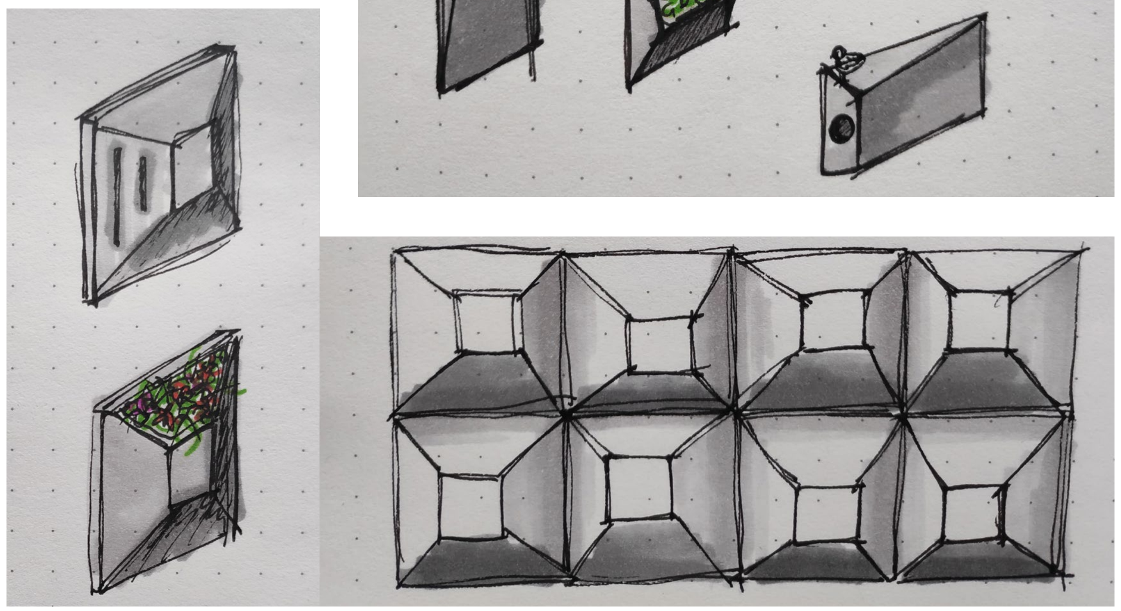


Figure 80 and 81. Sketches of initial inspiration for a three-dimensional façade element which could foster biodiversity (own illustrations).



During this design phase many geometrical origami models were made with the guidance of the book 'Geometrische Origami' by Mark Bolitho. It is decided to focus on the geometrical models of origami, because they might be the most relevant for designing a three-dimensional façade panel. In figure 82 below an overview of the folded models is given. Many of the shapes are unsuitable for a one-to-one application of a building façade, however they surely provided new inspiration for the project. From one of the origami shapes, several paper models were folded to explore the possibilities in terms of architectural language on the facade. This is visualised in figure 83.

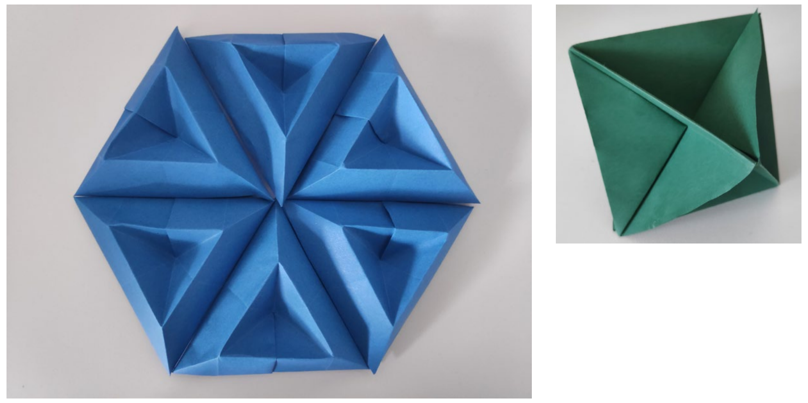


Figure 82. Overview of all the origami models that are folded (own image).

Figure 83. Exploration of an origami configuration (own image).

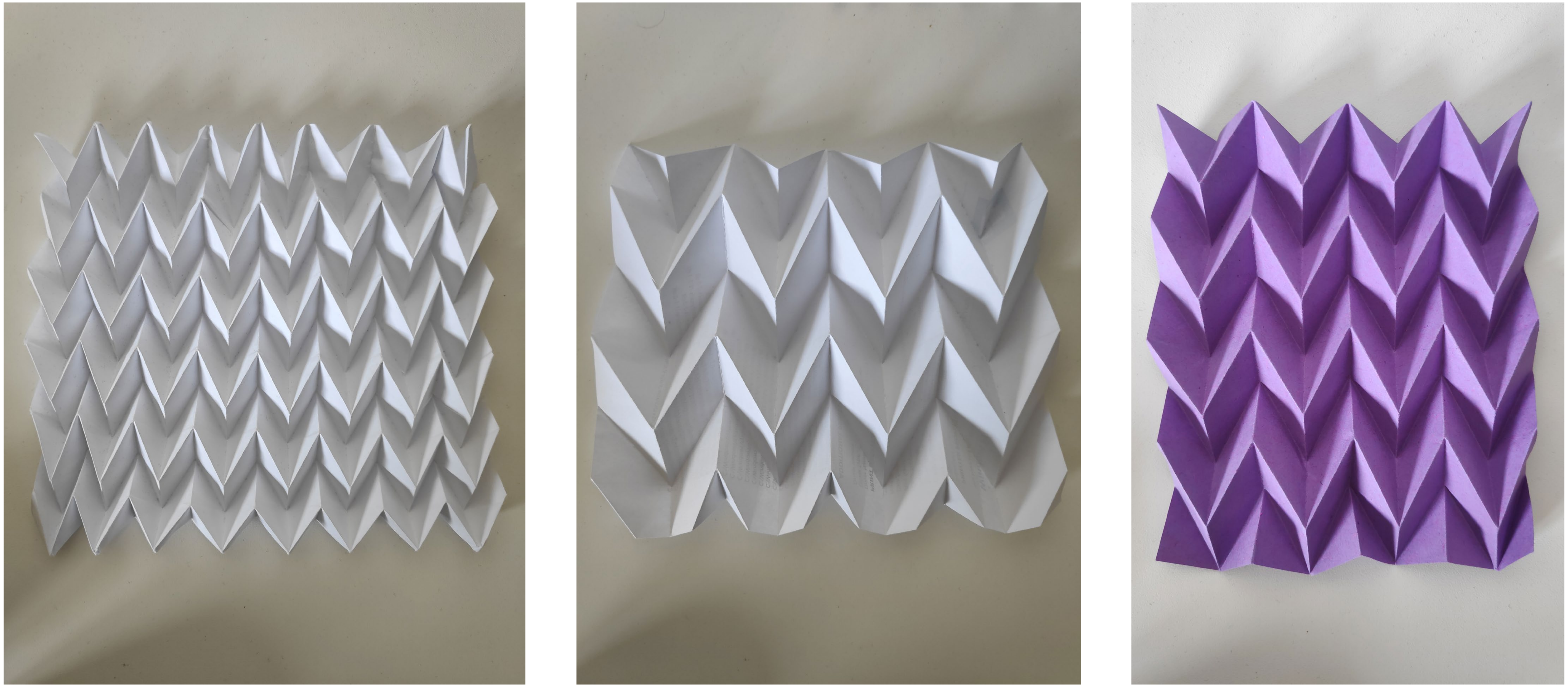
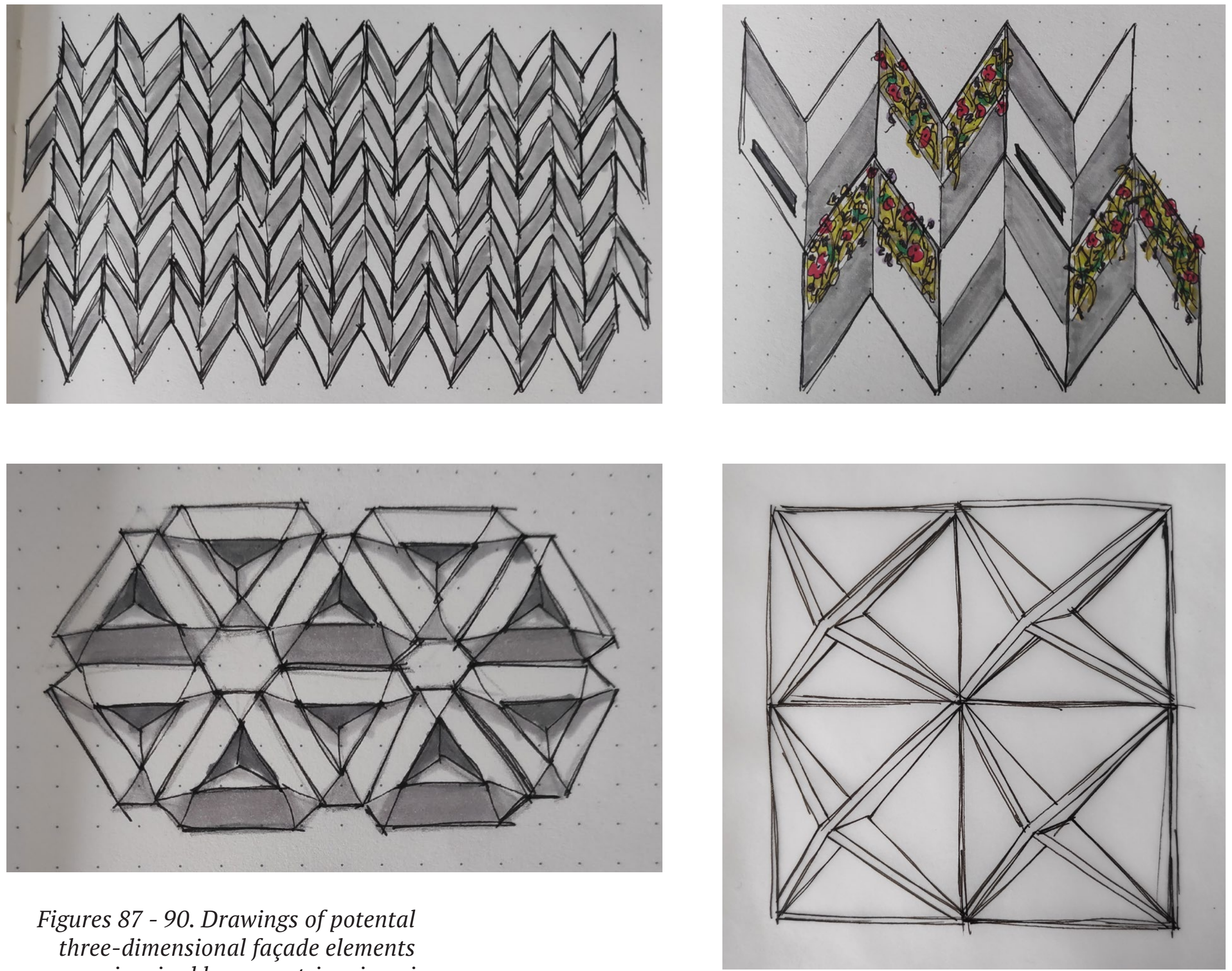


Fig. 84, 85 and 86. 'Zigzag' origami paper models (own image).

Aside from the models made from the book of Mark Bolitho, an online tutorial was consulted to fold a larger, more façade like element, which is presented in the pictures above. For this origami model it's possible to work with different paper sizes. This, and the fact that you can shrink and expand the model by pushing and pulling the edges, creates several design variations.

Based on the geometric paper models, some new drawings of certain shapes are presented in the figures 87 until 90 on the following page. The shape on figures on the left side, the zigzag-pattern origami, creates an interesting shadow play on the façade. However, the shape of one single element, an up or down pointing arrow, might limit the options of functions to implement in the façade. The angled surfaces provide options for small planters and when creating a hollow space inside, the elements might be suitable for bat boxes, but that same area doesn't seem attractive to birds for nesting, due to the sharp angles that form the hollow space inside. The pyramid shapes on the bottom left also create an intriguing shadow play when light falls on it, but these elements supply even less possibilities for the fillings of the system than the zigzag arrows.



Figures 87 - 90. Drawings of potental three-dimensional façade elements inspired by geometric origami models (own illustrations).

The drawing of the façade element on the bottom right is inspired by the octahedron origami model, but the sketch is in fact half of the original paper model, so the back side is a flat surface and suitable for façade applications. The triangular shaped crosses on each module form interesting interspaces when the modules are placed against each other, allowing many options for biodiversity related fillings of the elements, which is shown in the illustrations on the next page.

Judging by the made paper models and following sketches, the octahedron origami inspired module has the most potential for a circular, biodiverse façade system and is therefore chosen to continue with in the design process to develop it further into a multifunctional, applicable, add-on façade system.

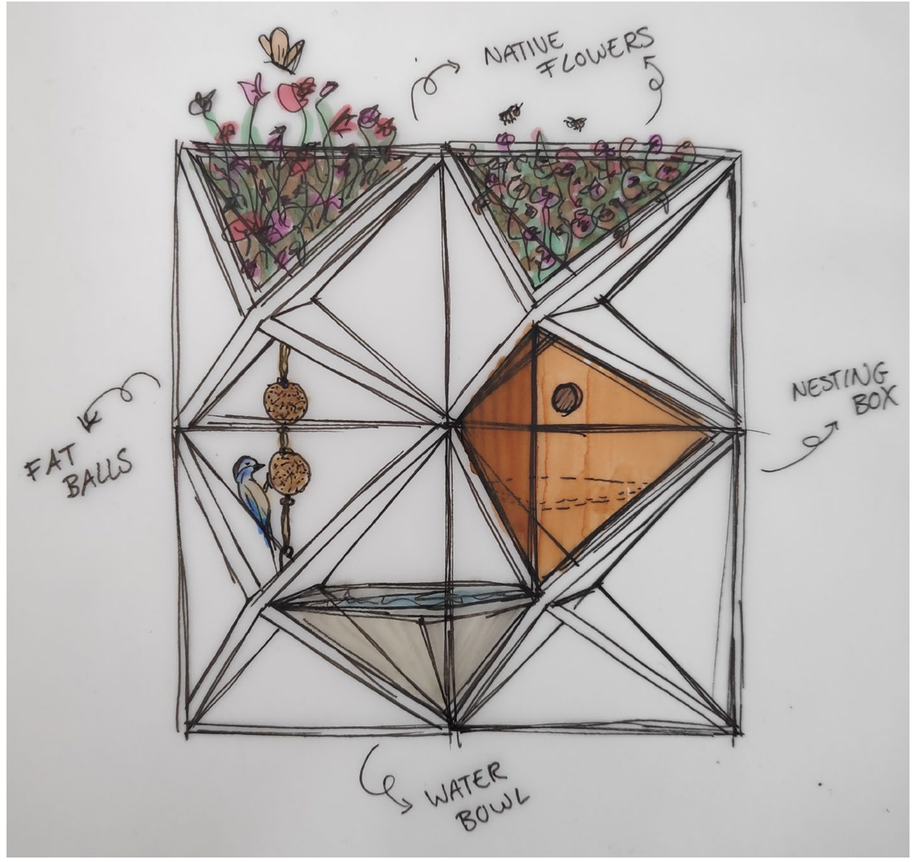


Figure 91 and 92. Preliminary Design: possible nature-inclusive solutions for the octahedron origami model (own illustrations).

06

Conceptual Design

6.1 Design guidelines: outcomes of the literature study

Orientation

In terms of orientation there appeared to be a significant contrast between the preferences of several biodiversity species. Each of the considered birds that could nest in a nesting box requires a placement where the nesting box won't overheat, so only the north, northeast and east orientated facades are suitable. Contrarily, insect hotels for bees and butterflies desire as much sun hours as possible, hence south, southwest and west aligned insect hotels have the highest success rate. Regarding the vegetation that could be added to the system, it could grow on an orientation depending on the chosen types, as well as bats that don't have a strong preference for a specific façade orientation as they use different boxes in different times of the year, all with their own unique indoor climate. By this manner, the façade system could be applied to any façade orientation, however the incorporated flora and fauna species would vary according to the available envelopes. For the diversity richness of the system, it is favourable to pick a building which could host the system on both the desired orientations for birds and insects.

Users

As earlier mentioned, for several reasons this system focusses on the implementation on school buildings, which make school children and their teachers the primary users of the product. Moreover, one aim of this project is to involve these users in the maintenance and preferably also in the construction of the modules. This results in the important design guideline that the system must be understandable, mountable and manageable for children between the age of roughly 8 until 12 years old, of course in assistance of their teachers and possibly an external professional.

Although it is not included in the design brief, the system could potentially also be used by private households on their building envelopes, since a low-tech product is the target and thus with the appropriate supplied information, individuals should be able to maintain the product themselves.

Elevation height

This guideline is largely dependent on two objectives of this project. Firstly, some of the fauna species require a certain height for the placement of their housing locations. Bats, for instance, need their boxes at a minimum height of three meters, but prefer it even higher to a maximum height of 50 meters. Additionally, many of the considered bird species desire a height of two meters or more because of safety against predators like house cats. Bees and butterflies, however, need their hotels to be at a lower height, i.e., maximum three meters high. Secondly, regarding the objective of this project to serve as a educational tool for school children as well, at least a part of the façade system must be within reach for the children. This determines the elevation height of these elements, that are regularly involved in lessons and workshops, on a maximum height of approximately two meters.

Materiality

In Chapter 3 several waste streams are discussed wherefrom a first selection of waste materials with potential to use, followed from the considerable requirements the materials must fulfil to function as an outdoor add-on façade layer.

From the preliminary origami design, three main design elements can be distinct which have divergent functionalities and therefore are likely to consist of different materials. These three design elements consist of (1) the module itself, (2) the fillings that will be placed inside the modules and (3) the structure that is necessary to assemble the system to the existing building envelope. As addressed before in Chapter 3, the availability of materials and products may differ in time and space, therefore, for each component several suitable materials are considered if they comply with the requirements of that function.

Manufacturing process

Considering the manufacturing techniques that are explored during the literature research, each of the low technical processes, like die cutting and laser cutting, shows potential regarding processing of reclaimed materials. However, the method that will eventually be used is highly dependent on the chosen material, as some techniques have limitations in terms of processing a maximum material thickness or the rigidity of the product. Yet, if all the low-tech methods prove unsuitable for the applied material, it would be possible to move on to one of the more complex, three-dimensional manufacturing techniques, such as moulding, although this is unfavourable as it would make the production less convenient for the involvement of the end-users.

(Dis)assembly methods

Consecutively from the manufacturing processes, the appropriate connection methods have to be selected for the circular system. The main conclusions drawn regarding this subject are that each type of connection should be dry, reversible and durable, to allow for repeated dis- and reassembling of the components. Additionally, the connections should be easily accessible, preserve the integrity of the materials and be weatherproof since the placement of the modules in an external environment. Various potential low-tech, modular connection types are bolts, joinery, clamping and tie-lashing and these will be tested during the design phase of the thesis, however the experiments are not limited to these techniques and other methods can be identified and studied along the process.

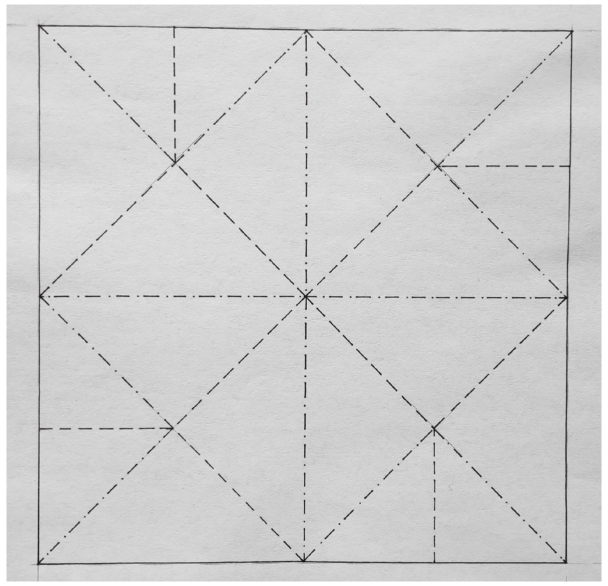
Module size

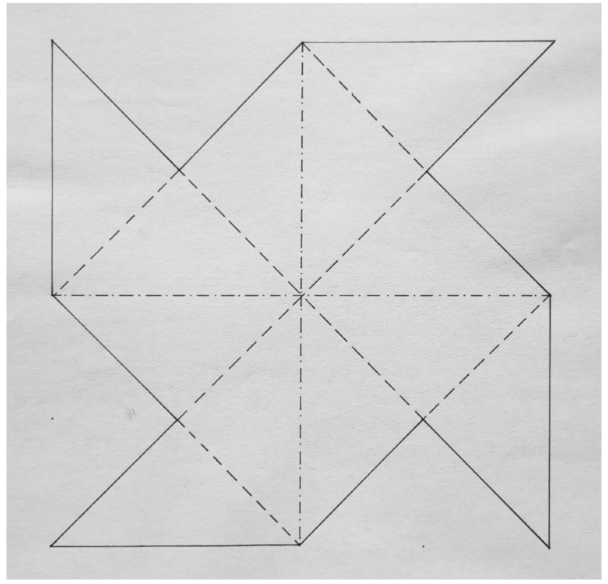
As the size of the façade elements might be influenced by the biodiversity pockets that are to be implemented in the system, it is mainly decided by the previously mentioned en- users of the product and their involvement in the product. Children must be able to manage the system in terms of assembling and maintenance, which consequently results in the modules not being too large or heavy. These two considerations form the basis of design experimentations regarding its size, aiming to find the right balance between a module that is small enough for children to manage, but large enough for flora and fauna to thrive in.

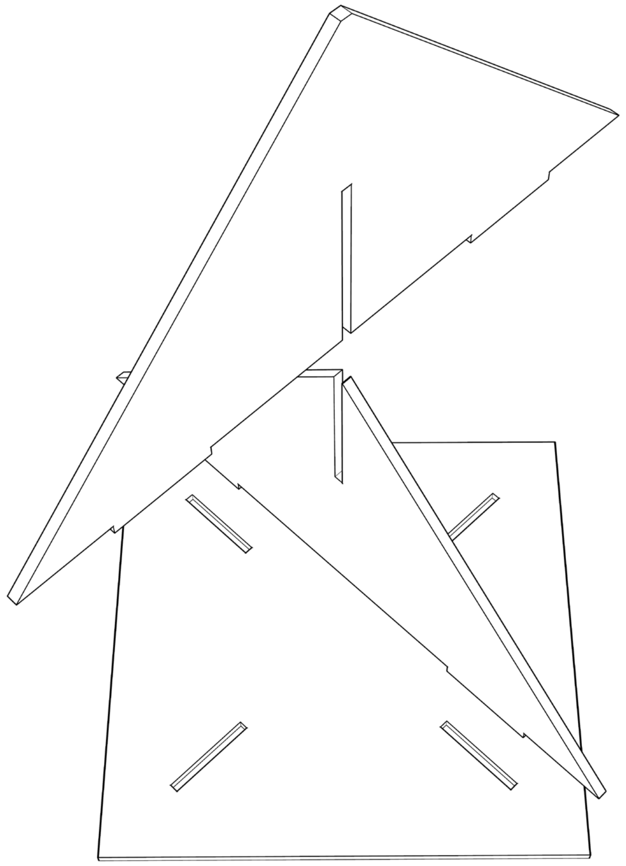
6.2 Conceptual Design

Building on the origami inspired octahedral shape, the first provisional 3D models were made and the first ideas regarding the modules' assembly emerged. Initially, the direction of the origami principle was followed, where the module would be built from one element which could be transformed into the desired shape by folding several pieces, as shown in the 2D drawings in figures 93 and 94. However, the conclusion that this system would be overly complicated in terms of manufacturing and assembling and moreover vulnerable to damage, was drawn quickly and another direction was chosen. With the simpler approach of building the module from separate elements sliding into each other, the design concept arose, as shown in figures 95 and 96. In terms of assembling the modules to the building, the concept of a secondary structure, consisting of metal bars, emerged. One method of attaching the modules to this structure would be by sliding them (see figure 97), however this would cause several problems such as demounting the whole system when one of the bottom modules requires maintenance. Therefore, other solutions were explored, like clamping or hanging the modules to the metal bars, which is elaborated in the next chapter.

Figure 93 and 94. Assembling the module according to the folding principle (own illustrations)







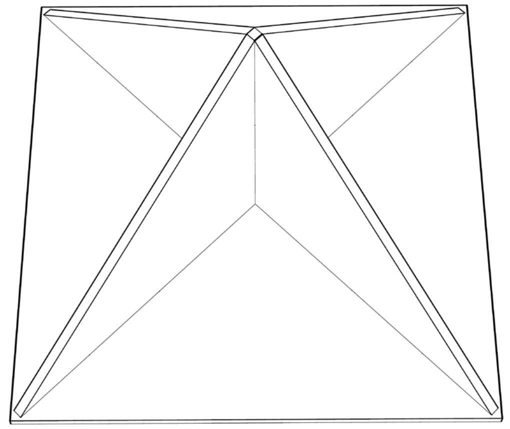
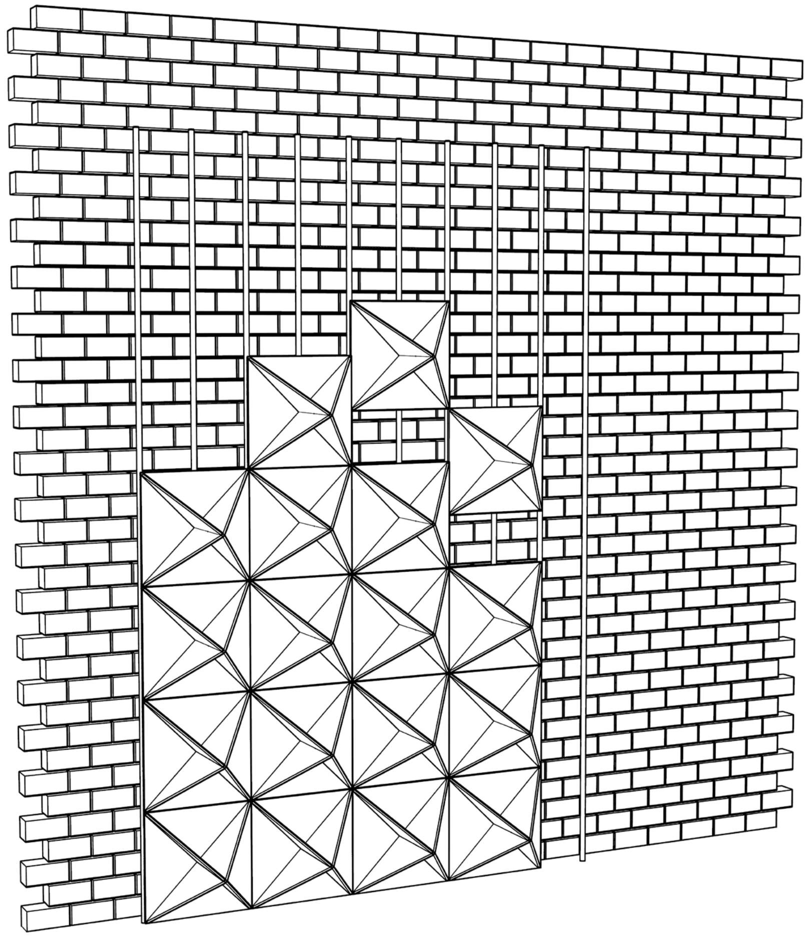


Figure 95. 3D module of one module (own illustration)

Figure 96. Assembling the module by sliding the 2D elements into each other (own illustration)

Figure 97. Applying the modules on the secondary structure by sliding them over metal bars (own illustration)



Considering the goal of implanting biodiversity in the system, the orientation of the module was something which required exploration. The initial concept of the modules was a square, symmetrical shape, however if the module was rotated 45 degrees, the spaces between the modules would change significantly. Moreover, they would be more convenient for the addition of fillings, since this orientation would allow for more rectangular shaped fillings which would increase the simplicity of

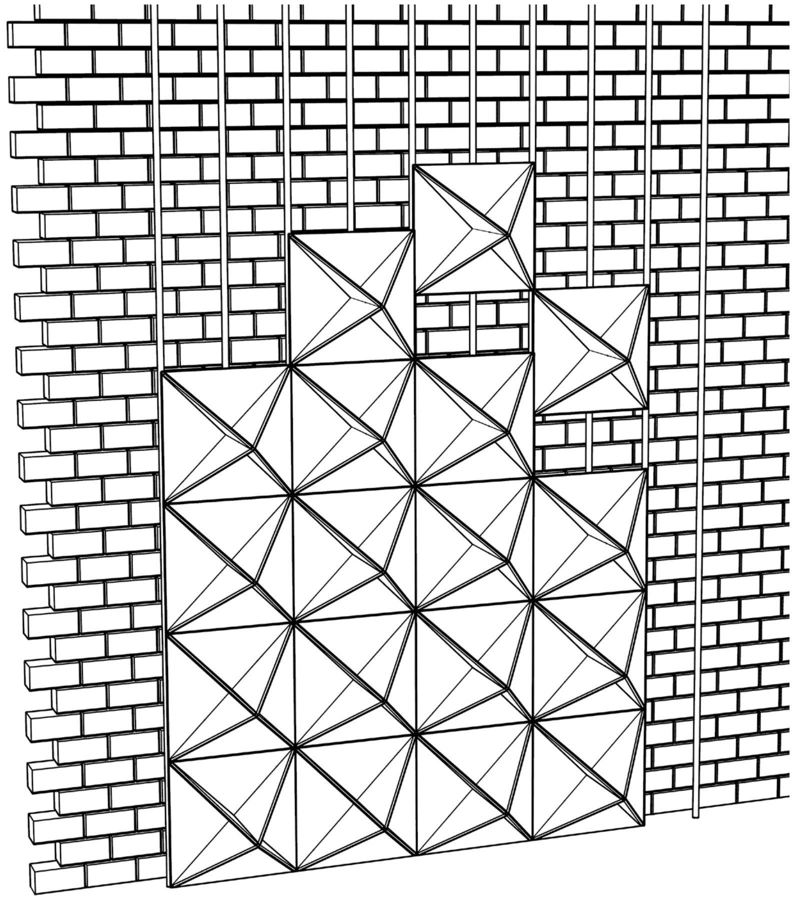


Figure 98. Original module orientation (own illustration)

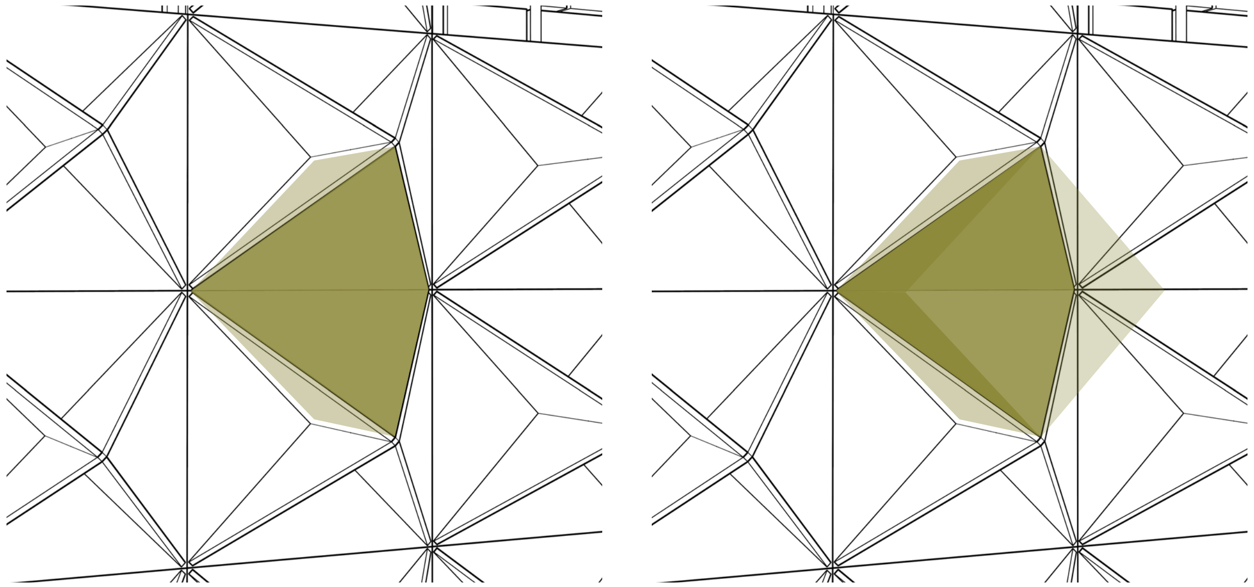


Figure 99 and 100. BioPod shape with original module orientation (own illustrations)

the overall design. This comparison is illustrated in the figures below.

Subsequently, this led to the following design concept:

*A circular façade **system** that consists of modular **modules**, made from two-dimensional **elements**, which are attached to a **secondary grid structure** fixed on the façade. These modules are filled with a variety of local biodiversity enhancing infills, the so-called **BioPods**.*

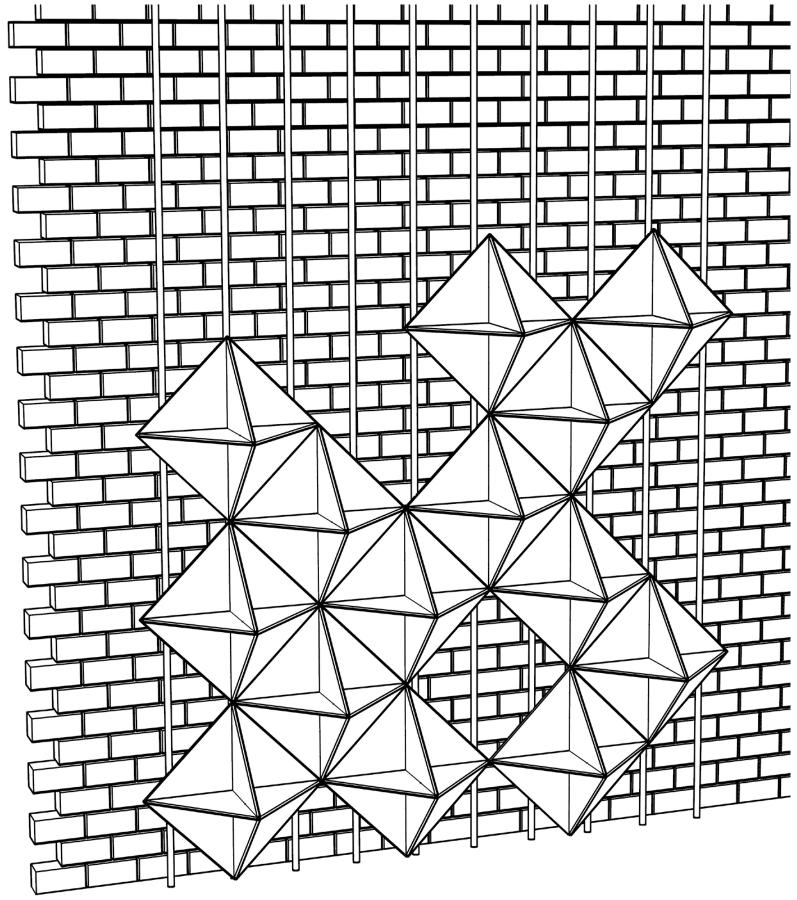


Figure 101. Newly proposed module orientation (own illustration)

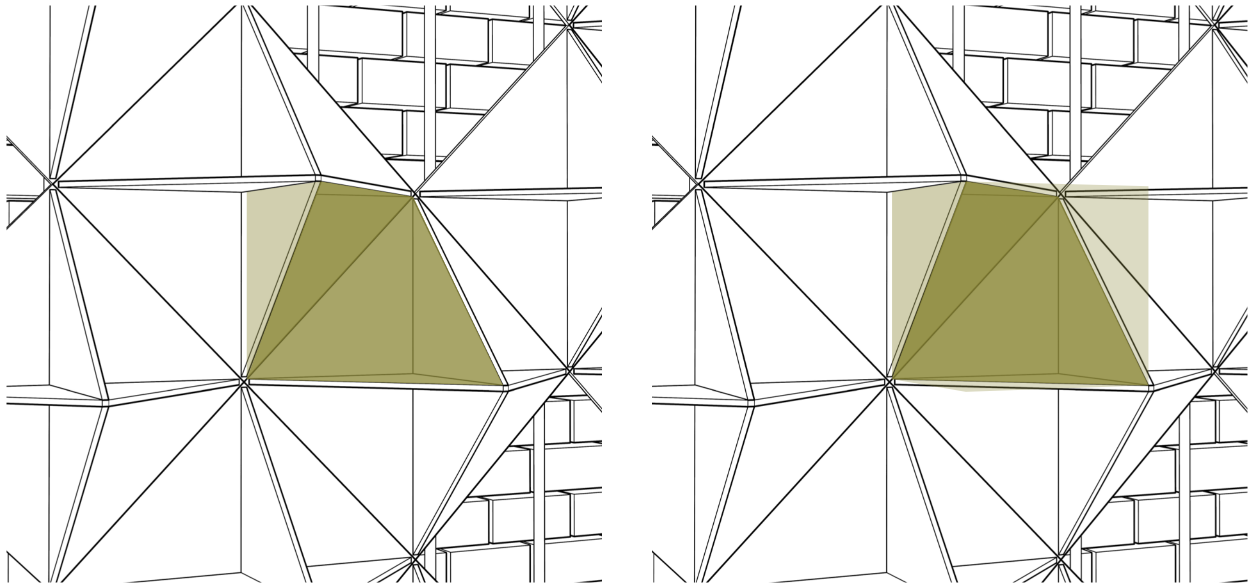


Figure 102 and 103. BioPod shape with newly proposed module orientation (own illustrations)

07

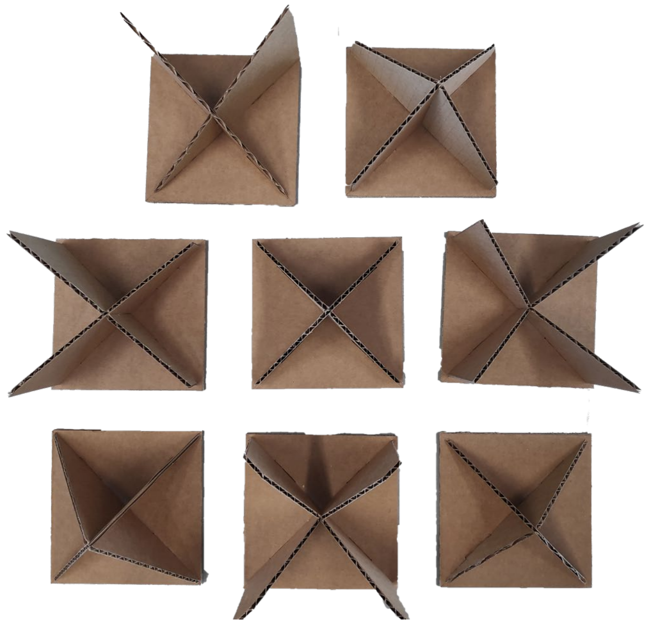
Experimentation & testing

7.1 The Modules

Shape

As the shape of the module was still identical to the original origami model, it needed to be developed further to a shape which was better fitting the design brief considering the design guidelines from the literature review. Primary influencing factor in this experimentation process was the BioPods, as the shape currently contained many sharp angles which would not be optimal for this purpose.

Accordingly, several cardboard models were made to experiment with the shape of the module, as shown in figures 104 and 105.



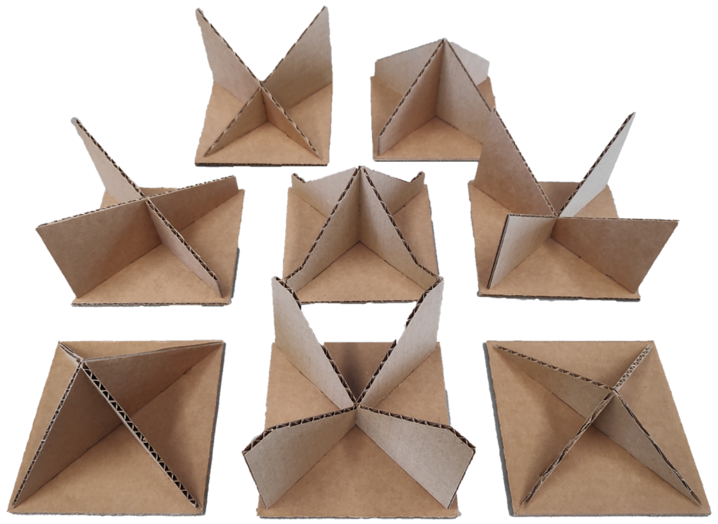


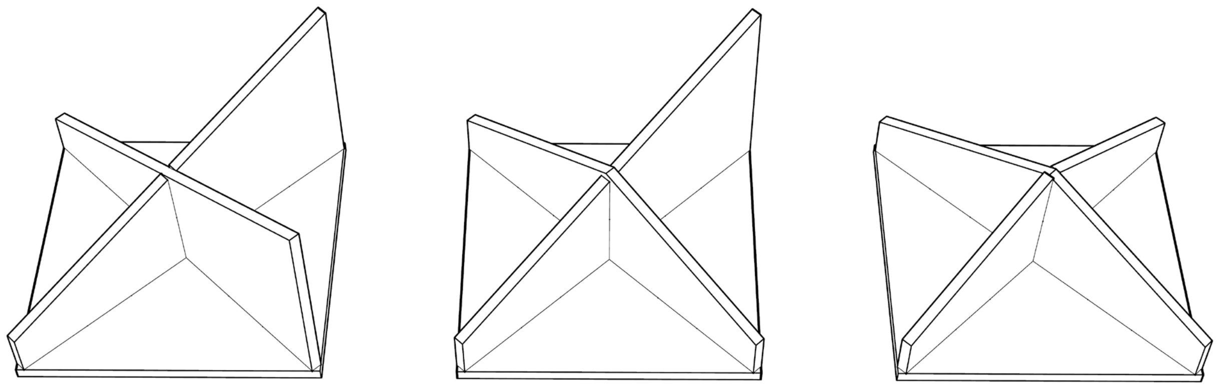
Figure 104 and 105. Cardboard models of module shape experimentations (own images)

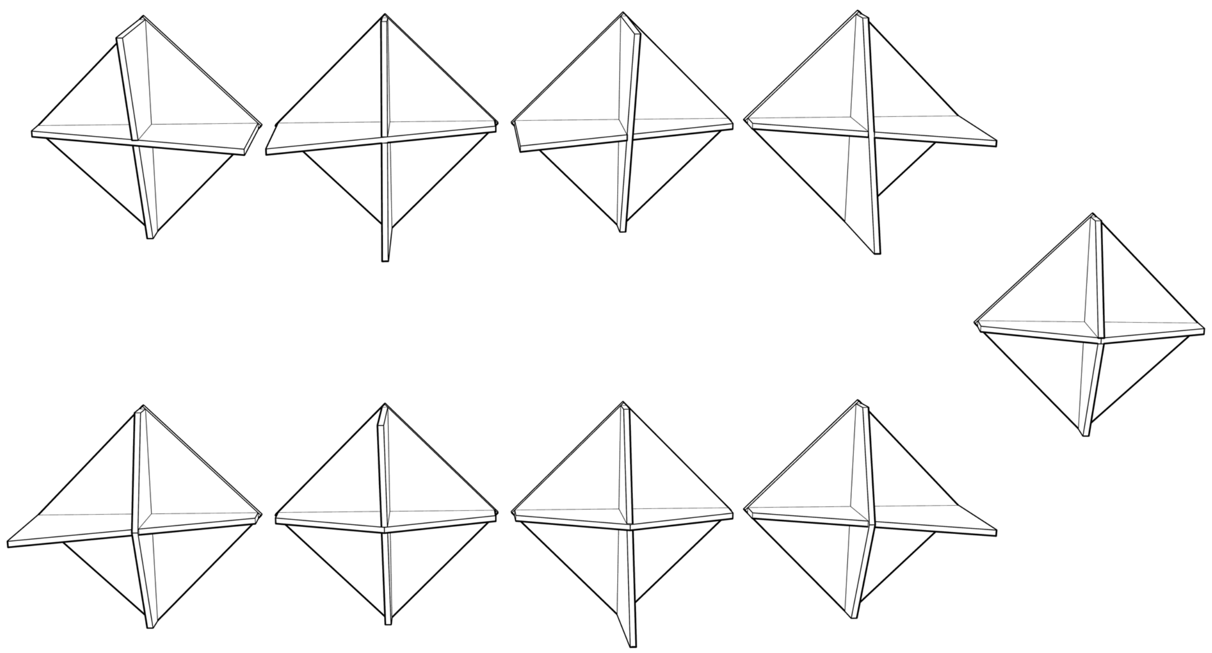
Configurations

The result of experimentation of the shape through these cardboard models were three interacting shapes, which are shown in figure 106. These shapes have contiguous elements which form an interesting architectural language as the varying depths of the modules create an attractive aesthetic appearance of the system. Additionally, by rotating these three modules, nine distinctive module orientations are found, as illustrated in Figure 107. Consequently, with only three base elements, nine modules can be created and even more unique BioPod volumes are generated, shown in the figure on the next page.

Figure 106. The three different modules (own illustration)

Figure 107. The nine possible module orientations of the three modules (own illustration)





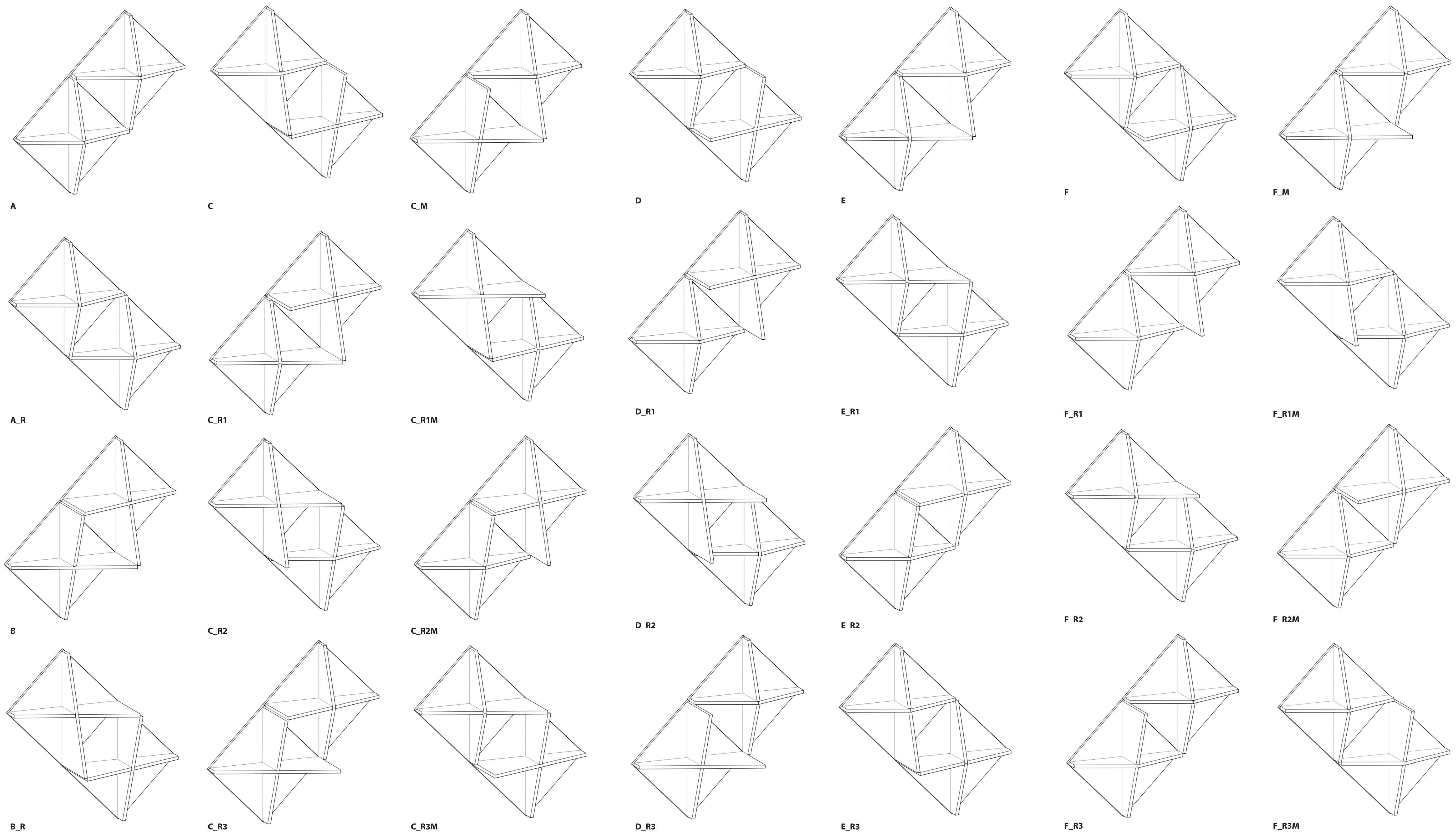


Figure 108. The 28 generated unique BioPod volumes through the rotation of the three modules (own illustration)

Next to the pod volumes that are formed by the placement of the modules directly attached to each other, larger open spaces can be created by leaving out one or more modules, which will generate volumes for larger BioPods. Additionally, this can be encompassed in the strategy of designing an attractive architectural pattern with the modules on the façade.

Concluding, these modules configurations are the fundament for design experimentations for the final shapes of the BioPods. As can be seen in both figure 108 and 109, not each space that is created inside the modules will be a useful shape as a base for the BioPods.

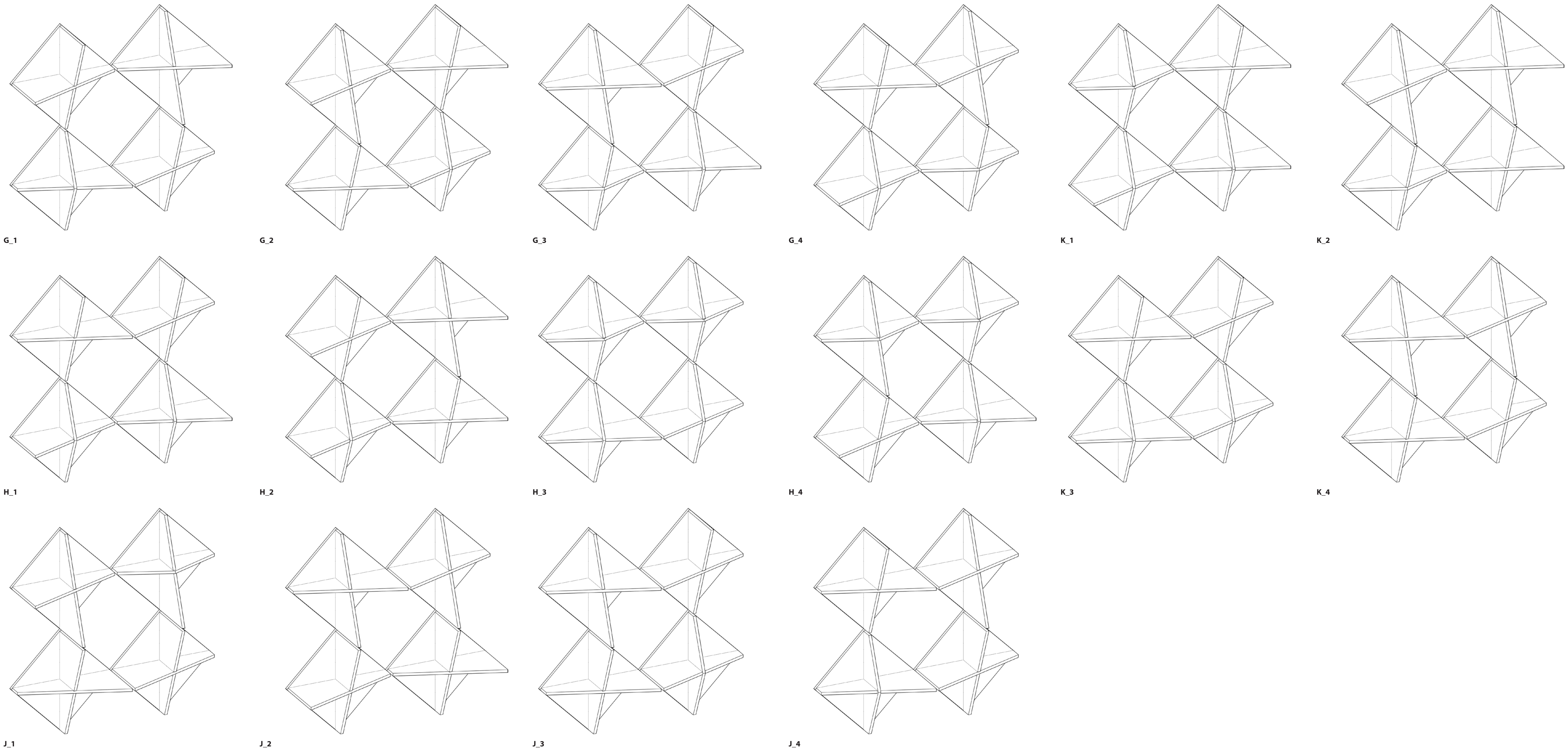


Figure 109. The 16 unique larger BioPod volumes (Own illustration)

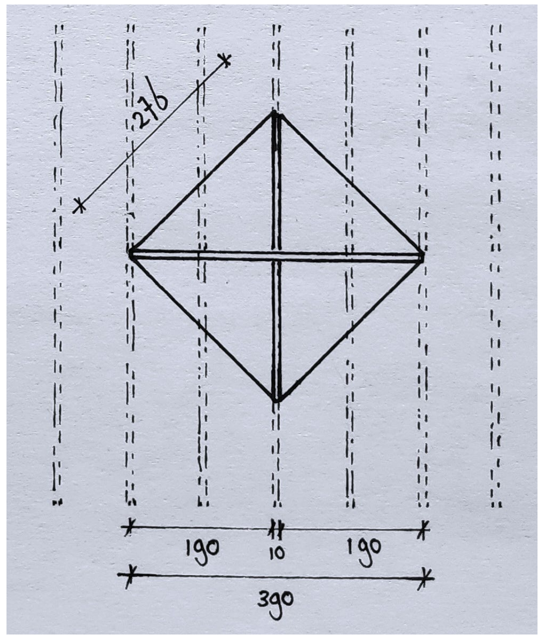
Size

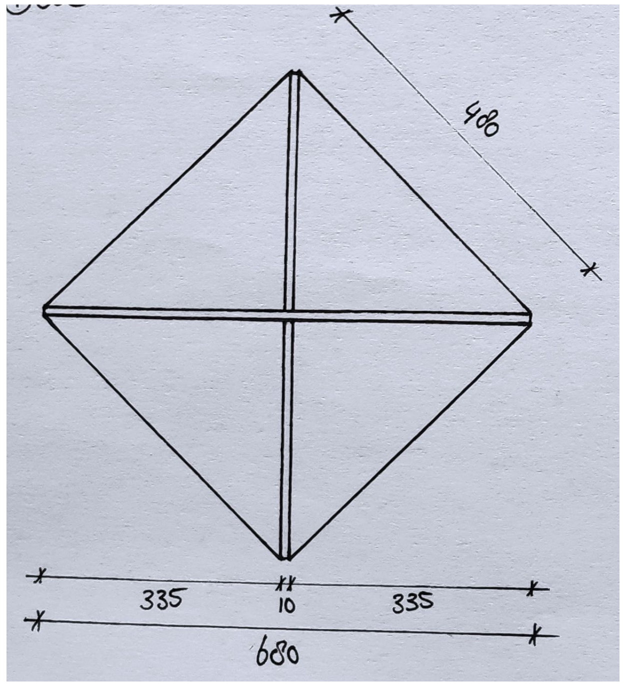
Regarding the size of the module, the main design guidelines of importance here are the manageability of the modules by children, while ensuring that there is enough space left for certain nesting boxes which require a minimum length, depth and height as explained in paragraph 4.2 and visualised in figure 112.

Furthermore, considering the structural grid the modules will be assembled on, initially a spacing of 100 mm between the bars were assumed. The potential module size which was the result of these conditions is shown in figure 110. However, this module is too small to fit the full height of each nesting box within one volume created by two joined modules, thus a size variation of the module in which this can be accomplished is shown in figure 111. However, this makes the module almost twice as large and depending on the utilised material, rather heavy as well.

Figure 110. Module size based on grid spacing and manageability (own illustration)

Figure 111. Module size based on fitting each bird nesting box (own illustration)





Further exploration of the size, some more size alternatives were investigated (see figure 113). A design with two module sizes was briefly contemplated, however this would duplicate the number of unique components, hence decreasing the level of standardisation, which is important for the modularity strategy, and would make a fitted configuration more complicated. Nonetheless, a different solution was established, being the approach of the size and shape of the BioPods not being restricted to the volumes of the pockets, but offering those forms more design flexibility. This brought the additional concomitant that the BioPods would stand out more in respect to the modules, making them an equal, distinctive part of the system.

Figure 112. Size requirements different nesting boxes (own illustration)

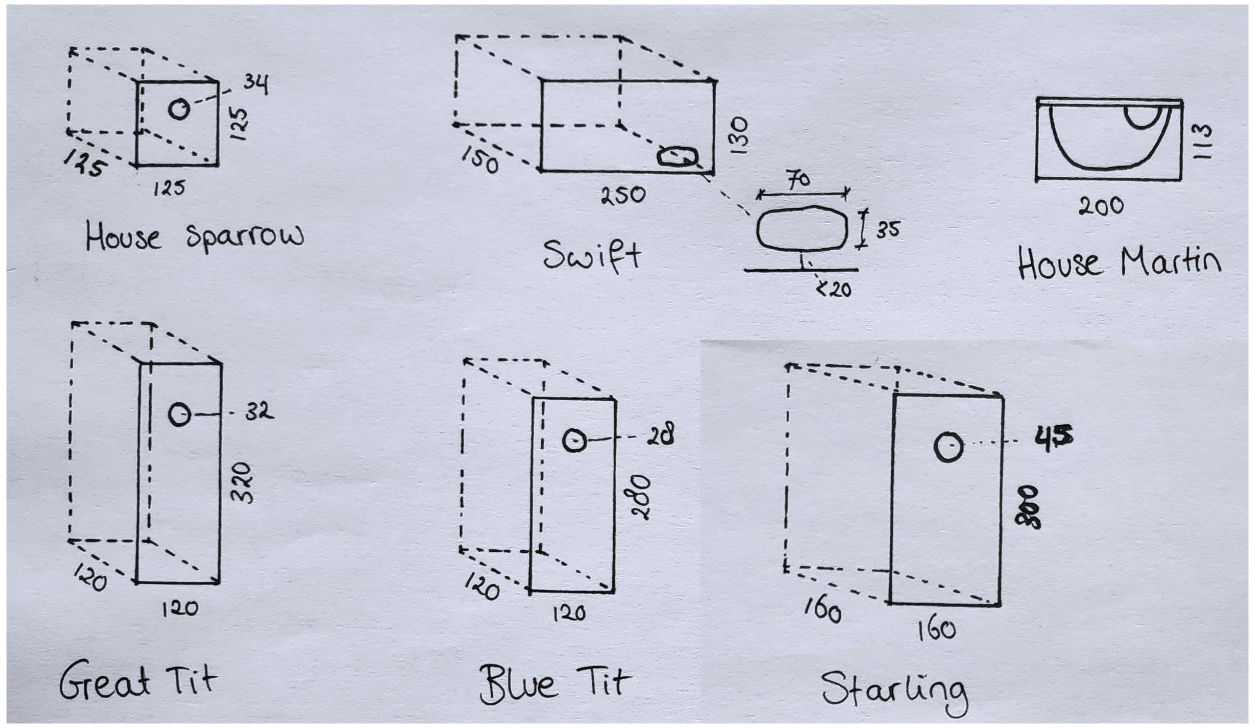
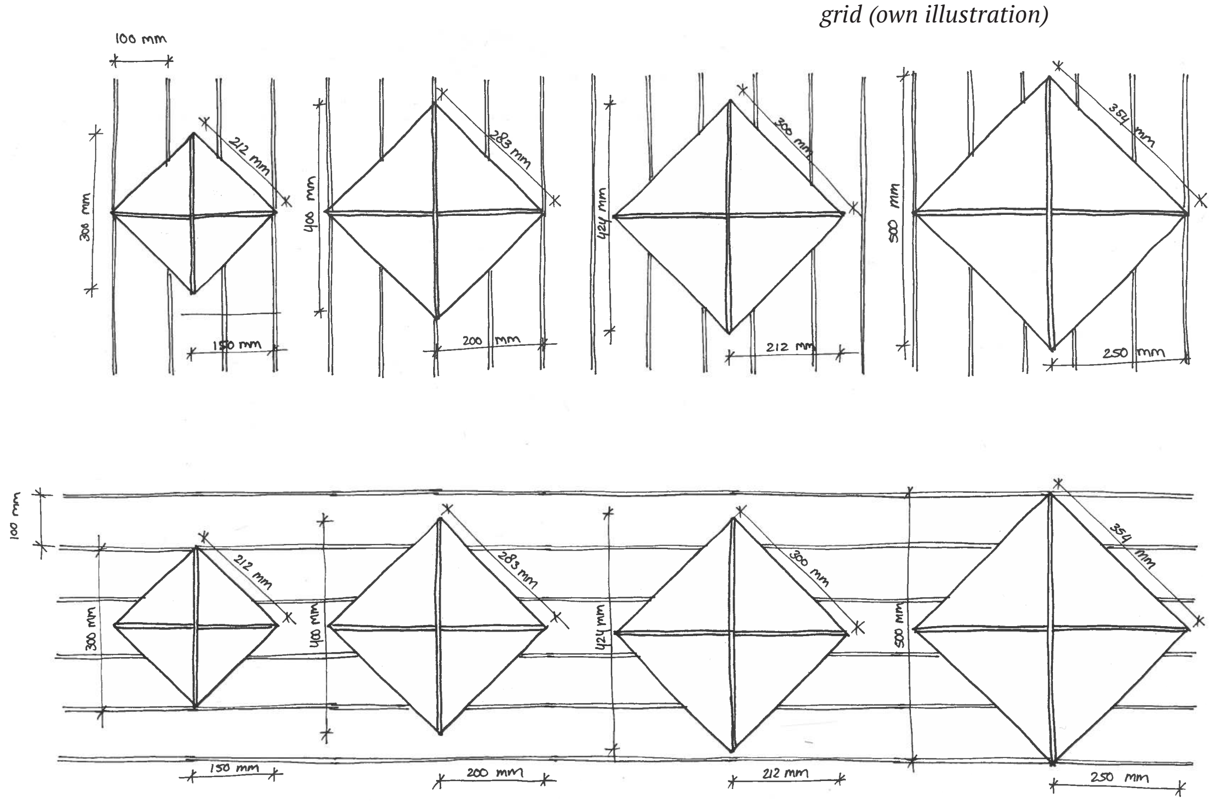


Figure 113. Size exploration of the module on a vertical and horizonal grid (own illustration)



7.2 The BioPods

Functions

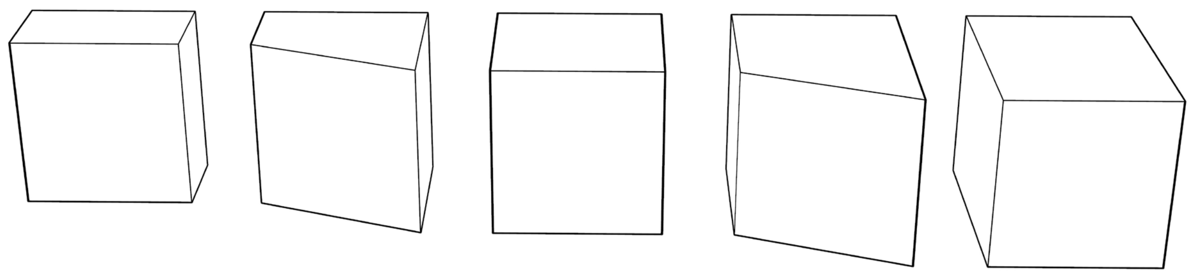
As explained before, the pod volumes generated by the configurations of the modules are essential to the pod designs. In general, there are six potential functions established to foster the local biodiversity in the system, of which five will be designed as BioPods, i.e., (1) nesting boxes for birds, (2) other bird facilities, such as nesting material storage places and feeding pods, (3) bat boxes, (4) planters in various sizes for a variety of vegetation types and (5) insect hotels, mainly designed for bees and butterflies.

Furthermore, the structural grid serves not just as support for the modules, but could support climbers as well, making it the sixth potential category of biodiversity implementation for the façade.

Shapes

As shown in figure 114, the volumes, created by all the different configurations of the BioPods, formed five basic boxes of different dimensions, primarily diverging in depth. These shapes were the starting point of design experimentations regarding the BioPods. Several drawings were made to explore potential designs, as presented in the following figures.

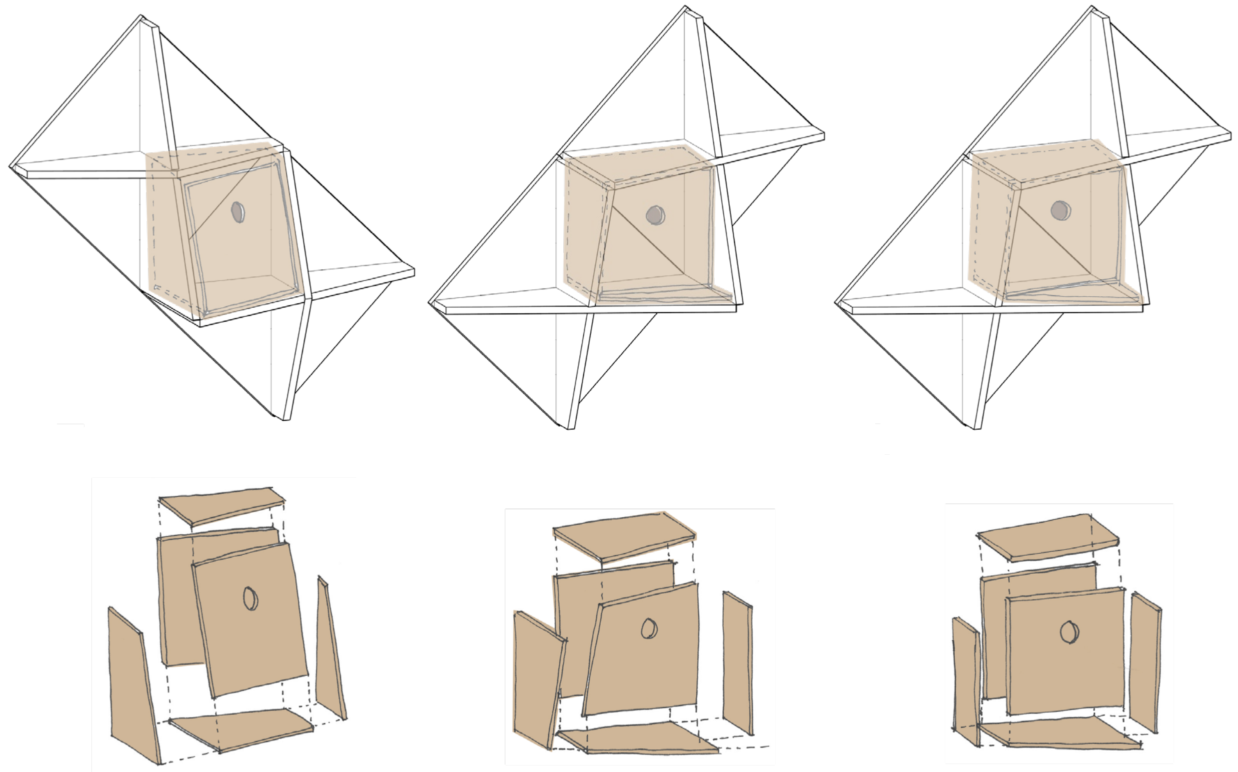
Figure 114. Basic BioPod volumes generated by the module configurations (own illustration)



The function of a nesting box was used to explore several design variations as shown in figure 115. The images on the left show the design of a nesting box, which fully follows the shape of the volume, generating different angles within the design. However, this would increase the complexity of the overall design and moreover its manufacturing and assembling tremendously. Consequently, this design is unfavourable considering the objective of a low-tech system, hence two alternatives were explored.

The design on the right is basically a box, merely consisting of straight angles on a base element that follows the diagonal line of the module, whereas the set of drawings in the middle is a combination of the two aforementioned designs. Considering the aim of a low-tech system and the fact that it could increase the pod's feasibility in different module configurations, the design on the right of figure XX was selected as a main design strategy for the design of the 'box shaped' BioPod functions, also including the insect hotels and planters.

Figure 115. Design exploration of BioPod shapes (own illustration)



Similar, the same experiment was conducted for planter boxes that were two modules wide, see figure 116, creating the possibility to add larger vegetation to the system as well and simultaneously, this generated a more interesting architectural language to the system, because of the greater variation in sizes. Also in this case, the conclusion was drawn up that the simplest design would fit the system best.

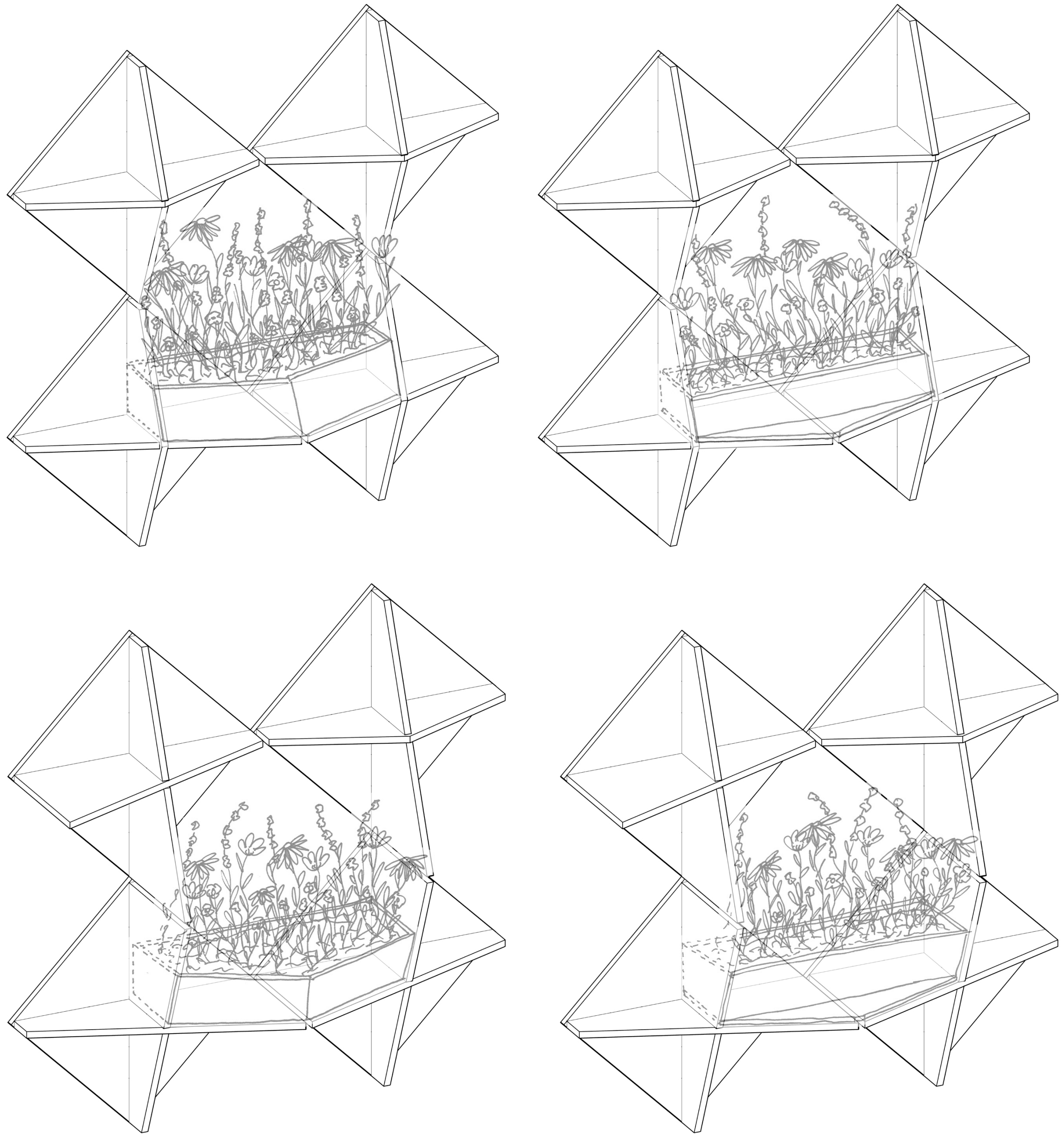
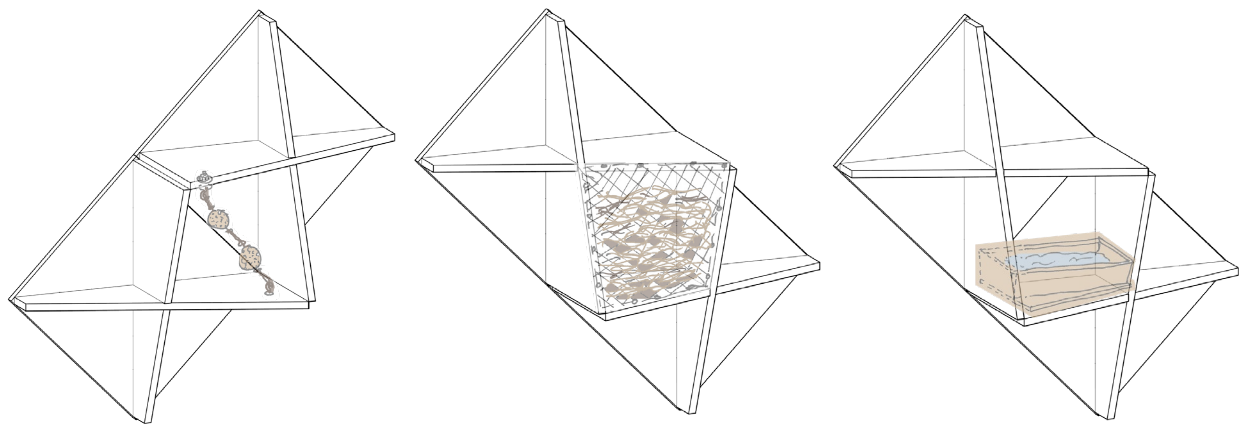


Figure 116. Design exploration of vegetation BioPods (own illustration)

Regarding the function of providing other bird facilities, three main designs were studied, as shown in figure 117. Firstly, providing food for birds as seed fat balls was qualified as a low-tech, Do-it-yourself function for the system. The end-users can make and replace them themselves with everyday objects and products, whereupon they can be fastened to the module with a rope. Secondly, storage places for nesting materials can be constructed by simply filling a pod volume with a variety of organic material and subsequently attaching a wired net in front of it. Thirdly, it would be an option to design small water baths for the system, however when doing so, the utilised material for this type of BioPod should be highly water resistant and

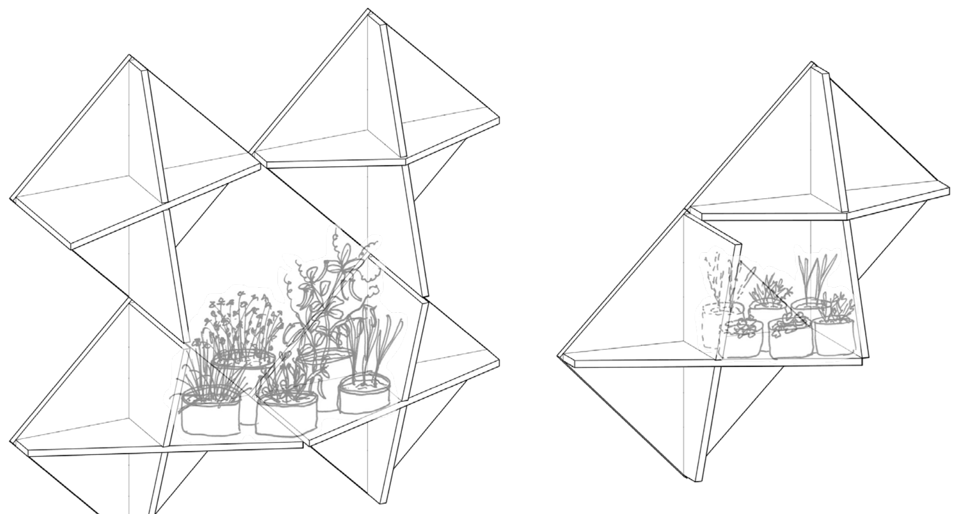
furthermore precautions must be taken to avoid the water level from flooding after substantial precipitation and thereby damaging other elements of the system.

Figure 117. Other bird facilities BioPod categories (own illustration)



However, as briefly mentioned in the previous paragraph, the size and shape of the BioPods are not restricted to the pocket volumes of the modules. Consecutively, more design freedom was generated for the BioPods. Next to the shapes developed to the measurements of the pod volumes that are described before, altering forms and designs were explored, as illustrated in figure 118 where small planters are made from old PET bottles. Not merely resulted this in a more diverse and low-tech appearance of the system, it also improved the possibility for the end-user to design and implement their own BioPod designs, constructed from ordinary available waste materials, contributing to the personalisation of and user-connection to the system.

Figure 118. Other bird facilities BioPod categories (own illustration)



7.3 The Connections

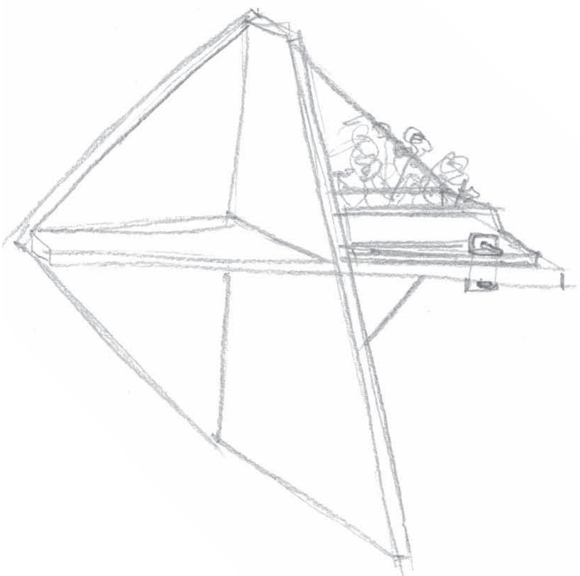
As the system contains of various components, there are several connections necessary to assembly the product. Three main connection positions were constituted and the design process of each is discussed below.

Internal connections

Firstly, there are the internal connections, being the ones between the planar components of the module and between the modules and the BioPods. Regarding the first mentioned, the principle of joinery is applied, which was already established in the conceptual design of the system. This type of connection requires no additional pieces, however the thickness of the material will highly affect this connection, as it will determine the width of the openings. Furthermore, this principle is an excellent approach for timber(like) materials, however its success regarding different materials is something to be tested in future research.

Regarding the latter connection, between the module and the BioPod, several design options were investigated, primarily being using nuts and bolts for the assembling, shown in the figures. For this connection, locating the connection in the front area of the module would make it easily accessible (see figure 119), which increases the DfD-value of the system. Alternatively, the bolted connection might also be replaced by a securing wedge or a clamp, however no physical experiments with these alternatives were conducted.

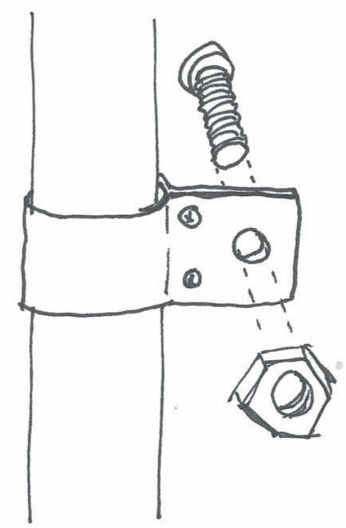
Figure 119. Potential connection between module and BioPod (own illustration)

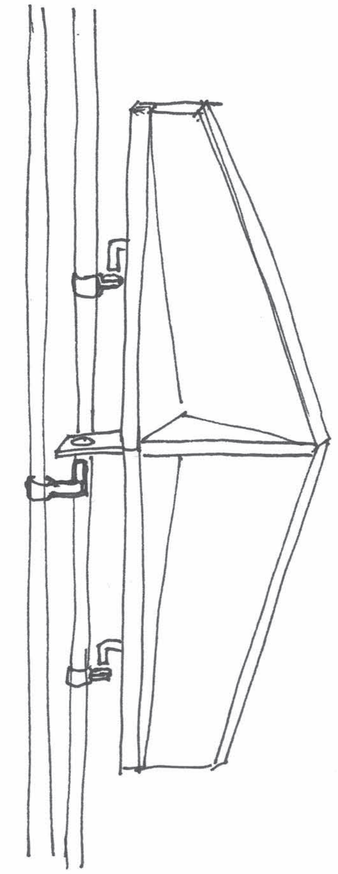


Module to structural grid

In the design concept is stated that the modules are attached to a structural grid for easily assembly and disassembly. After briefly considering a vertical bar structure, the horizontal orientation of the bars was beneficial for the system as it would reduce the necessary forces and simplify the method of connecting (see figures 120, 121, 122). However, a rectangular grid was chosen in order to function as climbing support for façade climbers as well. Nonetheless, hanging the modules on the horizontal bars was favoured over clamping them to the vertical pillars.

Figure 120 and 121. Potential module assembly on a vertical grid (own illustration)





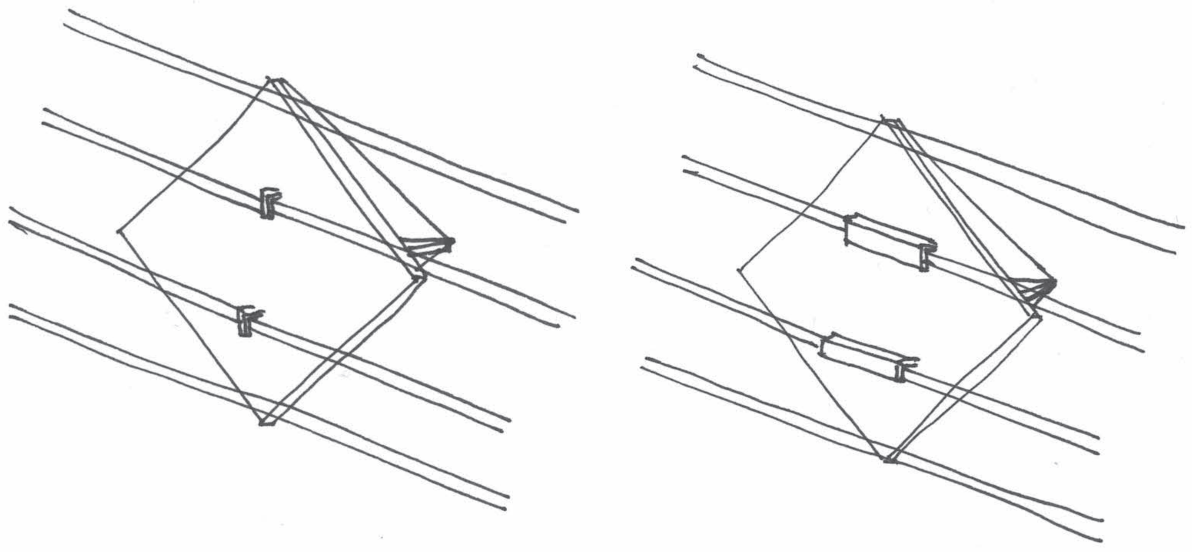


Figure 122. Potential module assembly on a horizontal grid (own illustration)

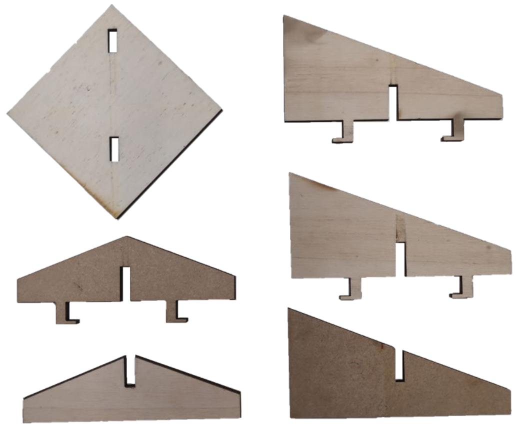
Designing these hooks as a part of the module components was researched, illustrated in figure 123 and 124, however, this resulted in more unique and complex shapes, less rotation flexibility and fragile corners and edges of the hooks. Subsequentially, obtaining the connection by using a separate component was explored. The first design from figure 125 consisted of a hook, connected to a clamping element that would embrace the planar module components and be fixed through bolts. However, the hook was still a weak point receiving a lot of forces and therefore this part was designed into the component (see figure 126). Additionally, the buckle in the shape was straightened out and the height and thickness of the connector were increased for increased strength, prolonging its durability (figure 127). To optimise this connector and prevent the modules from potentially falling off the grid due to impact, the opening width was reduced, illustrated in figure 128. This adjustment resulted in the modules being slightly locked in their place, as it would require a small amount of force to detach them from the grid.

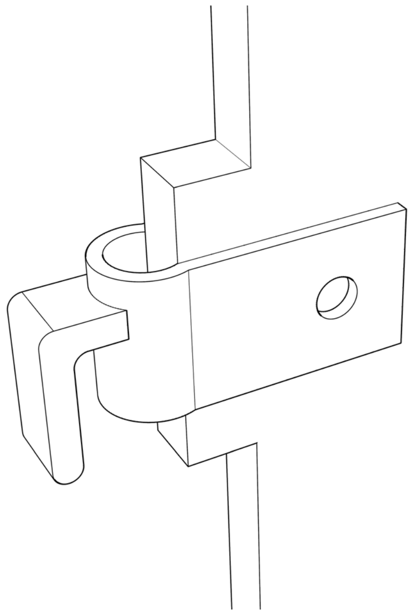
Figure 123. Module components in case of an integrated hook (own illustration)

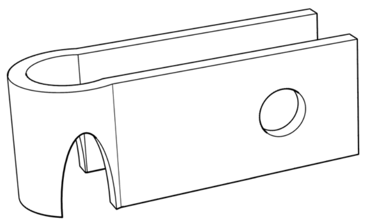
Figure 124. Assembly on grid with an integrated hook (own illustration)

Figure 125. Clamping hook connector (own illustration)

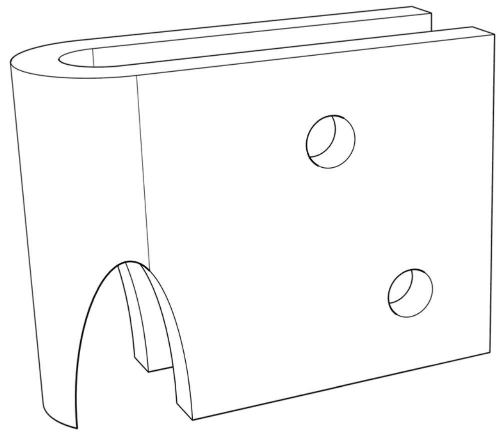
Figure 126. Connector with integrated hook (own illustration)

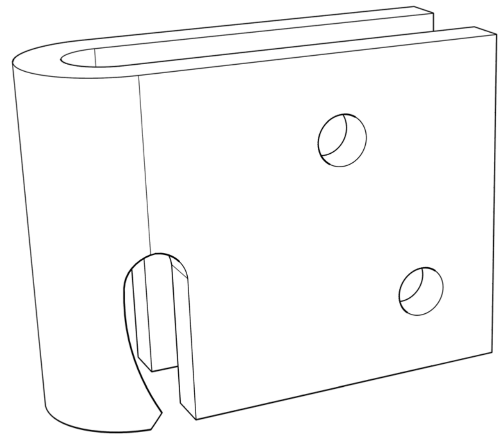






The U-shape of the clamp was developed since the connector would demand a certain flexibility considering the decision the depend the selected material on local availability, hence its thickness will also differ per design location. A half arc, generating the U-shape of the connector, provided a better solution for this design challenge than a rectangular shaped design.



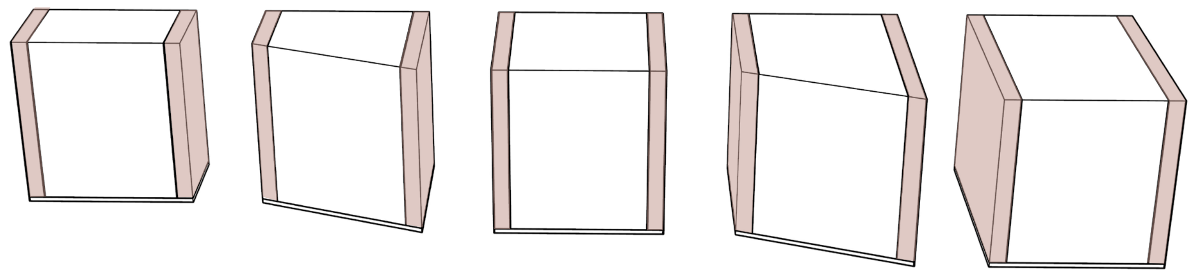


Lastly, as the location of this connection was right in front of the back component of the module, it could be blocked whenever a BioPod was added to the module. Consequently, if the designs of the BioPods are slightly smaller on each side (see figure 129), the bolts can be reached and replaced, without the necessity of disassembling the complete module.

Figure 127. Enlarged and reinforced connector (own illustration)

Figure 128. Connector with a reduced opening width (own illustration)

Figure 129. Non-usable spaces of BioPods (own illustration)



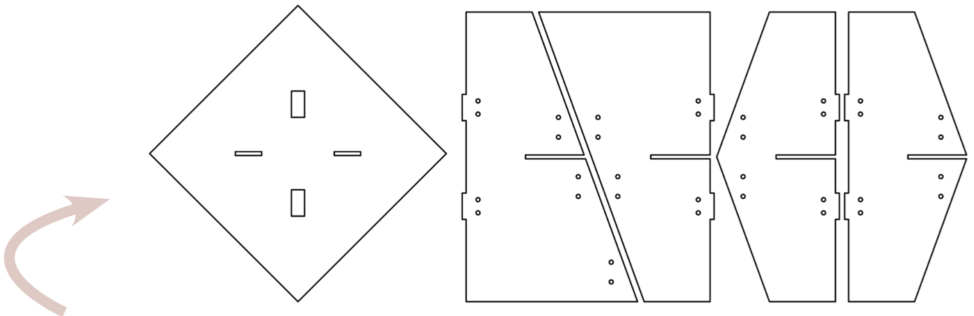
Structural grid to hosting façade

For the third main connection typology, not much research was conducted, as the decision to use a structural grid was made in an early stage of the design process and this would simplify the method of connecting significantly, compared to a strategy where each module would be attached to the hosting façade separately. Also, the scope of this thesis was limited to applying the design on brick facades and therefore the proven connection of using brick anchors was assumed to be a fitting solution. However, the circular value of this connection regarding its reusability and damage to the bricks was not investigated.

08

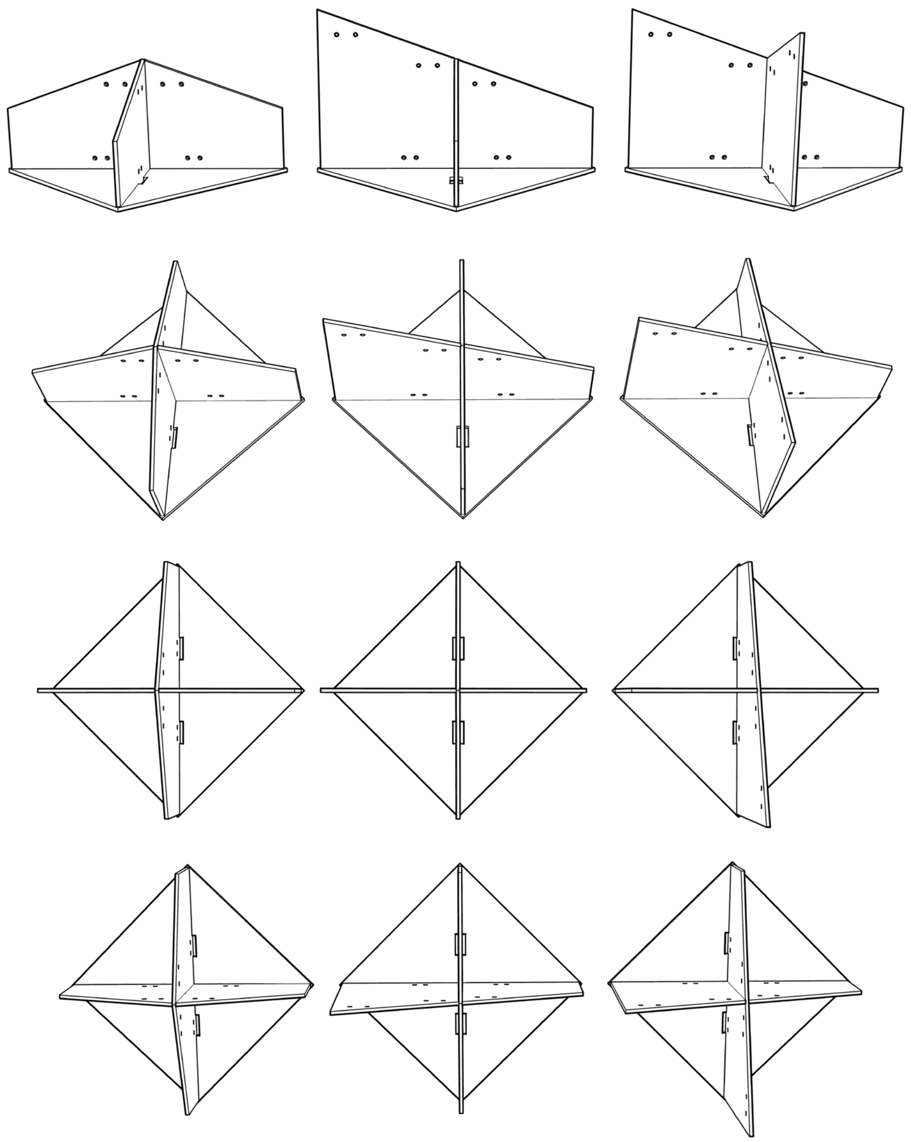
Final Design

8.1 The Modules

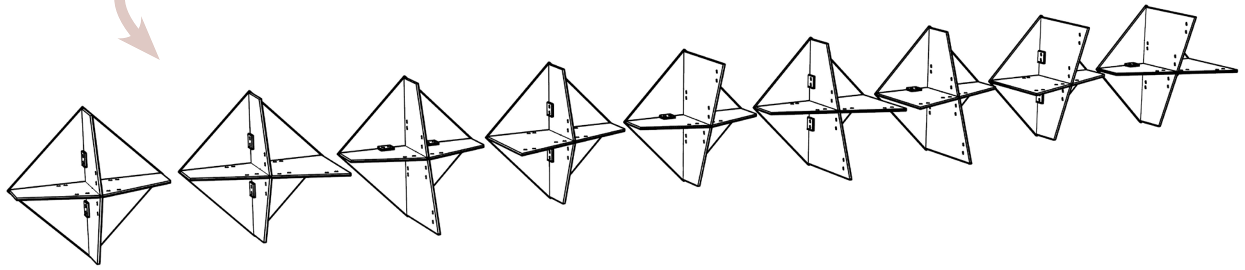


5 modular components...

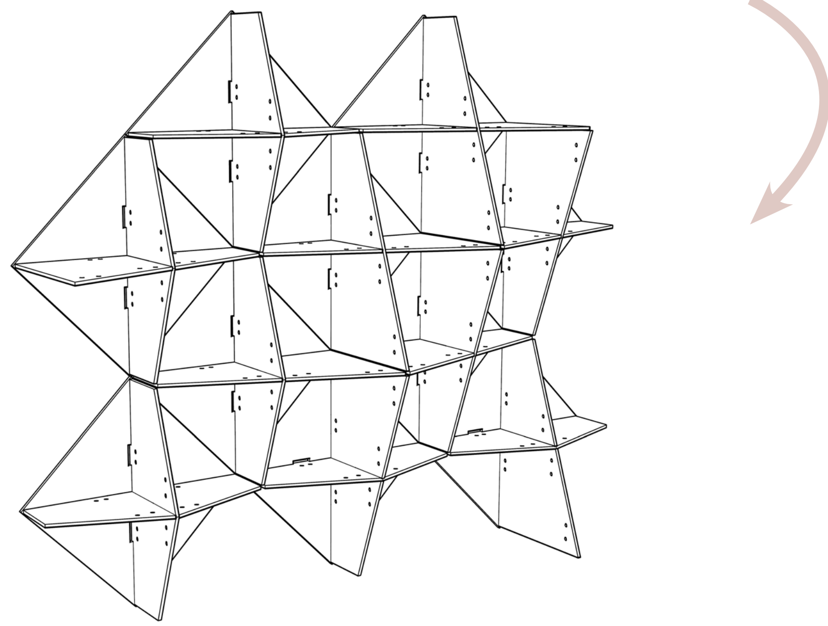
... to generate 3 modules...

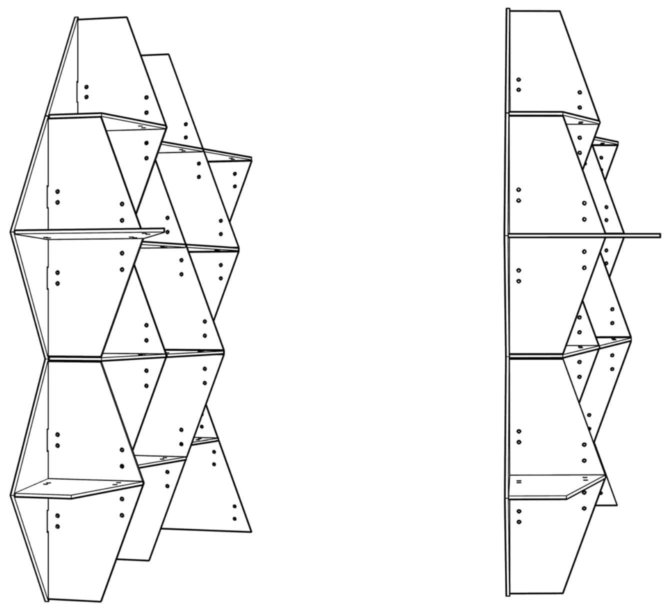


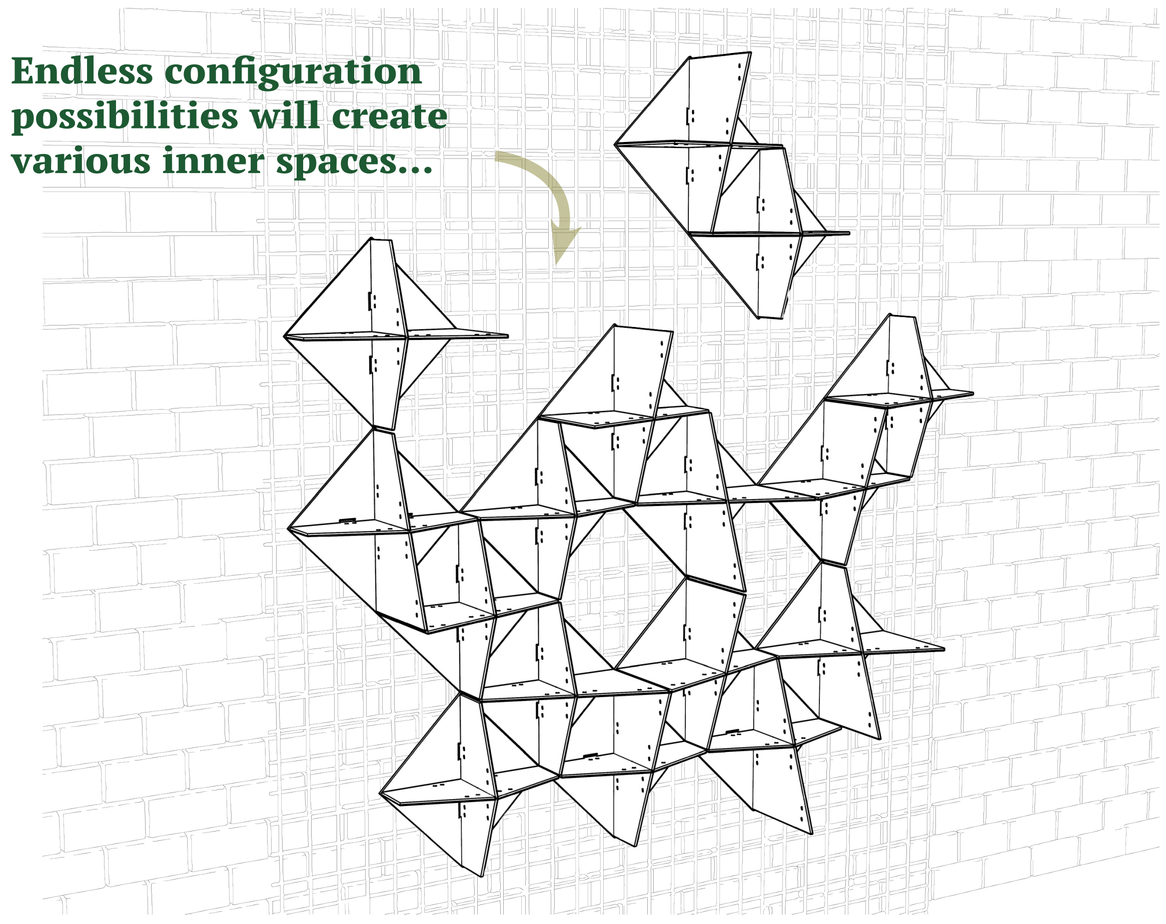
... enabling 9 orientations...

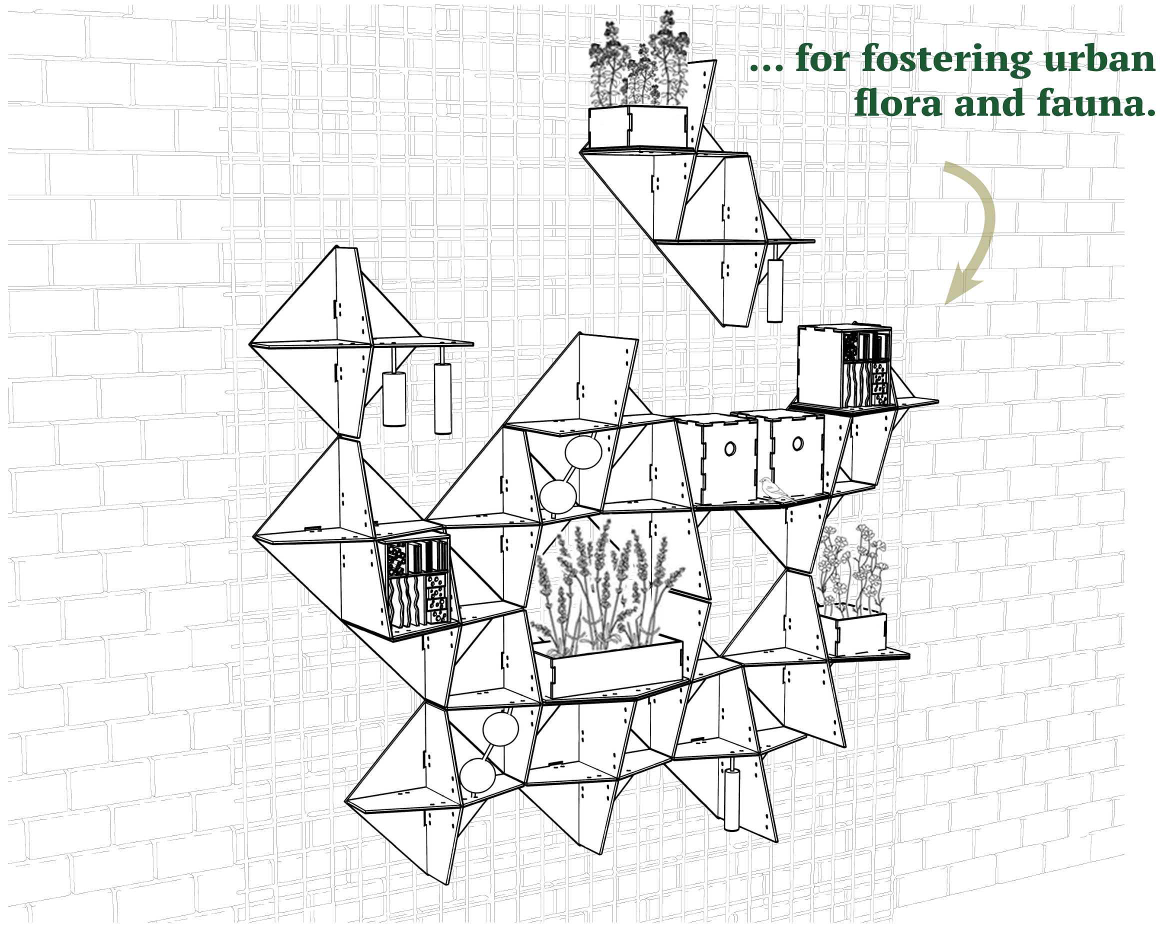


... creating an intriguing 3D language.



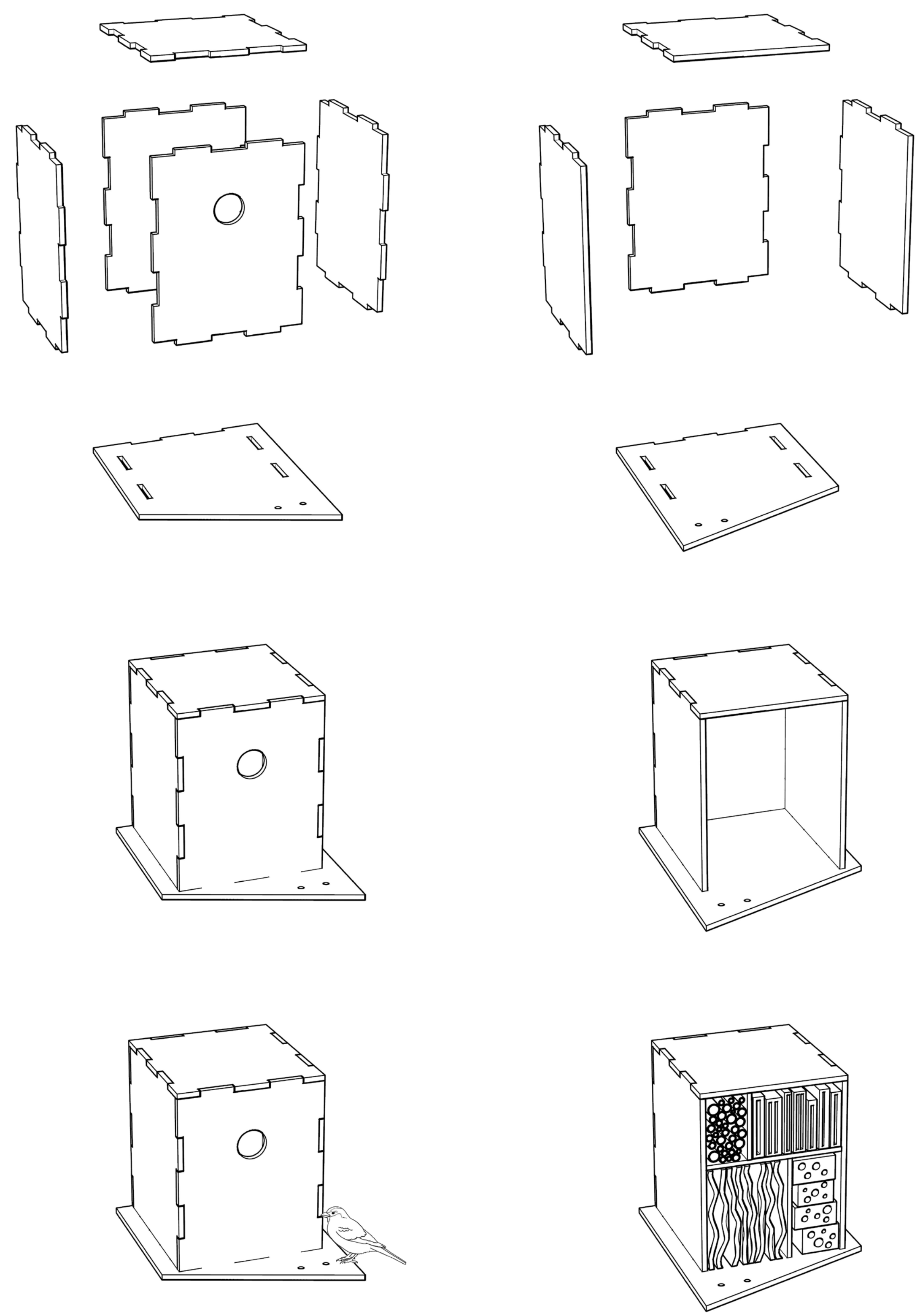




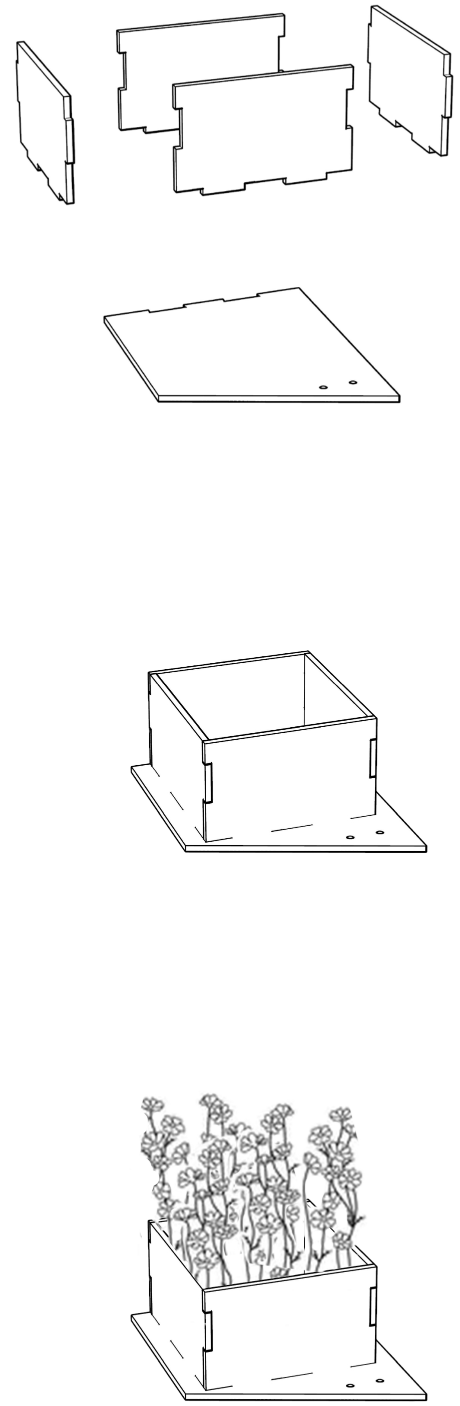


8.2 The BioPods

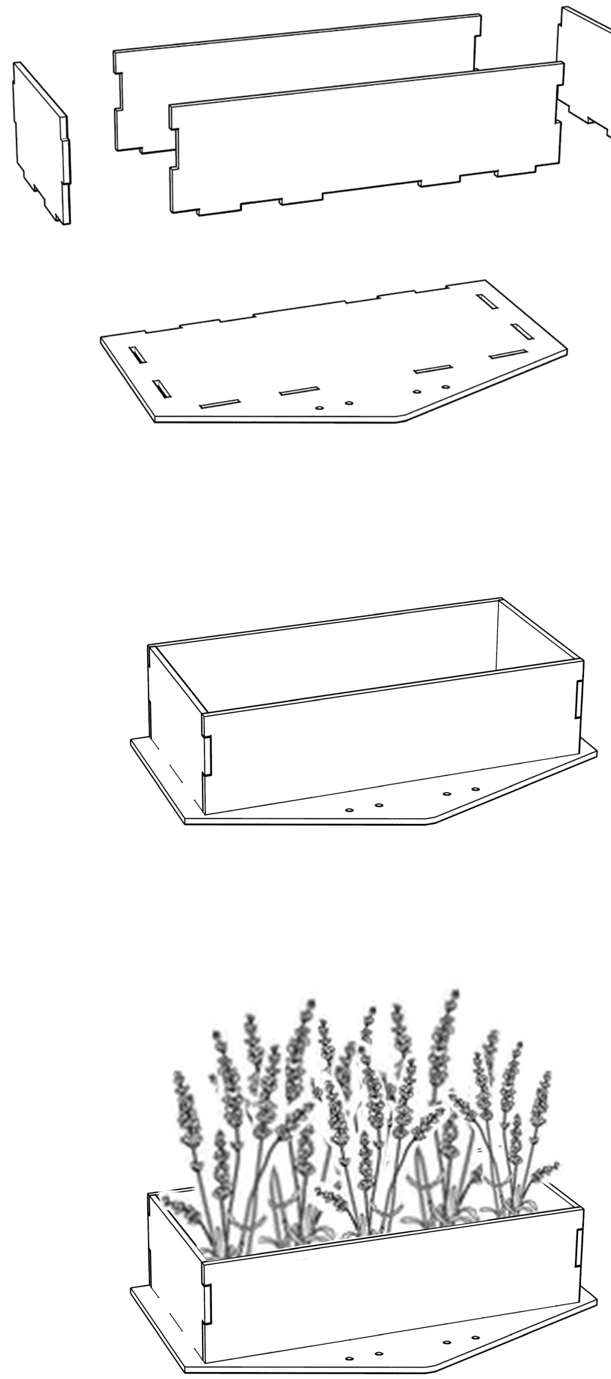
Nesting box | **Insect hotel**



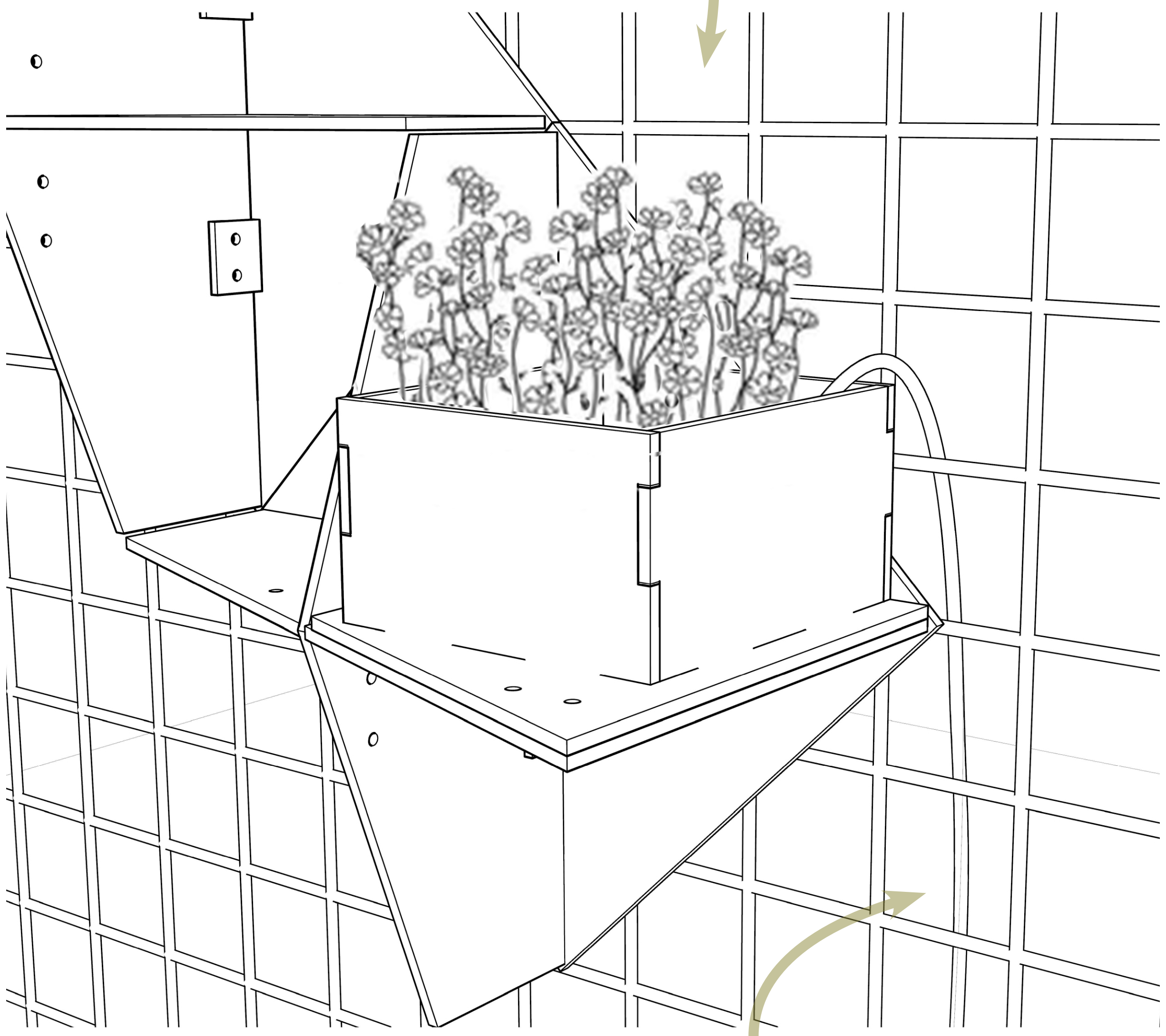
Small planter



Large planter



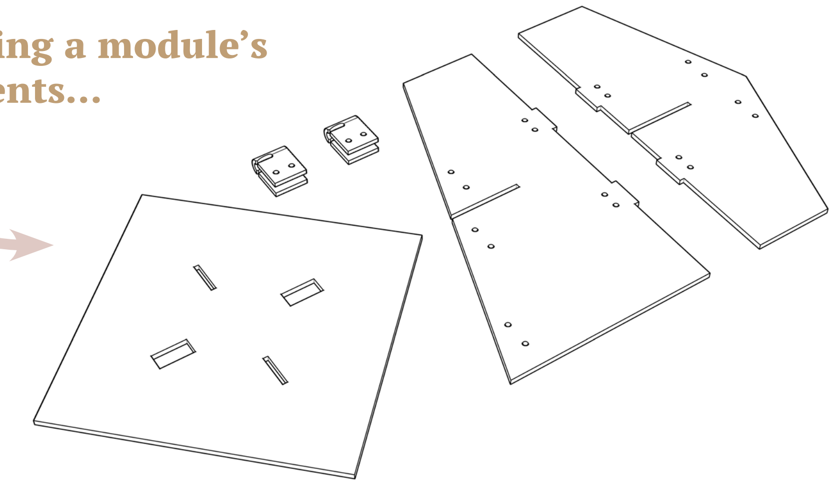
For irrigation demaning plants....



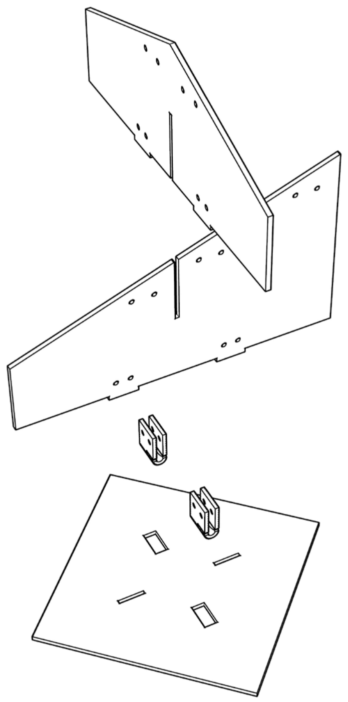
... the dripling system enters the planter from the back being attached to the structural grid.

8.3 The connections

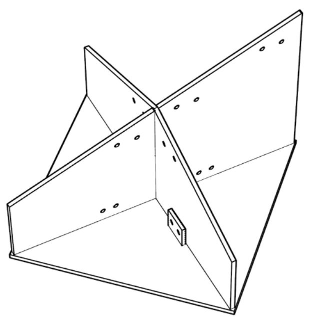
Assembling a module's components...



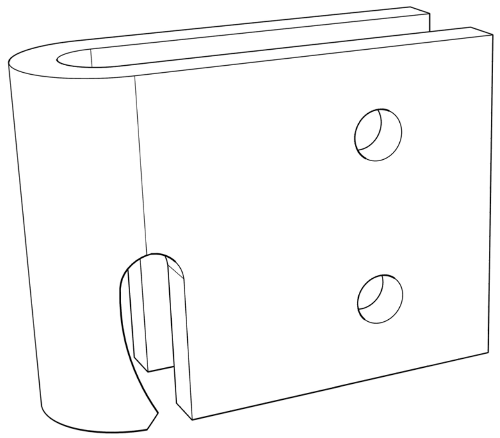
... by interlocking its components...



... and fixing the 3D printed connectors with bolts.

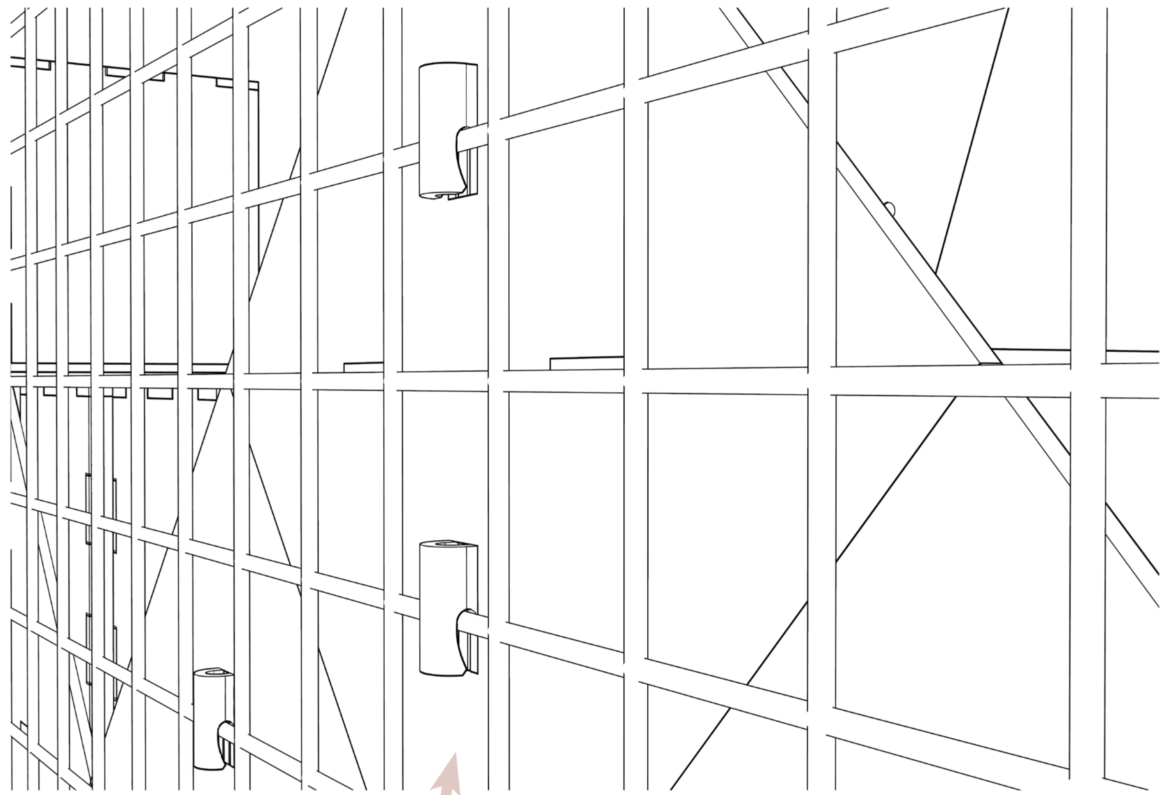


An U-shaped connector...

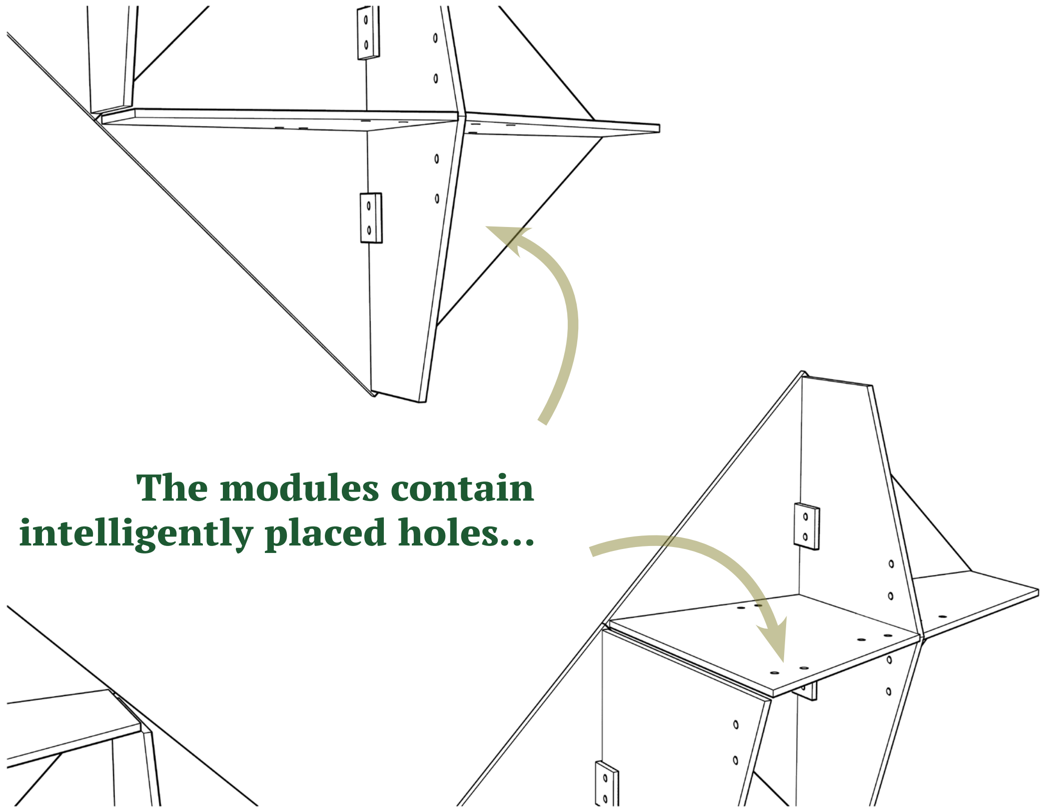


... to allow for multiple material thicknesses...

... with an integrated 'clamping' hook...

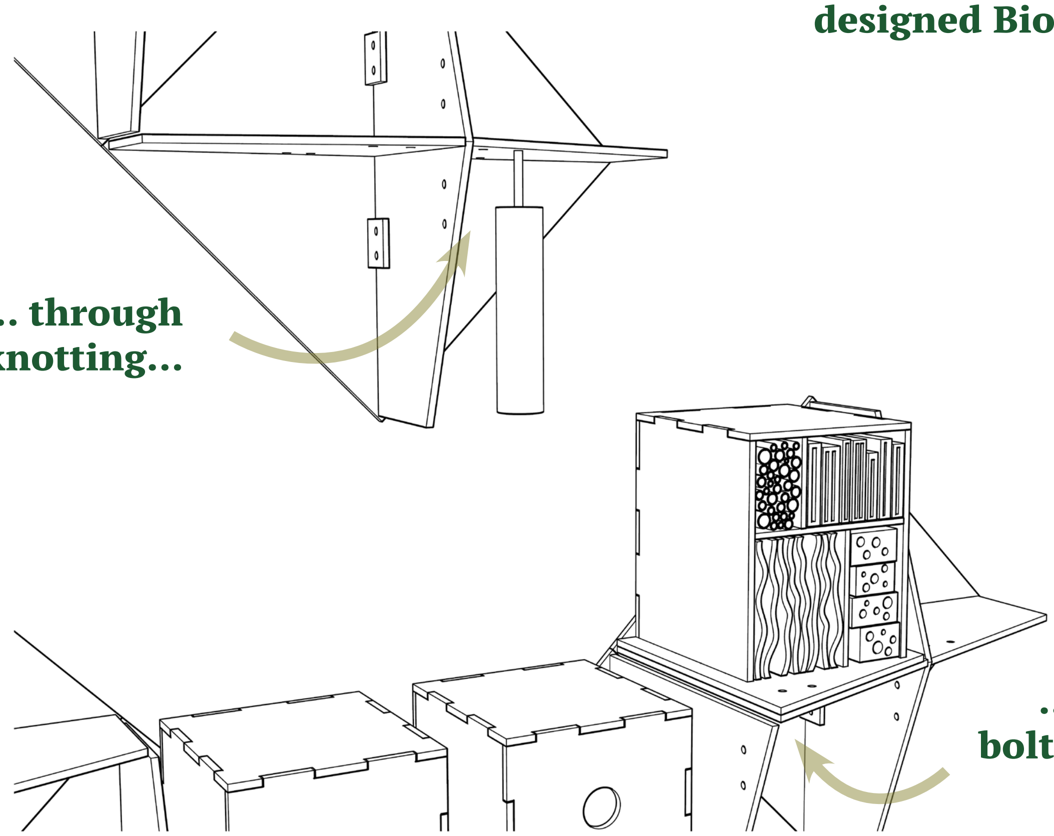


... locking the modules to the structural grid.



The modules contain intelligently placed holes...

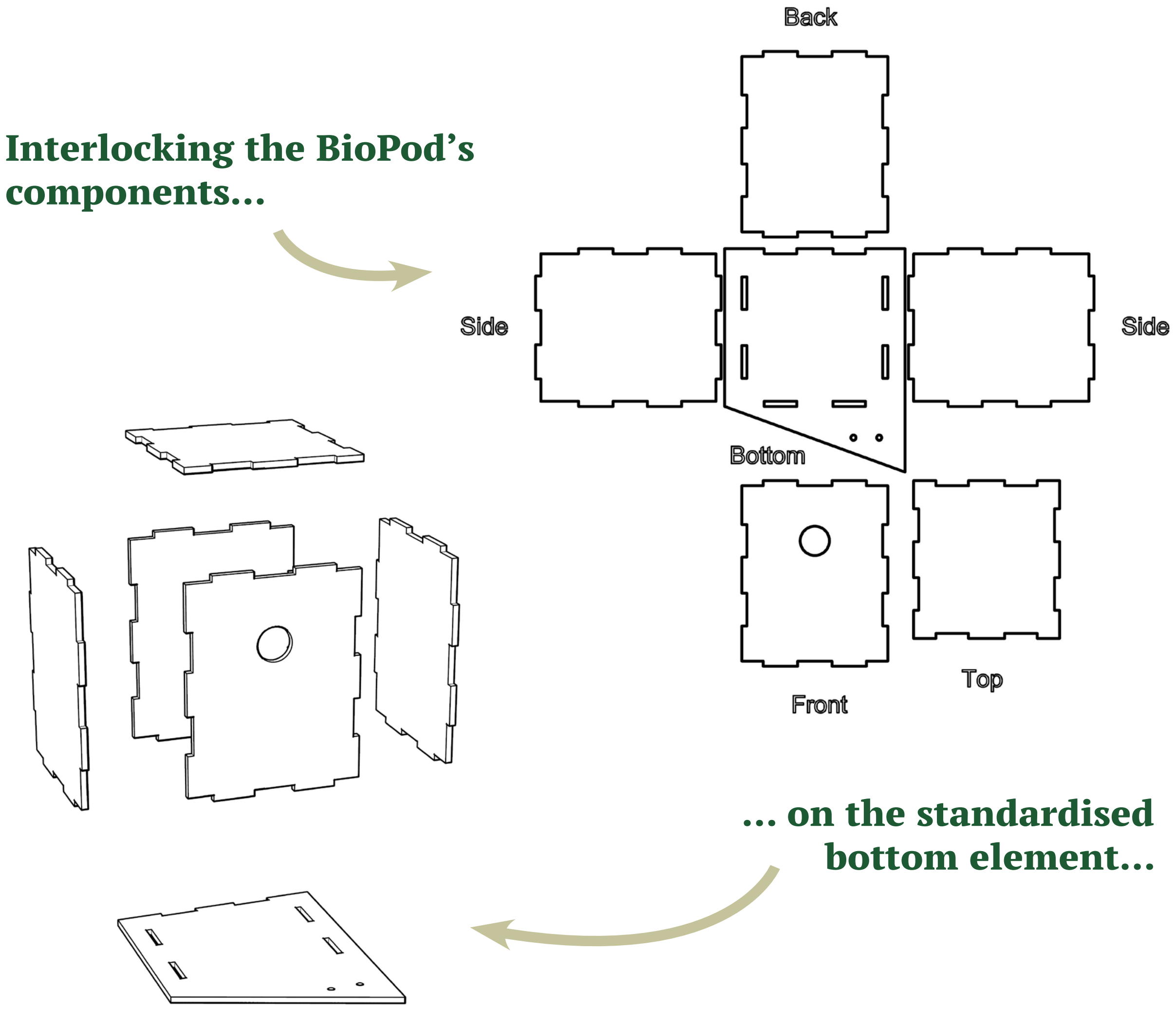
... being able to fix each designed BioPod...



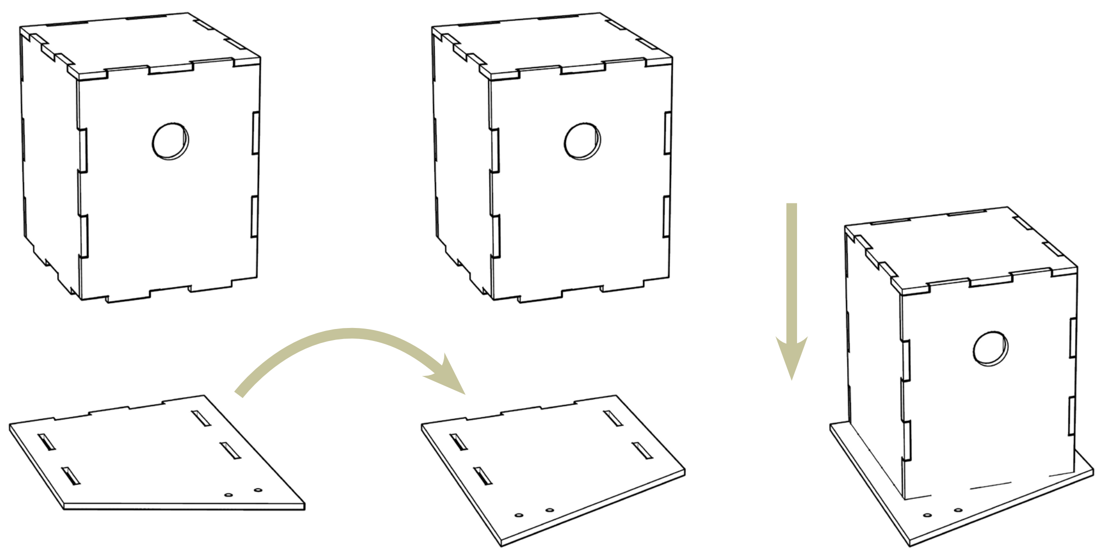
... through knotting...

... or bolting.

Interlocking the BioPod's components...



... on the standardised bottom element...



... that can be flipped to facilitate fixing to multiple module orienations.

8.4 The lifecycle of the system

In the figure presented hereafter, the circular lifecycle of the system is schematically illustrated. After selecting a (school) building for the implementation of the product an extensive site analysis is done to decide which flora and fauna species will be implemented in the design and a design configuration is proposed for the specific locations of the modules and BioPods. Based on this, suitable **reclaimed materials** are selected and harvested from the local area. These materials will then be processed into the needed components according to **low-tech manufacturing** methods that are proven to be successful for the chosen materials. During this production process, the school children, being the end-users, can be involved in two ways, either they go to the manufacturer for a workshop, or the manufacturer will visit the school, showing the children how the modules are made. However, the latter is only possible when the production technique allows for on-site constructing.

After the manufacturing of the desired components, the components will be transported to the location (if not already manufactured on-site) and the children can be involved in the assembly of the system under the guidance of one or more professionals. Furthermore, the school can build and add their own, personalised BioPods to the system, inducing the usage phase of the system. During this phase, a part of the **maintenance** can be done by the school itself, primarily restocking, watering or cleaning the BioPods. In the case of a component being damaged, the element can be disassembled from the system and returned to the product's company, thereby receiving a substitutional, reclaimed component in return. The damaged components are examined by the company and whenever possible, which is mainly dependant on the utilised material and its recycling-potential, repaired into a refurbished element. If reparation is not possible, the element will be recycled, constantly aspiring to achieve the highest possible circular value.

When the -involuntary- decision is made to remove the system from the location, all components will be disassembled from the facades, hardly leaving any traces at the site. After being returned to the company, they will assess each element whether they will be suitable for **direct reuse** on a different location or not. When this is not possible, the elements will be either repaired or recycled in the same way as described above, resulting in closing the loop of the system.

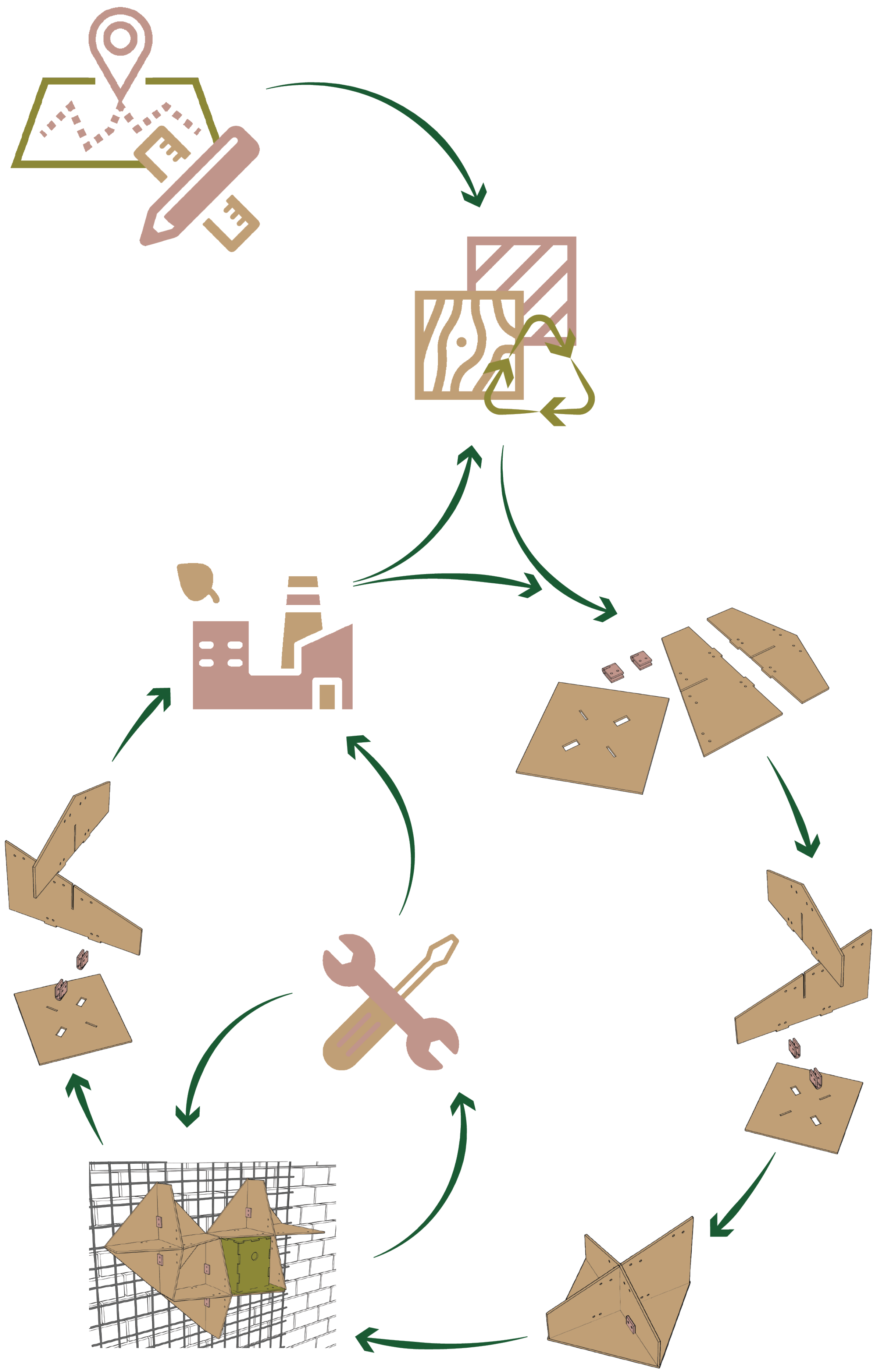


Figure 130. The system's lifecycle (own illustration)

09

Design case study

9.1 Potential school buildings for the implementation of the product

As mentioned in the Introduction Chapter, this thesis is focused on (primary) school buildings for the execution of the project as the potential of the educational aspects of the design could add a significant value to the product. Additionally, brick façades are appointed as the façade material to apply the system on.

For the second criterion, the school building's location must fulfil certain requirements. Since the thesis' objective refers to an urban area for this project, the selected school building must be located in such an area. Schools located at the edge of cities and near open, green landscapes are eliminated from the selection process, because the assumptions are made that the biodiversity richness is already higher at those places and these locations are less attractive to urban species and more to species that thrive better in green landscapes. However, school buildings which are located close to parks within a city are considered, because these schools could then function as a bridge to attract urban species from these green areas further into the cities where less vegetation is present.

The last criterion relates to the façades of the potential buildings. Namely, it is important for the diversity of potential biodiversity pods that the system is applicable to façades with different orientations. Thus, a school building with potential areas on the façades in multiple orientations is preferred over a school which has just one suitable façade and consequently, has just one façade orientation to work with.

As of practical reasons, the city of Delft is chosen as the search area for potential schools for this thesis. Via the website Scholen op de kaart (Scholen op de kaart, n.d.) the primary schools in Delft are localized and this map is shown in figure 131 on the right. With this map, a first selection of potential schools was made and then followed by short site visits to these locations to take some pictures and to get a first impression of the potential of the schools for the façade system.

With all the mentioned criteria in mind, a day of site visits to several primary schools in Delft has been held from where four schools made it to the final selection: Max Havelaar school in the city centre, CBS Gabriel school in the neighbourhood Hof van Delft and two locations of the school CBS Het Mozaïek, one in Hof van Delft and the other in Voordijkshoorn. These potential schools have been analysed on the following aspects: building height, building / façade orientation, potential areas for the façade system, direct environment in terms of present trees, green and blue areas and lastly, the option of extracting accurate real-life data of present flora and fauna species in the school areas was provided by the National Data bank Flora and Fauna (NDFF). A summary of the analysis of the four school buildings is presented on the next pages, whereas the full analysis can be found in Appendix A.

Figure 131. Overview of the primary schools in the city of Delft (Scholen op de kaart, n.d.)

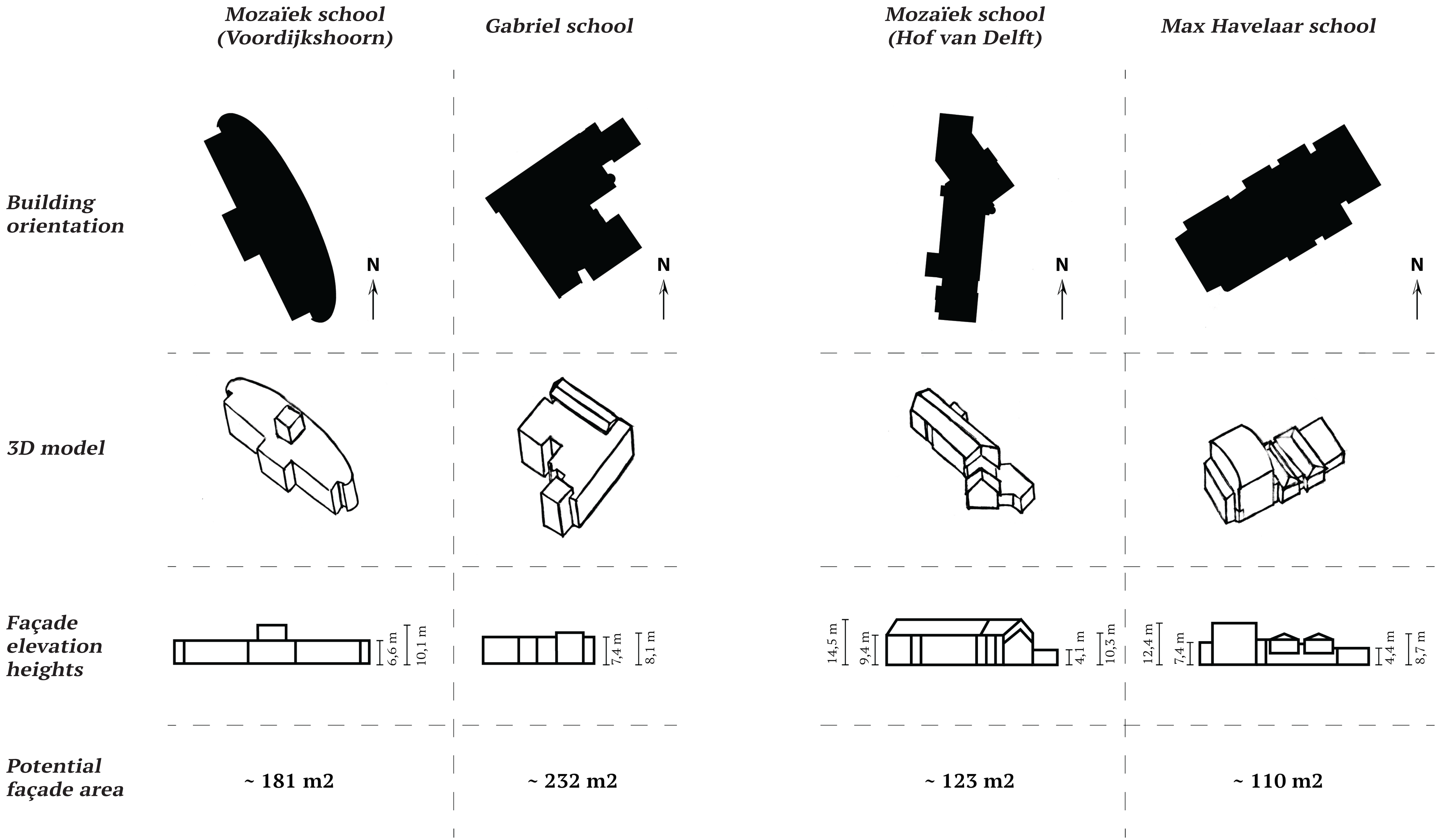


Figure 132. Summary of the school analyses (own illustration)

9.2 The Matrix: case study selection

As the requirements of each species are made clear in the Biodiversity Section, it is possible to match them to the four potential schools for the implementation of the façade system. This is handled as follows: the direct environment of each school is investigated and assessed for the location-based requirements of each species. Additionally, the requirements are weight based on their importance for that species and finally the requirements are all rated for each location and a point total is given per species per location to assess whether the species has potential to thrive in that location or not. The results of this assesment is shown below and an extensive overview per requirement is presented in figure 137. The full analysis can be found in Appendix B.

Table 10. Results overview biodiversity assessment per school (own illustration)

	House Sparrow	Bush breeders	Starling	Great Tit & Blue Tit	Swift	House Martin	Common Dwarf Bat	Bees & Butterflies	DIY Access
Max Havelaar school *City Centre*	17,75	0,5	10,75	9	11	14,5	12,75	7,5	1,5
CBS Het Mozaïek *Hof van Delft*	30	2	13,5	12,25	13,25	18,75	16,25	9	1,5
CBS Het Mozaïek *Voordijkshoorn*	26,5	3,5	12	10,5	11,5	14,25	9,5	7,75	3,75
Gabriël school *Hof van Delft*	30,75	2	14,25	12,25	16,25	19,25	16,25	7	3,75
Maximum possible score	46,25	10	17,5	21,25	20	22,5	22,5	12,5	3,75

Figure 133. Max Havelaar school (own image)

Figure 134. Mozaïek school in the neighbourhood Hof can Delft (own image)

Figure 135. Mozaïek school in the neighbourhood Voordijkshoorn (own image)

Figure 136. Gabriel school (own image)

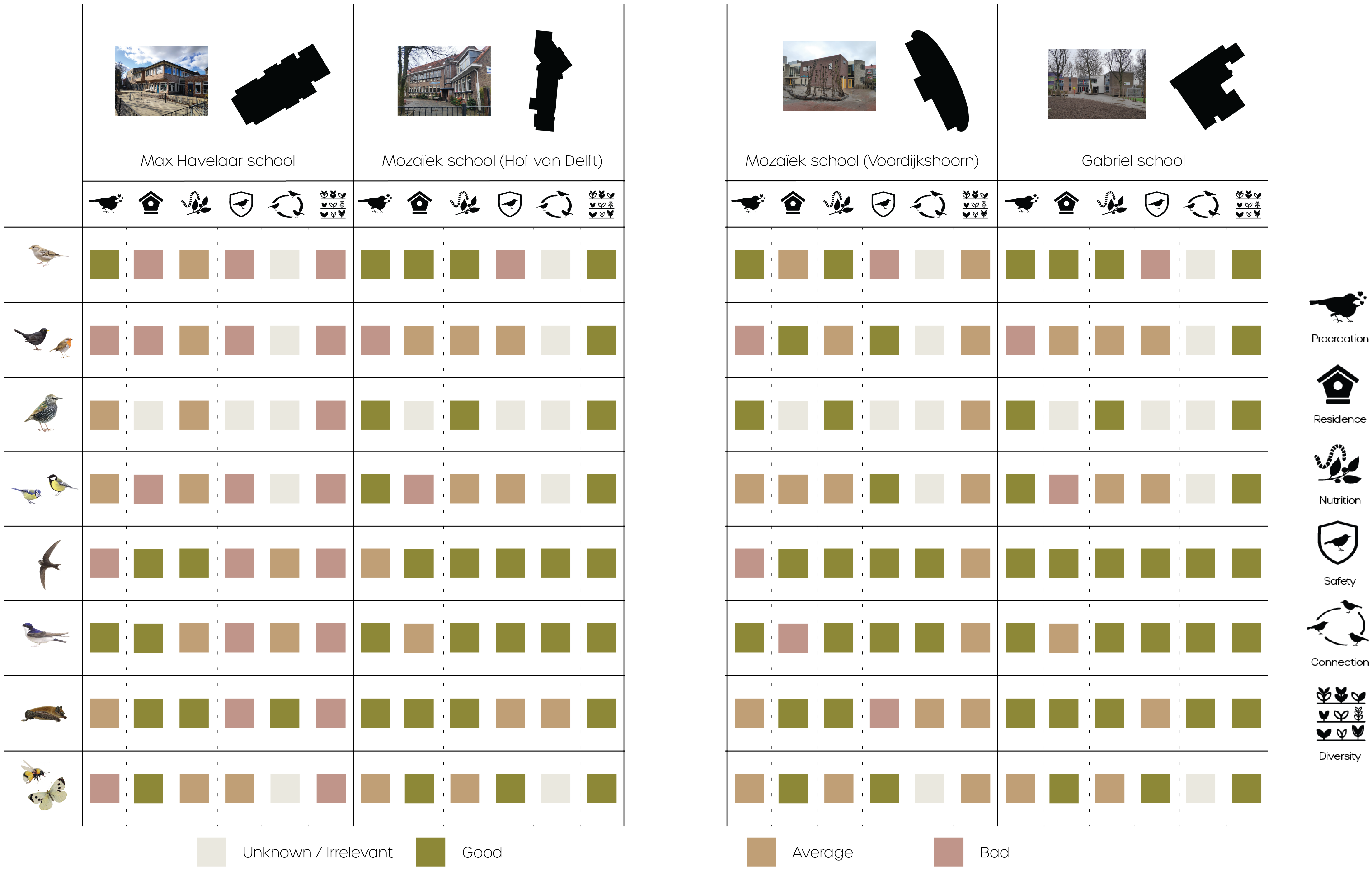


Figure 137. Overview of the assessment per school per species' requirements (own illustration)

9.3 Design implementation on the Gabriel school

The Biodiversity Map of the Gabriel school

Illustrated below in figure 138 is a 2D display of the Gabriel school facades given which are adjacent to the school's playground along with the orientation of each façade. A proposal for the design configuration is made for those facades that are made from bricks. The brick part of the North-west façade is left out from the design, as it won't catch much direct daylight since the open space in front is quite small which is made clear in the top view drawing of the school (see figure 139). Furthermore, the material which is behind the plaster of the two grey facades is not investigated, so potentially the South-east façade could be a valuable addition to the design configuration, assuming there are bricks behind the plaster. In the figure, the various biodiversity functions are illustrated with different colours, the gradient light-green rectangular area representing the implementation of climbers.

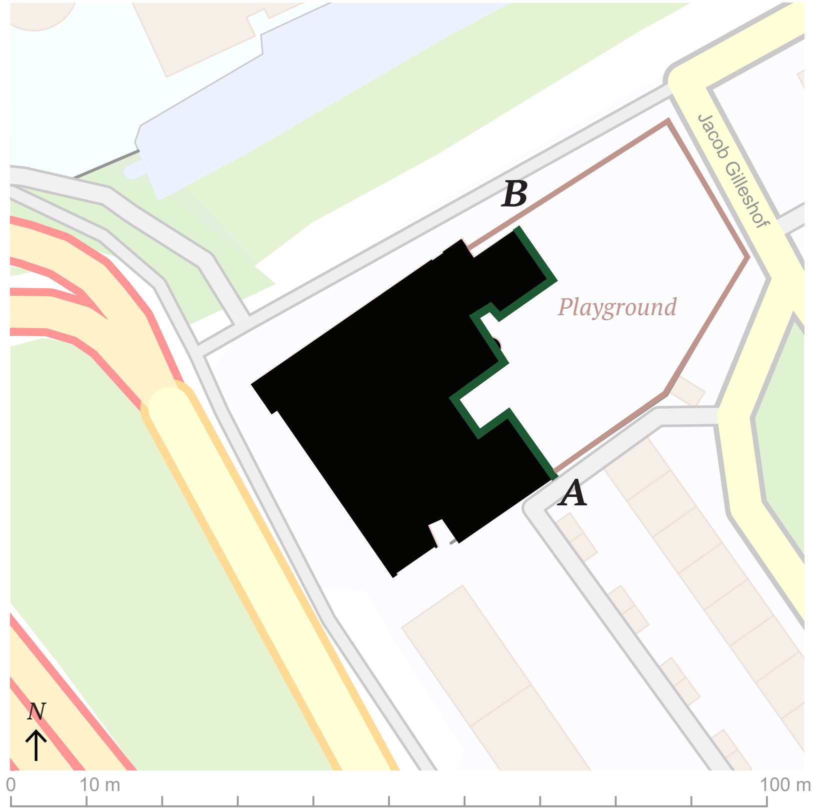


Figure 139. Top view of the Gabriel school (own illustration)

Figure 138. 2D display of the biodiversity mapping on the Gabriel school (own illustration)


Gabriëlschool

10

Discussion & Conclusions

10.1 Discussion

One could discuss the addition of a façade system as proposed in this research as a contribution to a sustainable environment as it ‘just’ serves as an additional layer to enhance biodiversity. Potential qualities of the system to improve the physical condition of (school) buildings in need of renovation was not a part of the proposed design. Exploration of a system that could function as a new, improved façade cladding element while preserving the current nature-inclusiveness would be an approach to improve the sustainable value of the product, significantly contributing to the urge of renovating (school) buildings and complying with the sustainability goals for 2050. However, the implementation of green elements already contributes to improving the local environment, even if the design is not optimised accordingly. Moreover, the educational purposes regarding children learning about circularity principles would be terminated when following the concept of manufacturing a cladding system for renovating a building, assuming this would make increase the complexity of the system and the low technicality of the product will be lost.

As it is not favourable to remove a biodiversity enhancing construction from a site where the presence of the hosting species became (partly) reliant on the availability of the designed façade system, one could question the ability of the product being designed for disassembly to this extend. It is likely that the product in practice is not often dis- and reassembled. However, not merely when the hosting building is demolished or when a singular module is damaged or broken and maintenance is necessary, the DfD-approach is beneficial, but also in regard to the educational purpose of teaching school children something about sustainable, circular design techniques.

The implemented strategy of selecting the product’s primary material according to local availability, could ultimately imply that the design of the system should be slightly altered, based on the utilised secondary material. Currently, the design and assembling principle is mainly established through design experimentation with wooden elements, however alternative materials will have diverging properties. At this stage, the assumption is done that this assembling method is also applicable for several other materials, but further research must designate potential necessary adjustments in design, assembly and fixing principles. Consequently, these adaptations would decrease the standardization of the system. A simple example of such amendments is the varying thicknesses of different materials or even within a material itself. Despite the 3D printed fixing connection which has certain flexibility in terms of material thicknesses, the assembly process of the façade module itself is based on the elements interlocking, meaning that the openings should be adjusted according to the material thickness.

10.2 Conclusions

Research conclusions

The presented research of this thesis aimed to explore how a low-tech, three-dimensional, circular façade cladding system could be manufactured from reclaimed materials while considering the local biodiversity which has to be fostered by the system. To eventually answer the main research question related to this objective, the several sub questions were compiled and answered with the information from the research conducted in the Circularity and Biodiversity Sections.

Resulting from the literature research, most of the three-dimensional manufacturing techniques are not appointed to be low-tech, especially if children are aimed to be involved during the manufacturing or construction process. Consequently, a different approach was chosen, meaning that the design would eventually be constructed from planar, two-dimensional elements assembled in such a manner that a three-dimensional module would emerge. This concept increases the potential of involving children, increasing their awareness and knowledge of circular and sustainable design strategies.

Regarding the applied circular approaches of modularity and Design for Disassembly, it became clear that they primarily affected the construction and method of connecting of the design, compared to conventional strategies. The design phase of this project was therefore influenced by these circular approaches during all stages of the process.

Another factor that highly influences the design process is the use of reclaimed materials instead of traditional, new resources. One of the fundamental considerations is the availability of reclaimed materials that will most certainly differ according to a particular location or a specific timeframe. This resulted in the decision to not select one prime material for the design of the system, but incorporate a certain flexibility in the design, making it suitable for several potential materials.

Regarding the implementation of biodiversity in the system, an important conclusion drawn from the research is that each species has specific requirements which all need to be fulfilled if that species is to be successfully engaged to the system. Selecting the most appropriate nature-inclusive façade systems from the ones distinguished, came down to two typologies: the indirect green wall system and the indirect living wall system containing modular planter pockets. These typologies are the best fit for designing a modular system and are therefore considered during the design phase of this project.

Design conclusions

Alongside the research phase of this thesis, it contained a large design part, aiming to design a system that could implement local biodiversity in various ways, fostering different flora and fauna species in urban environments. As well as with the research question, here the outcomes of the design sub questions also lead to the answer to the main design question. The design process was however strongly affected by the outcomes of the research phase, resulting in several design guidelines.

Resulting from this, the following design concept was developed: a circular façade system that consists of modular modules, made from two-dimensional elements, which are attached to a secondary grid structure fixed on the façade. These modules are filled with a variety of local biodiversity enhancing infills, the so-called BioPods.

After some experimentation with geometric origami as an inspirational source, the design ended up consisting of three different modules, that could be generated by just five different planar components, achieving a high level of standardization. These three modules could be rotated, creating a total of nine different module orientations. Placing these modules against each other enables a large variety of different 'pockets' and moreover generates an intriguing architectural design language, which could be tailored to the chosen location, combined successfully achieving the modularity concept.

Furthermore, the DfD strategy encompasses five different connections, all dry and reversible, being (1) the interlocking planar components of the module, (2) the bolted connection between the modules and the BioPods, preventing the latter from falling, (3) the connection between the modules and the 3D printed connectors, also bolted, (4) the hanging principle of the connector onto the structural grid, created by the hook integrated in the connector and finally (5) the structural grid which is attached to the hosting façade by brick anchors. Additionally, the use of secondary finishes is completely avoided and, as mentioned above, the number of diverging components is very limited, collectively operating as a strong DfD system.
So, in response to the experimentation conducted of the functions of the BioPods, eight main categories were selected, not including the possibility of adding climbers to the system as they are rooted in the soil and thus not officially using the BioPod spaces. Within those categories, two design strategies are distinguished, the first being BioPods that are manufactured like the modules and consist of interlocking elements. The second strategy enables more design freedom for the end-users as the form of the BioPod is not necessarily in accordance with the shape of the 'pockets'. In fact, the BioPod can in this case be made from any waste material the users, like the school children, have at hand, for instance PET bottles for planters or random pieces of wood for a nesting box, contributing to the Do-It-Yourself feature and sense of ownership of the product. These BioPods can be secured if needed with a small safety bar or rope that is mounted to the module through small, premanufactured holes.

Concluding, the combination of an extensive research and design phase of this thesis creates a holistic design, suitable for low-tech applications of greening urban (school) environments with several possibilities of involving the end-users in the manufacturing or assembling of the system and sequentially increasing their awareness and knowledge of circular, sustainable and biodiversity design related subjects.

10.3 Limitations

This thesis designed a circular façade system for primary school buildings which utilises reclaimed materials and endeavours to foster local urban biodiversity. However, due to the defined timeframe of the thesis, several limitations were encountered during the process aside from the ones already mentioned in the scope of this research in the Introduction chapter.

- The production and/or processing techniques for potential reclaimed materials of the system are tested to a limited extend and are their applicability is therefore mainly based on theoretical assumptions.

- The potential waste materials for the modules, BioPods and connectors are not tested on weather resistance.

- Although the intention was to base the selection and configuration of the BioPods in the design example of the school building on real life flora and fauna data and this data was actually requested from the NDFF, it was a too time-consuming process to extract the useful information out of it. Hence, the design example was eventually primarily established by considering the requirements of the flora and fauna species.

- Related to the previous, the success rate of the biodiversity enhancement aspect of the system is not examined, as this could only be proven to be achieved by real-life application or testing.

- Despite several efforts to get in touch with a primary school and gain information regarding the educational purposes of the design and the children's involvement, this has not been achieved.

10.4 Recommendations for further research

Real-life prototype testing to assess the weather resistance of potential materials and connections, the success rate of biodiversity implementation for the direct urban environment and the potential manufacturing processes for selected waste materials of the design. For the consecutive results, the system could be optimised accordingly.

In terms of processing methods for several waste materials to accommodate them for the system, research can be done regarding the sustainability, easiness, time-intake and costs of the processing techniques.

End of Lifecycle analysis for the product regarding the circular value of the modules, connections and BioPods and their materialisation and furthermore the several proposed functionalities of the BioPods.

Further development of assembling opportunities of the modular system onto various façade cladding materials to make the system available to a broader audience, as it is currently particularly designed for brick facades.

Design optimisation and exploration regarding it's circular value and the potential of the circular approach whereas the system would operate as a service. This could include investigating the possibility of the designed system being a product on the market that could be purchased, assembled and maintained by people themselves at their own home as their (tiny) biodiversity fostering façade garden. Alternatively, people won't be the owner of the product, but they lease it. This would improve its circular value, as reparation of elements are to be done by the leasing company, where the damaged part rejoins the circular loop and the customer gets a 'new' piece for their system. A third option would be that individuals with access to suitable low-tech production methods of the elements, can produce the modules themselves once they posses one or more applicable materials and just the required instructions and digital models can be accessed from the founding company. These are all thoughts that are recommended to be further researched.

Conducting extensive research on the involvement of children in the design of the system, could increase its contribution to awareness regarding circular, sustainable and biodiversity design related subjects.

Exploring and assessing the large-scale effects of this relatively small additions of nature and biodiversity in urban areas. Although the interventions are small, they could have a substantial impact on the greater picture of green and blue networks within and even across city boundaries.

10.5 Reflection

Graduation topic in relation to the Master track Building Technology

From this graduation topic “Designing a Low-tech Three-dimensional Circular Façade System Utilizing Waste Materials: Fostering Local Biodiversity in Urban Environments” the two main pillars of ‘Circularity’ and ‘Biodiversity’ can be extracted and this logically leads to the topic not just fitting in one, but two of the Building Technology Graduation Studios, namely the “Circular Building Design” graduation studio from the Façade and Building Products chair and “Nature-inclusive Design” from Climate Design.

The first mentioned studio is addressed through the design of a façade system which is built from the circular principles “Eliminate waste and pollution” and “Circulate products and materials” and uses the design approaches of Design for Disassembly and Modularity. As the system consists of modular elements which can be manufactured from various reclaimed materials, such as timber plates, concrete plywood and HPL façade panels, it responds to the local stock of available discarded materials. Placing these modules in different patterns on the façade generates not only an intriguing architectural language, but moreover establishes diverse spaces between the modules. Within these spaces the local biodiversity thrives via numerous insect attractive plants and herbs, bee and butterfly hotels, nesting boxes and several nutrition spots. Hence, this is where the graduation topic is connected to the Nature-inclusive Design studio. The combination of these two studios in this thesis fits perfectly in the innovative perspective and approach of the Master track Building Technology.

Approach and methodology

The original research methodology was constructed of literature study in three interrelated topics with case studies in each division, a research-by-design approach resulting in a final product and finally, a site selection to implement the product in a suitable configuration according to the characteristics of that local environment. The three divisions in which the literature review was conducted, were circularity, reclaimed materiality as a part of the circularity section, and biodiversity and findings in one department could affect the decision-making for another.

As utilising waste materials is an element of a circular design approach, the literature review in these fields encountered frequently overlap. However, the initial focus for circularity lied with three-dimensional circular façade cladding systems and the aim to find suitable circular three-dimensional production techniques for a modular system following the principle of Design for Disassembly, whereas the materialisation research concentrated at waste streams in the Netherlands and identifying potential reclaimed materials for the design phase of the thesis. Consequently, the latter had influence on the circular production techniques of the first-mentioned.

Production techniques are however not deeply researched, as during the research process the decision was made to not select one particular reclaimed material for the system, thus also the production techniques became less relevant since it was assumed the manufacturing technique would depend on the material used. Additionally, during the process it became clear that the system had to be constructed according to low-tech principles to achieve the DIY aspects for the final users: primary school children and their teachers. Hence, complicated manufacturing techniques affording complex machinery is not preferable. However, a more profound research could have been conducted about the potential low-tech approaches, like die cutting, moulding and vacuum forming to further explore the possibilities of producing the modules on site by the children themselves.

As for the materialisation of the product, some basic research was conducted about waste streams in the Netherlands, wherefrom potential materials were selected for the product, honouring the approach of the chosen reclaimed material for an execution of the design being location and time dependent. Nonetheless, this selection of potential materials is based on some theoretical research and the materials are not physically tested, due to practical and time limitations and therefore reliability of the as suitable assessed materials could be questioned.

Lastly, there was the biodiversity research, which initially consisted of the analysis of various urban flora and fauna species in the Netherlands and influencing factors for biodiversity in urban areas. Collectively, this resulted in the selection of species to be potentially attracted by the system, based on the region where the design would be established. However, because of the limited time frame, it was not possible to profoundly investigate the potential vegetation types that are best fitted for a living wall system and which fauna species they would appeal, however, based on available theoretical information some vegetation types were proposed and for each some examples were given. Similarly, from the conducted research it unravelled that bee and butterfly species are very selective in which pollinating flowers they draw on, but this has neither been explored in detail.

Reflecting on the time spent on the three research fields, more time has been invested in the biodiversity research than in the remaining two, as it was an important (personal) aim to develop a biodiversity fostering system, which could actually have the potential to succeed in practice. Additionally, deeper research on the educational and DIY possibilities of the system, could also have improved the feasibility of the system, for instance through visiting primary schools and gathering information about common nature and sustainability related lessons and workshops for children.

Regarding the Research-by-design phase of the thesis, this originally would have commenced mainly after the literature review had been completed. However, to maintain a more holistic approach, the design phase was executed more simultaneously with the literature research phase. This influenced for instance the research process in a way that it shifted away from investigating on how singular three-dimensional elements could be manufactured, since the preliminary design consisted of multiple two-dimensional objects that collectively generate a three-dimensional module. Hence, whereas the literature research initially - and in retrospect yet mainly - provided the guidelines for the design phase of this graduation project, the forward shifting timeline of the research-by-design phase caused some redirections in the literature study.

Finally, reflecting on the proposed design being implemented on a chosen school in Delft including the modules’ and BioPods’ architectural configuration which fits within the context of the building, this latter is proposed majorly according to theoretical data about the biodiversity species, due to time limitations. However, it would have given the design more decisiveness if the composition was established by analysing real life flora and fauna data. This data has been provided by the NDFF, yet it required an excessive amount of time to process this data and extract the useful information out of it.

Strengths

The design concept which resulted from the conducted research has little complexity and therefore makes it an approachable system for many potential users, not just children; Additionally, the low technicality yields a wide range of potential reclaimed materials of which the system could be manufactured.

Weaknesses

The proposed architectural configuration of the design implemented on the case study school is based on theoretical data rather than actual data which was provided by the NDFF.

Threats

The potential materials are based on assumptions and not tested as a prototype in a physical environment.

Opportunities

Improving the design regarding educational possibilities by visiting schools and gathering information about this topic.

Figure 140. SWOT analysis of the Methodology

Societal impact

The results of this project hold significant promise for practical application, even though they have not been physically tested. The theoretical foundation of the design is very promising and aligns well with real-world product implementation. This is primarily because the project is built upon proven circular principles, emphasizing Design for Disassembly (DfD) and modularity. Furthermore, in terms of nature-inclusive design, the design of the façade system is accompanied by a Biodiversity Map which guides the eventual designers and users in the selection of the most eligible species for their target location.

Regarding sustainable development, this graduation project makes noteworthy contributions. Its emphasis on the encountered circular principles of DfD and modularity aligns with sustainable practices. By utilizing waste materials and reducing the demand for new resources, it positively impacts the environment and helps to reduce the amount of waste in the Netherlands. Moreover, it also fosters biodiversity in urban settings, enhancing the overall ecological health of the area and promoting a more sustainable urban environment among children by increasing awareness and interest regarding sustainability, circularity and biodiversity related topics.

Concerning the projects impact on the built environment and the broader social context, it introduces the concept of low-tech, nature-based solutions into the urban environment in an accessible manner. Beyond its practical benefits, it adds an aesthetic dimension that can enhance the neighbourhoods' overall ambiance and experience. Importantly, it reconnects people with the natural world around them, fostering a deeper appreciation for nature. Not only does this improves individuals' health and well-being, but moreover it contributes to a broader societal shift towards sustainability and ecological awareness.

11

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12

Appendix

A. Full analysis of the potential school buildings as a design case study

Max Havelaar school - potential surface areas

1. North-east /+- 50 m2

2. South-west / +- 20 m2 outside (and +- 20 m2 inside)

3 + 4. South-west / 2x +- 10 m2

Het Mozaïek (Hof van Delft) - potential surface areas

1. South / +- 15 m2

2. East / +- 50 m2

3. East / +- 18 m2

4. North-east / +- 40 m2

Het Mozaïek (Voordijkshoorn) - potential surface areas

1. South-east / +- 15 m2

2. South-west / +- 30 m2

3 + 6. South-west / 2x +- 8 m2

4. South-east / +- 16 m2

5. South-west / 48 m2

7. North-west / +- 16 m2

8. South-west / +- 40 m2

Gabriel school - potential surface areas

1. North-east / +- 28 m2

2. South-east / +- 16 m2

3. North-east / +- 14 m2

4. North-east / +- 64 m2

5. North-west / +- 21 m2

6. South-west / +- 21 m2

7. North-west / +- 40 m2

8. North-west / +- 28 m2

B. Full matrix of the assessment of the potential schools regarding the species

House Sparrow

	Minimum of 5 nesting boxes, each 50 cm apart	Height of nesting boxes: 3 - 10 m	Opening of nesting boxes on N, E or NE façade	Nesting boxes far away from windows	Nesting boxes close to gutters	Other populations nearby	Evergreen bushes to rest and sleep	Not too many tall trees	Grass within 100 m	Sand within 100 m	Water (clean and shallow) within 100 m	Climbing plants and (thorny) bushes: > 3 m height	Food-providing plants (e.g. seeds, grains, flower buds, berries)	Insects (like aphid) or insect-attracting plants	*Point total*
Max Havelaar school *City Centre*	+	++	+	+/-	-	+/-	-	+	+/-	+/-	-	-	+/-	+/-	*17,75*
CBS Het Mozaïek *Hof van Delft*	+	++	++	+	+/-	+/-	+/-	+	++	++	+	-	+	+	*30*
CBS Het Mozaïek *Voordijkshoorn*	+	+	+	++	-	+/-	++	+	++	++	-	-	+	+	*26,5*
Gabriël school *Hof van Delft*	+	++	++	++	+	+/-	+	+/-	++	+	+	-	+	+	*30,75*
Maximum possible score															46,25

Bush Breeders, e.g. Robin & Blackbird

	Thorny bushes	Evergreen, dense hedges	Façade vegetation, like climbing plants	Food-providing plants: i.e. nectar-rich and berry-bearing	Point total
Max Havelaar school *City Centre*	-	-	-	+/-	*0,5*
CBS Het Mozaïek *Hof van Delft*	-	+/-	-	+/-	*2*
CBS Het Mozaïek *Voordijkshoorn*	-	+	-	+/-	*3,5*
Gabriël school *Hof van Delft*	-	+/-	-	+/-	*2*
Maximum possible score					10

Starling

	Minimum of 5 nesting boxes clustered	Height of nesting boxes: 2 - 5 m	Opening of nesting boxes on NE façade (or N or E façade)	Other Starlings nearby (preferred)	Lawns (grass fields) for insects and their larvae within 500 m	Food-providing plants: i.e. berry-bearing	*Point total*
Max Havelaar school *City Centre*	++	+/-	+	-	+	+/-	*10,75*
CBS Het Mozaïek *Hof van Delft*	++	+	++	-	++	+/-	*13,5*
CBS Het Mozaïek *Voordijkshoorn*	++	++	+/-	-	++	+/-	*12*
Gabriël school *Hof van Delft*	++	++	++	-	++	+/-	*14,25*
Maximum possible score							17,5

Great Tit & Blue Tit

	Nesting boxes, tree cavities or sheds for breeding	Distance between nesting boxes: > 3 m (both species) or > 10 m (one specie)	Opening of nesting boxes on N, E or NE façade	Thorny bushes and hedges	Tall tree(s) with a dense foliage (e.g. beech, oak or hawthorn)	Ascending, evergreen bushes	Food: beechnuts and other seeds	Food-providing plants: i.e. nectar-rich and berry-bearing	Insects (like caterpillars) or insect-attracting plants	*Point total*
Max Havelaar school *City Centre*	+	+/-	+	-	+/-	-	+/-	+/-	+/-	*9*
CBS Het Mozaïek *Hof van Delft*	+	+	++	+/-	+/-	-	+/-	+/-	+/-	*12,25*
CBS Het Mozaïek *Voordijkshoorn*	+	+/-	+/-	+	+/-	+/-	+/-	+/-	+/-	*10,5*
Gabriël school *Hof van Delft*	+	+	++	+/-	+/-	-	+/-	+/-	+/-	*12,25*
Maximum possible score										21,25

	Swift							*House Martin*							
	Minimum of 5 (built-in) nesting boxes, each 80 cm apart	**Height of nesting boxes: 6 - 40 m**	**Opening of nesting boxes on N, E or NE façade**	**Free approach area of the nesting boxes (in front and below): > 3 m**	Water-rich area within 500 m	Insect-rich (and herbal) lawns within 500 m	*Point total*	**Minimum of 5 nesting bowls clustered**	**Height of nesting bowls: 4 - 10 m**	**Opening of nesting bowls on NE façade**	**Free approach area of the nesting bowls (in front and below): > 3 m**	White cantilevers near roof edges	Water and lawns nearby	Insect-attracting plants in a water-rich area	*Point total*
Max Havelaar school *City Centre*	+	+/-	+	-	++	+/-	*11*	++	++	+	-	+	+/-	+/-	*14,5*
CBS Het Mozaïek *Hof van Delft*	+	+/-	++	+/-	++	++	*13,25*	++	++	++	+/-	+/-	++	++	*18,75*
CBS Het Mozaïek *Voordijkshoorn*	+	-	+/-	+	+	+	*11,5*	++	+	+/-	+	-	+	+/-	*14,25*
Gabriël school *Hof van Delft*	+	+/-	++	+	++	++	*16,25*	++	++	++	+	-	++	++	*19,25*
Maximum possible score							20								22,5

	Common Dwarf Bat									*Bees & Butterflies*							*Access*	
	Height of bat boxes: 4 - 50 m	Multiple bat boxes on different heights and wind directions	Several small cavities for residence	**No artificial light at place of residence**	Non-lit areas in the direct environment	Water lines and tree lanes	**Food: water-rich area for mosquitos**	Food: insect-rich vegetation	*Point total*	Insect stones, sand, dead wood, small cavities in stems or stacked stones	**Openings of butterfly hotels and bee bricks on S, SW or W façade**	Host plants for procreation (varies per specie)	Food: trees with blooming period from early spring until late fall	Food: nectar and pollen plants (flowers and herbs)	Variety in vegetation with different structures for safety	*Point total*	**(Part of) façade system must be within reach for DIY & maintenance: 0 - 2 m**	*Point total*
Max Havelaar school *City Centre*	+	+/-	+/-	+/-	-	+	++	+/-	*12,75*	+/-	+	+/-	+/-	+/-	+/-	*7,5*	+/-	*1,5*
CBS Het Mozaïek *Hof van Delft*	+	+	+/-	+	+	+/-	++	+/-	*16,25*	+	+	+/-	+	+/-	+	*9*	+/-	*1,5*
CBS Het Mozaïek *Voordijkshoorn*	+/-	+/-	+/-	+/-	-	+/-	+	+/-	*9,5*	+/-	++	+/-	+/-	+/-	+	*7,75*	++	*3,75*
Gabriël school *Hof van Delft*	+	+	+/-	+	+/-	+	++	+/-	*16,25*	+/-	+	+/-	+/-	+/-	+	*7*	++	*3,75*
Maximum possible score									22,5							12,5		3,75

C. Models from the design process