Integrating Tailored Fibre Placement and Biobased Materials: Building Envelope Greening and Habitat Elements

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TABLE OF CONTENTS

ABSTRACT

In the context of environmental change, critique often targets an anthropocentric view that perpetuates power dynamics and alienates human-nature relationships. Urbanisation, as a centre of innovation and knowledge production, is pivotal in confronting environmental challenges and presenting adaptation possibilities. Design tendencies that embrace a holistic perspective, acknowledging humans as parts of ecosystems, offer opportunities for adapting to environmental change and establishing new ways of relating. Multispecies design embraces human-nature interactions and aims to incorporate design as a flexible, conversational tool to establish new ways of relating.

In cities, buildings provide manageable grounds for experimentation of multispecies dynamics and relationships. Integrating multispecies habitats within building envelopes and repurposing underutilised surfaces offer avenues for fostering such a shift. Additive Manufacturing (AM) technologies emerge as promising tools, enabling the mimicking of natural features and fabrication of lightweight, durable components using biobased materials.

This research focuses on developing a living facade that integrates multi-species interests through habitat creation on a building level, using advanced additive manufacturing and bio-based materials. This approach responds to the need for a paradigm shift in architectural and urban practices, driven by current global challenges and their ecological and social implications. It explores Tailored Fibre Placement and biocomposite materials, specifically Flax Fibres for architectural applications.

The outcome presents an architectural application of the materials and methods and underscores the potential of Tailored Fibre Placement for multispecies ends. It highlights the need for further research into the application of computational approaches in addressing artificial wildlife habitats in urbanised areas and a gap in methodologies to understand wildlife behaviours and needs as well as in evaluating the effectiveness of such structures.

The subsequent sections provide background on the emergence of multispecies design, introduce additive manufacturing technologies, and describe Tailored Fibre Placement, biocomposites, and flax fibres. The methodology and design process are then outlined, leading to the formulation, description and fabrication of the envisioned structure. Finally, the discussion addresses this living wall from the perspective of multispecies design and the application of TFP as a fabrication technology. Conclusions are drawn directing to the necessity for further research.

1. INTRODUCTION

Preserving healthy ecosystems is increasingly important in light of global environmental and climate challenges. Mitigation and adaptation strategies have largely focused on establishing and preserving healthy natural ecosystems through protected areas, ecological corridors and restoration projects. Although valuable, they seem insufficient in facing the gravity of change (Soga, & Gaston, 2016). Urbanised areas are hotspots that drive environmental change at multiple scales while characterised as centres of economic growth, innovation and knowledge production (Grimm et al., 2008; Grobman et al., 2023). Consequently, cities hold significant potential as surrogates for global changes and for predicting broader ecological and evolutionary processes. Studying urban dynamics can provide valuable insights into how these global phenomena manifest and evolve. By observing and analysing the dynamics within cities, large-scale trends can be recognised, understood and predicted, aiding in addressing global challenges. Thus, cities also represent key opportunities for the emergence, implementation and evaluation of new ideas (Lahr, Dunn, & Frank, 2018).

In this context, critique targets prevalent urban and architectural practices that embrace a divide between human and nonhuman, an anthropocentric approach. In Western thought, cities have traditionally been conceived as intentionally isolated human habitats, fostering a physical, ethical, and spiritual disconnect from the natural world. This, in turn, led to the expulsion of living creatures and the purge of disorderly growth of species. At the same time, it is important to acknowledge that despite the hierarchical perspective, cities cannot adhere to this framework. Urban environments house diverse species indicating that the conceptual reality of modern cities often fails to acknowledge and frequently rejects the integration of other species despite their persistent presence in urban territories (Borch, & Kornberger, 2015; Franklin, 2017; Rigby, 2018; Plumwood, 2009).

Buildings epitomise this anthropogenic separation, not only as fundamental components of urbanisation but also as manifestations of exclusively human-centric spaces. However, targeting buildings represents significant opportunities for experimentation. While addressing urban challenges at a city-wide level can be complex, buildings provide a more manageable scale. They harbour the potential to confront contemporary and future challenges directly, offering accessible platforms for innovative experimentation and engagement (Schuurmans, Dyrboel, & Guay, 2018; Zhong, Schroeder, & Bekkering, 2023).

1.1 DEPARTURE FROM ANTHROPOCENTRIC ARCHITECTURE

Design approaches offer counterpoints to anthropogenic tendencies in architecture. Biophilic design, for instance, aims to foster connections between humans and nature by maximising opportunities for engagement and connection (Richardson, & Butler, 2022). Similarly, more-than-human design extends beyond individualism, emphasising interconnectedness and viewing humans as part of a larger web of life. This approach does not disregard humans as beneficiaries but promotes a more holistic perspective where `more` can encompass biological agents, landscapes and weather patterns (Bornschlegl, 2023; Cotsaftis, 2023).

Another approach, multispecies design, refers to designing systems and artefacts that address the needs of both humans and other species, aiming to reduce conflict and promote mutually beneficial interactions. In architectural practice, multispecies design focuses on human-nature interactions, with a tendency to use design as a tool not to enforce power relationships but to promote empathy, inclusion and relationality. This approach steps away from an anthropocentric tradition, viewing human habitats as extensions of natural ecosystems (Metcalfe, 2015). These methodologies advocate for adapting to and thriving in changing environments, extending this imperative to other species in terms of habitat, behaviour, adaptation, and shared space (Borch & Kornberger, 2015; Franklin, 2017; Rigby, 2018; Plumwood, 2009).

Such a shift in design is seen as instrumental in fostering ecological resilience, biodiversity conservation, and sustainable urban development while addressing the imperative for nature integration within the built environment. It responds to the urgent need for diverse and biodiverse human habitats, necessitating adaptation due to a mutual influence at the intersection of ecological and urban settings. Embracing diverse species in urban spaces can imply economic, ethical, ecological, and health assets as well as, conflict and nuisance. Modifications to anthropocentric systems encompassing both physical infrastructure and sociocultural systems can help to mediate interactions (Grobman et al., 2023; Gatto, & McCardle, 2019; Weisser et al., 2023).

Design and architecture play important roles in shifting narratives and perceptions surrounding urban wildlife, and facilitating biodiversity conservation efforts. Urban and architectural design can address practical challenges arising from urban wildlife presence, including population surges and health concerns. Leveraging insights from urban wildlife management, design interventions can support the natural functions and structures of urban ecosystems while considering both ecological and social needs (Grobman et al., 2023; Gatto, & McCardle, 2019; Wisser et al., 2023). Additionally, actions such as connecting green areas in the city to generate habitat continuity; communicating to people the benefits of living amongst other species; mobilising people to transform their surroundings; negotiating the meeting points between humans and animals; designing mutually, respectful encounters; and helping people recognise and interact with existing urban nature can all contribute to a shift and prepare urban environments for future enhancements in line with multispecies values (Gatto, & McCardle, 2019).

1.3 IMPLICATIONS OF MULTISPECIES DESIGN IN DESIGN PROCESSES

Multispecies design ends necessitate the inclusion of novel considerations into design workflows. Firstly, there is an emphasis on understanding other species as beings that use, interact with and are otherwise affected by manmade systems. This requires the development of new design practices that incorporate the representation of diverse species. This is a challenging endeavour due to a lack of methodologies to understand the point of view of other creatures and the associated difficulty in integrating knowledge and data from various fields to inform the design of multispecies spaces in a meaningful way. There is a lack of design approach that relies on effectively combining data and simulations but also contextualises and complements scientific information through observation methods, photography, visual diaries, video and sound recordings, and site research (Weisser et al., 2023; Metcalfe, 2015). Developing such a design approach would aid in understanding the needs and criteria for multispecies spaces, assessing their evolution and analyzing interactions between subsystems and their impact (Weisser et al., 2023). Finding an effective methodology is crucial as misinterpretations of other species' needs in design can lead to artefacts that encourage dependency or reduce the animals' ability to support their needs. Designs often appeal to humans but are ignored by the intended species or, worse, pose risks to the animals (Metcalfe, 2015).

However, the findings of Daneluzzo, Macruz, Tawakul, & Hashimi (2023) indicate that a mutualistic relationship rooted in co-performance is possible. This highlights the importance of human-nature interactions when designing multi-species spaces. Metcalfe, (2015) pinpoints that encounters are not predetermined but shaped by landscapes, products, services, beliefs and perceptions. Therefore, there is a possibility to shape human-nature encounters through design and education potentially reducing conflicts and shifting perceptions towards more inclusive and biodiverse habitats (Metcalfe, 2015).

Additionally, there is a recognition that current socio-economic system norms often conflict with accommodating other creatures and multi-species perspectives, adding to the difficulty in planning for concrete future stages. Instead, it may be more productive to think in terms of exchanges and procedures rather than fixed destinations. This shifts the focus from the making and implementation of plans to experimentation and specifying rules of engagement. In this context, design can play a useful role (Roudavski, 2020).

One approach that emerges is the use of design as a means of communication to explore and redefine the relationships between humans, other species and the environment. This suggests that design should be deployed not as an affirmative discipline but as a process-oriented analytical tool to express and reflect on human interactions with the natural world and to discuss potential future scenarios. The role of design and designer is pronounced in fostering dialogue, understanding complex relationships with nature, and envisioning inclusive ways of living together (Gatto, & McCardle, 2019). Establishing methodologies that encourage ways of behaving, thinking and experiencing next to technical aspects can encourage an open-ended design process, which implies a dynamic process capable of changing and evolving alongside ecological and geomorphological processes to create connectivity and complexity (Metcalfe, 2015).

1.4 MULTISPECIES AT THE BUILDING SCALE

Focusing on the building level allows for small-scale experimentation, enabling the exploration of interactions and methodologies in a controlled environment. Therefore, this approach allows for actively addressing contemporary challenges (Schuurmans, Dyrboel, & Guay, 2018; Zhong, Schroeder, & Bekkering, 2023).

To envision multispecies design at the building level, Grobman et al. (2023) explore two strategies: integrating elements for other species within public spaces of buildings (such as roofs, balconies, inner courtyards, and vertical circulation) and embedding multispecies features within the building envelope. Their research, based on ten different multi-species residential projects developed in a case study design course, provides initial insights into the relatively unexplored realm of incorporating the needs of multiple species into the architectural design process of contemporary residential buildings. The research identifies a significant gap in understanding the behaviours and requirements of non-human stakeholders, including their needs for food resources, environmental conditions and factors of habitat creation (such as dimensions, proportions, and materials). It also highlights the delicacy of species interactions and their implications for overall ecosystem well-being. One proposed solution is managing cohabitation through accessibility, such as providing separate feeding or nesting sites to reduce competition and conflict. Furthermore, the research uncovered a potential conservation bias, where aesthetically appealing or popular species might receive preferential treatment, overlooking the needs of less visually appealing species (Grobman et al., 2023). This research highlights opportunities and challenges associated with multispecies building-scale design solutions and articulates a gap in actively and synergistically integrating diverse species into building design.

Focusing on the building envelope, large areas which are typically unreachable by humans and mainly act as barriers between inside and outside, present significant opportunities for habitat creation for animals, plants, and microbiota (Bobraszcyk, 2023; Grobman et al., 2023). These surfaces can serve as interfaces for managing cohabitation by accessibility, creating ecological and human-nature relational connections within the urban context. However, there is limited knowledge about specific building features that best encourage positive interactions with animals in the case of partial allocation of space in the building envelope for other species. While attempts are made to promote positive interactions between the built environment and animals, there is a notable gap in defining clear methods or evidence to achieve and evaluate these interactions. These attempts are also mostly limited to urban design features such as green walls and roofs, which often entail biases towards specific species rather than covering a wider range of ecological niches in urban environments. Consequently, viewpoints held by design professionals regarding animals are often anthropocentric, utilitarian, subjective, contextual, and influenced by their understanding of various species' significance within an ecosystem (De Wilde et al., 2022).

Additionally, Grobman et al. (2023) argue that humans only marginally benefit from integrating animals into building envelopes. Balancing the needs of humans and other species can be challenging. Multispecies design questions the need to prioritise excessive anthropocentric value and advocates for balancing functionality for a broader audience (Metcalfe, 2015). In a capitalist society, where profit drives most decisions, such extensions to building envelopes are often perceived as unnecessary expenses. This conflict highlights the tension between societal norms and emerging environmental considerations in architecture and other fields.

Nevertheless, the greening of building envelopes, especially when combined with habitat-creating elements, offers diverse benefits for both humans and other species. Greening building envelopes can impact the survival and behaviour of various species, offering opportunities for predation, competition, and exchanges of aggression, as well as coexistence and cohabitation. In an urban context, building envelopes can provide shelter, food, and better living conditions for animals (Bobraszcyk, 2023). Such a design can bring similar implications and challenges as living walls. Living walls serve to integrate vegetation uniformly by the implementation of continuous or modular elements that support the in situ growth of plants (Manso, & Castro-Gomes, 2015). Living walls offer potential benefits, including mitigating the urban heat island effect, enhancing air quality, sound insulation, carbon sequestration, aesthetic enhancements, physiological well-being, and support for biodiversity. At the building scale, they may contribute to improved energy efficiency, enhanced indoor environmental quality, increased air purification, oxygenation, health benefits, building envelope protection, noise reduction, and increased property value (Wood, Bahrami, & Safarik, 2014; Radić, Dodig, & Auer, 2019; Tudiwer & Korienic, 2017). Living walls have also been associated with reduced stormwater runoff and increased biodiversity (Radić, Dodig, & Auer, 2019). However, as these elements are often intended as aesthetic features, there is an expectation of an evergreen appearance that is often unattainable due to variable climatic scenarios. Consequently, there is a potential negative perception due to high maintenance costs and climate-related fluctuations, leading to a diminished appeal and limited wider acceptance and implementation (Grobman et al., 2023).

Overall, building envelopes present a unique opportunity to benefit diverse actors and balance their needs. Although uncertainties persist, such as insufficient evidence on what species find attractive and beneficial, and the need for a shift in perceptions, design practices and urban landscapes, these challenges can be addressed through controlled, small-scale experimentations. Focusing on integrating multispecies elements within building structures can provide grounds to explore new methodologies and interactions that actively tackle contemporary environmental challenges.

2. ADDITIVE MANUFACTURING, TFP AND BIOBASED MATERIALS

A significant challenge in multispecies design lies in the manufacturing processes needed to create aesthetically and functionally appealing geometries for target species. Additive Manufacturing (AM) technologies are gaining traction in the field due to their inherent advantages. Utilising methodologies based on digitally controlled, layer-by-layer material application, AM allows for the creation of shapes that embody both functionality and aesthetics, unattainable through traditional manufacturing processes. This adaptability and customisation capability (Gardan, 2016; Larikova et al., 2022) make AM particularly suitable for designing features that mimic natural forms. Additionally, AM methodologies can be directly driven by digital data that fosters the exploration and realisation of natural forms (Sørensen, 2020).

Additionally, AM allows the simultaneous consideration of shapes, sizes, hierarchical structures, and material compositions, allowing for product performance optimisation and high individualisation. The integration of computational design and simulations expands architectural possibilities, enabling the customisation of multiple functions through geometric and material freedom. Consequently, AM presents revolutionary methods for creating new architectural designs (Sørensen, 2020). For instance, Parker, et al., (2022) advocate for the use of computer-aided design, form-finding and morphological analysis to approximate the characteristics of complex natural features, balancing the requirements of both humans and other species to inform better targets for design.

Similarly, Larikova et al. (2022) highlight the potential of computational and AM tools for facilitating wildlife-inclusive facade design, focusing on species needs, design quality, and building retrofitting in urban contexts. Their research explores the potential of AM and digital planning for crafting tailored, site-specific facade redesigns accommodating cavity-dependent animal species. The prototype demonstrates how emerging digital technologies may augment traditional architectural planning and fabrication tools in the context. Another study by Parker et al. (2023) employs 3D-printed clay, textiles, and composites to create a modular system accommodating mycelium composites based on species-specific requirements, material strategies, and infrastructural limitations. The role of computational design and 3D printing manifest as tools in the creation of intricate, customised geometries for their endeavour to support coexistence among insects, fungi, and humans. This study highlights relevant design features that accommodate diverse nesting needs and underscores the value of computational design and AM technologies in shifting design practices. Another study titled `The Meristem Wall` by Goidea (2023) emphasises AM's capacity, particularly binder-jet 3D printing technology, to cater to multiple functions simultaneously through performative geometries.

By leveraging the precision, adaptability, and customisation capabilities of AM, designers can create intricate and functional geometries that mimic natural forms, optimise habitat conditions, and enhance architectural aesthetics. These technologies enable a nuanced approach to habitat creation, allowing for the simultaneous consideration of various species' requirements and environmental conditions. As research continues to explore and refine these methods, AM stands out as a transformative tool in developing innovative and sustainable urban ecosystems that foster coexistence and resilience. This integration not only shifts design practices towards more inclusive and ecologically sensitive approaches but also opens new avenues for interdisciplinary collaboration and ecological research, paving the way for cities that are more harmonious with the natural world.

These projects reflect that integrating Additive Manufacturing (AM) technologies within multispecies design presents a significant advancement in addressing the complex needs of both humans and wildlife in urban environments. By leveraging precision, adaptability, and customisation based on direct data input, designers can take a more nuanced approach to foster coexistence on a building scale. This also presupposes interdisciplinary collaboration and innovative solutions in urbanism.

2.1 TAILORED FIBRE PLACEMENT (TFP)

While the literature predominantly explores 3D printing employing diverse media approaching coexistence through design, other AM methodologies, such as Tailored Fibre Placement (TFP), offer significant potential for experimentation. TFP, a specialised technique derived from traditional embroidery, enables the deposition of continuous fibre onto a stretched textile affixed to a movable 2D frame using a zigzag double lock stitch (Figure 1). Precise numerical control and digital programming automate the textile frame, guiding it along a predefined continuous path (Martins, Cutajar, van der Hoven, Baszyński, & Dahy, 2020). This method allows for the production of textile preforms for composite components, with fibres arranged in orientations tailored to specific requirements. TFP facilitates the creation of consistent fibre routes and narrow curves with small radii, offering unique characteristics unattainable with traditional unidirectional laminates (Spickenheuer, Schulz, Gliesche, & Heinrich, 2008).

This flexibility to customise fibre structure arrangements offers the opportunity to tailor materials to specific requirements. TFP's ability to customise fibre orientation can lead to stronger, more efficient structures optimised to withstand specific stresses and loads (Sippach et al., 2022). This customisation can also result in products with elevated specific strength, decreased material consumption, and reduced need for supportive materials. The reconfiguration of material and design features through

TFP holds significant promise for architectural applications, particularly when combined with biobased materials (Martins, Cutajar, van der Hoven, Baszyński, & Dahy, 2020).

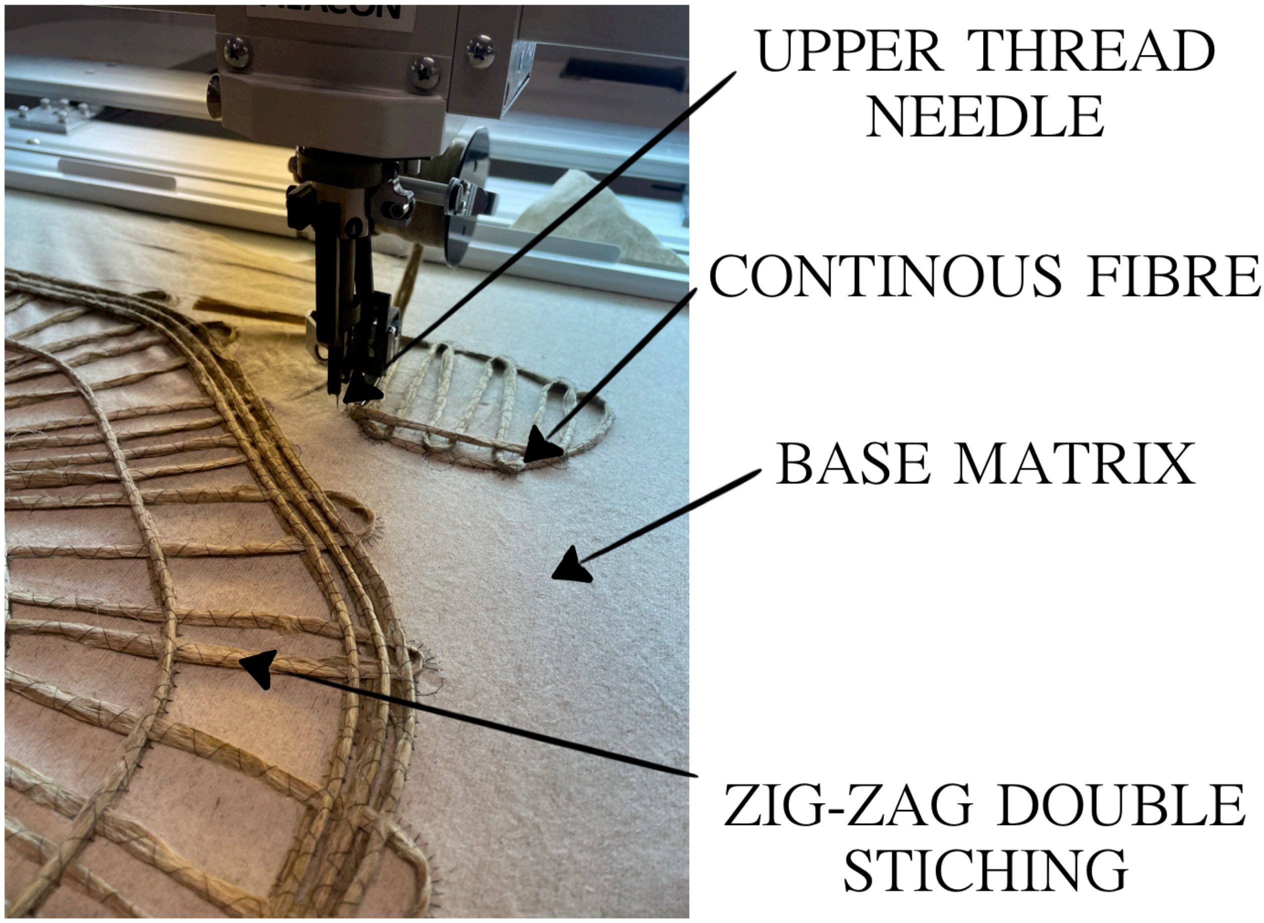


Figure 1. Tailored Fibre Placement Technique

Although TFP is well-recognised in industries like aerospace, its application in architecture is to be further explored. Previous projects aim to demonstrate the value of TFP for the fabrication of lightweight structures and pavilions that demonstrate its potential for building components. FlexFlax Stool, a lightweight stool design, models TFP preforms to eliminate complex, expensive and rigid moulds (Martins, Cutajar, van der Hoven, Baszyński, & Dahy, 2020). Similarly, the mock-up created by Rihaczek et al. (2020) presents that folding along material-embedded hinge zones can create stable geometric structures. This approach effectively transforms the inherently two-dimensional outcomes of the TFP process, showcasing its versatility. It proves that TFP with flax fibre reinforcement can be used on a building scale, potentially resulting in precise shell or panel structures with controlled fibre orientation. These projects highlight TFP's ability to create geometrically stable structures and validate its use for architectural purposes. However, the widespread application of TFP in architecture is still developing much like many other AM technologies, due to the ongoing optimisation of parameters, material feedstocks, and workflows (Ghaffar, Corker, & Fan, 2018).

The appeal of combining TFP with biobased materials for multispecies design lies in its versatility to manufacture complex shapes and geometries, its potential for folding and consequent mouldless fabrication possibilities, and its ability to produce diverse shapes within a unified framework. This capability may support the creation of habitats that mimic natural environments in form, geometry and visual experience, thus proving to be interesting for fostering diverse ecosystems and species interactions in urban contexts.

2.2 MATERIAL CONSIDERATIONS

TFP is a fabrication technique used to create composite materials. Natural fibre-reinforced biocomposites are increasingly employed in architecture driven by ecological and sustainability imperatives (Gurunathan, Mohanty, & Nayak, 2015). These biocomposites, reinforced by natural fibres, offer superior traits through fibre orientation and have been traditionally applied across various industries, including automotive, aerospace, packaging, and building (Zini & Scandola, 2011). Their high specific strength, formability, low weight, and resistance to corrosion and fatigue make them favourable over traditional materials. Their low cost, density, high toughness, thermal properties, biodegradability, and reduced tool wear also contribute to their appeal (Rana, Mandal, & Bandyopadhyay, 2003; Gurunathan, Mohanty, & Nayak, 2015). However, natural fibres exhibit high moisture absorption and an anisotropic nature that must be considered in design and application processes. The hydrophilic properties of natural fibres can lead to weak interfacial bonding with hydrophobic polymer matrices, affecting the composite's mechanical properties and ultimately hindering their industrial use (Gurunathan, Mohanty, & Nayak, 2015). Surface modification techniques are required to improve compatibility and interfacial bonding, necessitating a deep understanding of structural characteristics (Jawaid & Abdul Khalil, 2011; John & Sabu, 2008; Li, Tabil, & Panigrahi, 2007).

While TFP allows for diverse material use, it is apparent that the technology can effectively handle flax fibres and integrate them into composite materials, enhancing the overall sustainability and reducing the environmental impact of the final product (Martins, Cutajar, van der Hoven, Baszyński, & Dahy, 2020; Rihaczek et al., 2020). Flax is one of the most widely used bio-fibers. It is a cellulose polymer derived from the fibrous bundles in the plant stem. Given that Canada is the leading producer of flax, with France, Belgium, and the Netherlands also significant producers, flax is a renewable and locally available material in Europe (Yan, Chouw, & Jayaraman, 2014). Its popularity in composite material research can be attributed to its high strength, stiffness, and significant elongation, which make it highly relevant and valuable for enhancing material properties. Flax materials are cost-effective and due to their mechanical properties show the potential to replace glass fibres as reinforcement in composite materials

(Goutianos, Peijs, Nystrom, & Skrifvars, 2006). Variability in properties shows a great advantage while the obvious need for treatment to avoid degradation from environmental effects is seen as the biggest weakness. This factor is especially present due to its high moisture absorption quality. Treatment can also enhance tensile strength and strain, depending on the type of treatment, fibre diameter, and gauge strength. Flax fibres combined with thermoplastic, thermoset, and biodegradable polymer matrices exhibit promising mechanical properties. However, a significant limitation is poor fibre/matrix interfacial bonding, which reduces tensile properties. Selecting appropriate manufacturing processes and applying physical or chemical modifications can improve the mechanical properties of flax composites (Yan, Chouw, & Jayaraman, 2014).

Flax composites have the potential to be next-generation materials for structural applications in infrastructure, the automotive industry, and consumer applications. Future research should focus on environmental assessment, durability, mechanical property improvement, and moisture resistance. Additionally, novel manufacturing processes and surface modification methods should be further developed (Yan, Chouw, & Jayaraman, 2014).

Overall, TFP´s ability to optimise fibre orientation and create composite materials can be effectively applied with flax fibres. However, surface modification techniques are essential to improve interfacial bonding and material performance.

3. PROBLEM FORMULATION

Cities are recognised as hubs for innovation and knowledge creation, playing a critical role in observing, analysing, and addressing global phenomena and environmental challenges. Through observing dynamics in urbanised areas, critique targets an anthropocentric approach that perpetuates power relationships and separation between humans and the natural world. In contrast, a holistic approach, integrating humans as part of nature promotes balanced human-nature interactions to respond to global challenges and offer ways for adaptation.

Urban Context and Building Experimentation

In urban settings, buildings offer unique opportunities for experimentation, providing accessible spaces to examine interactions and relationships between species. Implementing multispecies spaces at the building level can involve creating habitats within building envelopes, and utilising unused surfaces to support other species.

Role of Additive Manufacturing Technologies

Additive Manufacturing (AM) technologies are becoming increasingly relevant in this field due to their versatility and capability to accurately replicate natural features through computational design tools and direct data input. Tailored Fiber Placement (TFP) is a promising but underexplored methodology that offers significant advantages, including high customisation potential of materials, diverse design capabilities, and lightweight, durable component fabrication.

Research Objectives

The research objectives aim to address the need for a paradigm shift toward a more holistic approach by investigating a multispecies design concept at the building scale, adopting the emerging potential of Additive Manufacturing technologies in this context. Specifically, it investigates the applicability and potential of Tailored Fiber Placement (TFP) using biobased materials (flax fibres) to create a living wall that integrates insect, bird, and plant habitats. The research has two primary objectives:

1. **Design Concept Articulation**: Develop a design concept grounded in ecological research, assess the approach's strengths and weaknesses within the context of multispecies design, and identify challenges and potential advancements in the field.
2. **TFP Application Exploration**: Examine the application of Tailored Fiber Placement (TFP) using biobased materials (flax fibres) for architectural purposes, focusing on its potential within this research domain.

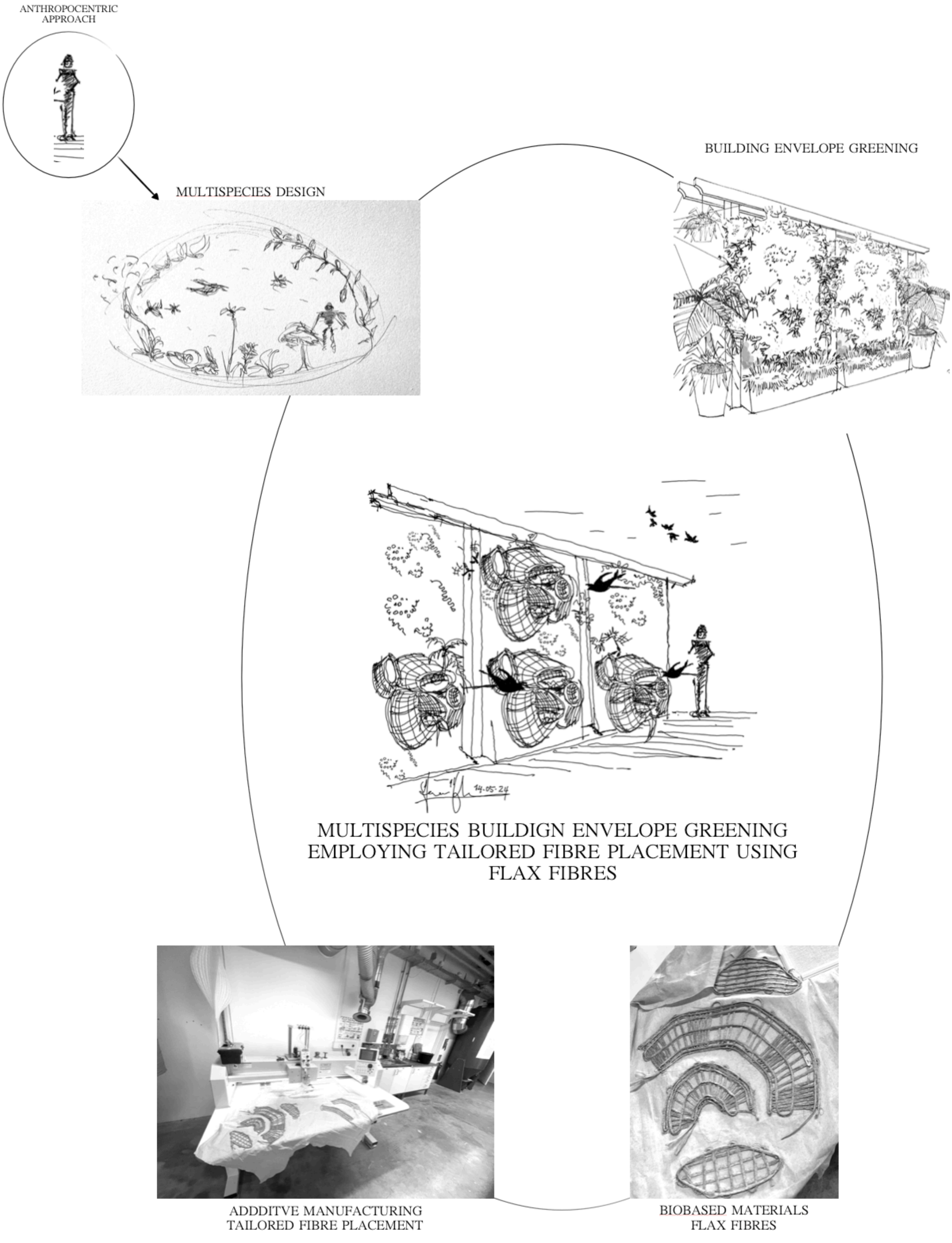


Figure 2. This figure illustrates the problem formulation process, representing the flow of arriving at the research ´s design outcome. It outlines the identification of key issues, starting from a critique of anthropocentric approaches and targeting building envelope design solutions that aim to integrate multispecies perspectives. The aim is to integrate habitat elements for insects, birds and plants using Tailored Fibre Placement and biobased material applications. The central point is the design concept used to assess multispecies design and the relevance of the materials and methodologies in the field.

Methodology and Structure

To this aim, the research methodology includes a detailed exploration of relevant design methodologies and their application, followed by the formulation of an evidence-based design concept. The design concept departs from ecological research on species needs, natural habitat formulation behaviours and artificial habitat element diameters to establish the design criteria for the living wall design, as depicted as a central point in Figure 2. The living wall elements and their fabrication are then elaborated on, beginning with a 3D model, material properties, and Tailored Fibre Placement (TFP) pattern definitions, and culminating in the assembly of a 1:2 scale model. The discussion addresses the work within the context of multispecies design and TFP, highlighting its strengths and shortcomings. The conclusion centres around revisiting the most important outcomes and takeaways of this research and identifying areas for further research investigations.

4. THEORIES AND METHODS

The theories and methods underpinning this research focus on the concept and design development, as well as the fabrication of the facade system. Initially, the concept and design development are described by outlining guiding principles and demonstrating their application. This is followed by a discussion of the different phases involved.

4.1 CONCEPT AND DESIGN DEVELOPMENT

The concept and design development aimed to achieve functionality through an intuitive design process. This process is rooted in the philosophy of "materials as a design tool," which is a circular design thinking approach that places materials as the foundational input for design rather than a subsequent step. This methodology encourages examining the selected material to achieve desired outcomes through inherent development, customisation, and adaptation possibilities. It promotes exploring material capabilities and structural performance through prototyping, mechanical tests, and numerical simulations from the beginning of the design phase. Additionally, the fabrication technique's consideration is crucial due to its influence on material qualities and geometric possibilities. This circular design philosophy fosters high creativity and interdisciplinary collaboration to assess materials, explore potential outcomes, and continuously adapt to functional demands. Therefore, it enables a certain freedom in creating sophisticated solutions (Dahy, 2019).

As for the limitations, interdisciplinary collaboration is identified as a key factor that can enhance or hinder effectiveness across various aspects, including material properties, material development, fabrication techniques and target applications (Dahy, 2019). In this case, the choice of materials and fabrication technique served as the foundation and starting point for developing a solution for urban habitat creation within building envelopes.

This foundation was complemented by the work of Efeoğlu, & Moller (2023) which explores a simplified and intuitive design process. The work aims to redesign the design thinking method to equip novices and non-designers to initiate design activities and embrace design-led problem-solving by reducing complexity and language. Their inclusive and participatory method embraces heterogeneity and co-design, drawing synergies from the collaboration of designers and non-designers in a complementary process. The guided procedure is rooted in sequential activities combined with loops to connect data and sense-making activities. This flexible rendition of design thinking shows potential for co-creation with non-human entities, incorporating scientific knowledge and design novices from various relevant fields.

Here, the structure is employed to focus on organising workflow and articulating design criteria for the living wall and habitat system. Following Efeoğlu and Moller's approach, three key steps are adopted: Insight, Ideation, and Embodiment. The workflow diagram describes these phases.

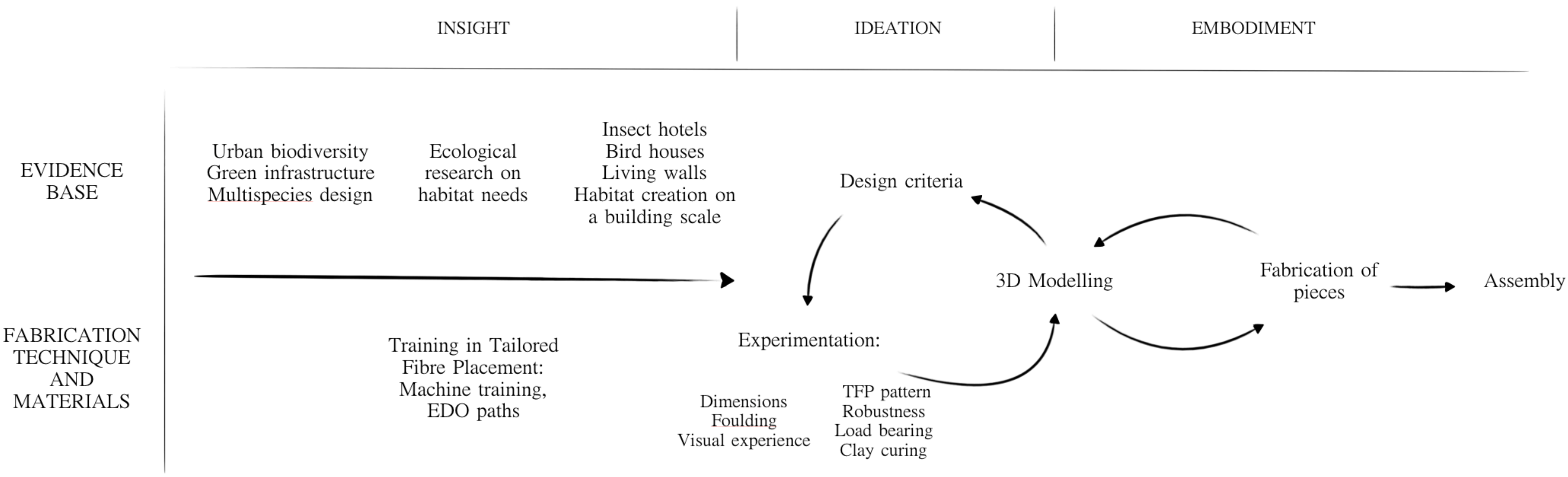


Figure 3. Workflow diagram of the design thinking process integrating materials as design tool philosophy. The insight phase involved evidence collection to articulate parameters to be included in the structure. Simultaneously, it entailed training in Tailored Fibre Placement methodology and the exploration of material properties. The ideation phase encompassed a circular process of establishing design criteria, experimentation and translation into 3D modelling. The embodiment phase utilised the 3D model for fabrication and assembly.

4.2 INSIGHT PHASE

The Insight phase is built on the premise that no solution can be found to the unknown. Therefore, this phase necessitated researching urban biodiversity, green infrastructure, and spaces dedicated to other species in buildings. Synthesising this information defined target areas and subjects feasibly included in the current design, focusing on insects, birds, and plants. The needs of these groups were further researched to specify their nesting and habitat requirements, some basic interactions between them and artificial habitat elements in an urban context. Simultaneously, by exploring the material characteristics of flax fibres and the fabrication technology, Tailored Fibre Placement (TFP), their potential for a facade system is understood. This included a training process focused on machine training and the use of related computational tools such as EDO paths, Rhinoceros 3D and Grasshopper. This phase concluded with identifying key features for the Ideation phase.

4.3 IDEATION PHASE

During the Ideation phase, the focus was on collecting inspiration from diverse disciplines to unlock creative and innovative solutions. This included researching traditional, artistic, and alternative facade designs, particularly those incorporating similar philosophies, such as applying Additive Manufacturing for multispecies cohabitation. This phase also centred around experimentation in relation to flax fibre and TFP capabilities. It involved exploring existing works on TFP and its capabilities with flax fibres, which helped understand the visual experiences and functionalities achievable with the chosen materials and methods. It was rooted in exploring geometries, bending, and testing their performance to meet functional requirements through paper, textile and computational models. This iterative process led to the final design, presented as a 3D model in Rhino, used to assess dimensions and determine material requirements (Figure 4.).

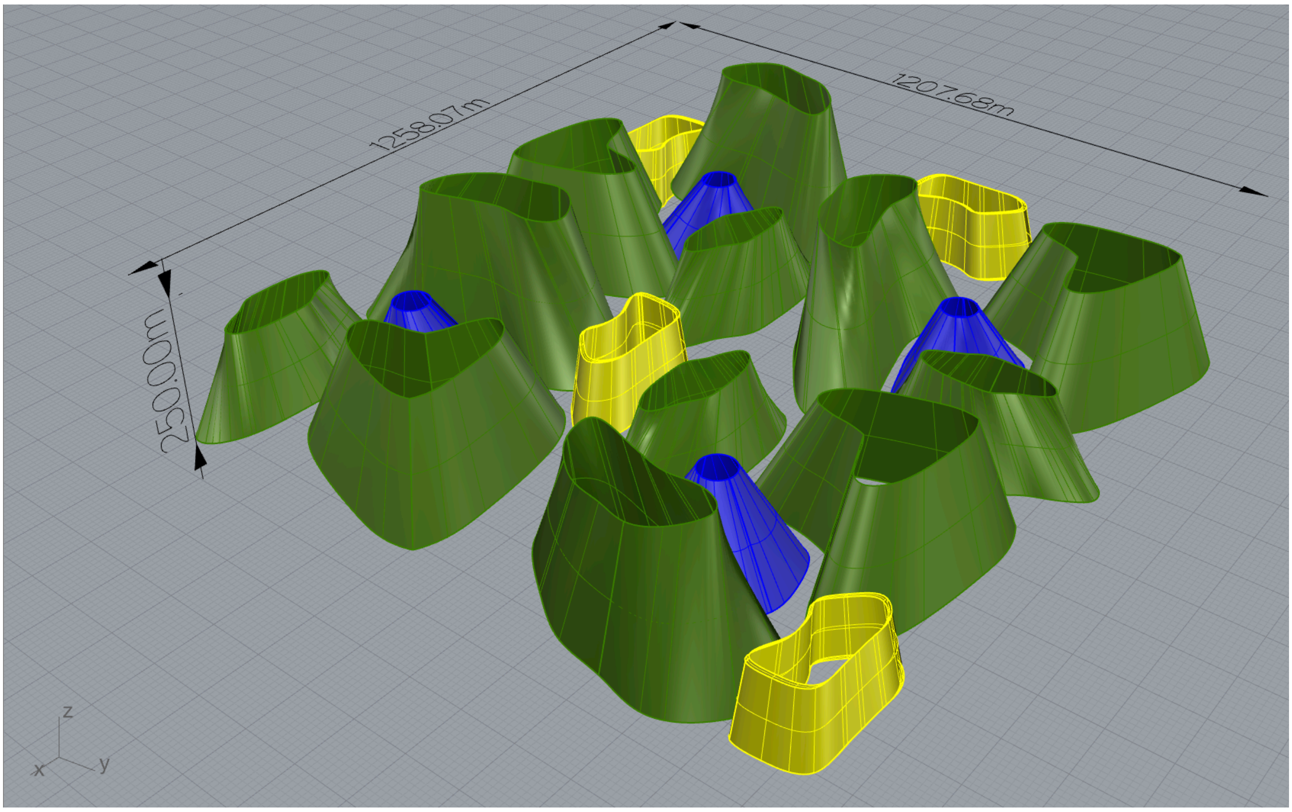


Figure 4. 3D model used to assess dimensions and determine material requirements

4.4 EMBODIMENT PHASE

The Embodiment phase focused on executing the envisioned design of the facade element. This included defining geometry, developing and adjusting TFP patterns, experimenting with dimensions, and adjusting stitching parameters. Geometry definition involved revising the 3D model and adjusting it to fit the design criteria (mainly habitat parameters). TFP pattern development entailed translating the

3D model elements to a 2D grid and punctuating it for bending and connecting areas based on material properties. Additionally, experimentation with dimensions was necessary to create a representative model with the size capabilities of the machine available. Defining stitching parameters focused on achieving tight turns and accurate stitching, allowing for reinforcement where needed. The fabrication of separate pieces was followed by hand assembly to create a representation of the design concept. This culminated in a 1:2 scale model (Figure 5.).

Figure 5. A 1:2 scale model of an element group that includes habitats for insects, birds, and plants.

5. DESIGN

This chapter explains how insects, birds, and plants were chosen as the focus groups for this design. Drawing on research in green infrastructure, biotic communities, and urban building envelope greening, it emphasises the importance of habitat connectivity, trophic relationships, and structural heterogeneity of habitats. The chapter outlines the needs of the target groups, which are translated into design criteria, culminating in structures tailored to each group.

5. 1 GREEN INFRASTRUCTURE

To create a facade that meets the needs of multiple species while also serving human requirements, it is essential to first assess the current situation. Urban spaces often result in habitat fragmentation for biotic communities. Green spaces and green infrastructure are seen as remedies to this fragmentation. Filazzola, Shrestha, MacIvor, and Stanley (2019) identify green infrastructure in cities as providing substrates that support the growth of plants and fungi, act as water sources for aquatic species, and serve as refuges and food resources for pollinators and detritivorous insects. However, Fattorini (2016) examines the population dynamics of biotic communities in urban spaces, viewing green infrastructure as habitat islands separated by inhospitable areas. Key assumptions from this work include: species richness increases with the size of natural habitat fragments, extinction levels decrease with the proximity of green spaces, higher connectivity reduces species isolation, and small green spaces might not support stable populations but can sustain individuals in search of more suitable habitats.

Many studies align with these assumptions, highlighting the role of urban green infrastructure for transitional habitat formation in urban spaces, and connectivity contributing to natural colonisation and reinforcement of populations (Vega & Kuffer, 2021; Filozzola, Shrestha, Macloc, & Stanley, 2019; Ye, Jin,& Yang, 2021; Theodorou et al., 2020; Mayrand, & Clergeau, 2018). Therefore, catering to a wide range of species through general approaches can bring more benefits (Fattorini, 2016). Similarly, Thorpert et al. (2022) specify that green walls designed for greater species diversity can increase urban biodiversity. Filozzola, Shrestha, Macloc, & Stanley (2019) argue that a multi-trophic approach to design can be beneficial for comprehending urban ecosystem dynamics and establishing biodiversity conservation objectives. It is argued that tailoring to support trophic interactions and considering the broader landscape significantly increases effectiveness and benefits.

5.2 INSECTS AND URBANISATION

When aiming to benefit diverse species, trophic relationships and habitat heterogeneity were identified as important factors. Insects are examined in more detail due to their pivotal role in ecosystem integrity, connecting primary producers and consumers, and serving as food sources for higher-level consumers in both aquatic and terrestrial environments. Diverse insect species offer valuable ecosystem services essential for human well-being, including pollination of crops, biological control of pests, and macro-decomposition, which plays critical roles in nutrient cycling, soil formation, and water purification (Wagner, Grames, Forister, Berenbaum,& Stopak, 2021).

The significance of insects in urban environments is pronounced and their behaviour varies. Buenrosto and Hufbauer (2022) found species-specific associations with urban habitats, indicating that species adaptation and nesting preferences differ. González-Césped et al., (2021) found that insects responded differently to environmental and landscape variables depending on spatial scale and varying between orders and functional groups. Their analysis found that vegetation characteristics became markedly important at smaller scales, linked to the environmental quality of green areas. Furthermore, it is marked that several species (including plants, vertebrates, and invertebrates) can persist in small to medium-sized urban green spaces, however, responses to urbanization vary significantly among groups, with insects forming a particularly heterogeneous group. For instance, parasitoids, predators, and phytophages respond to smaller scales, while pollinators and saproxylic species respond to larger scales. Additionally, urban area and temperature negatively correlate with total diversity, while vegetation quality variables positively correlate. In line with this, Villarroya-Villalba et al. (2021) emphasise the importance of vegetation heterogeneity highlighting vegetation characteristics and quality in small connecting patches. Additionally, nocturnal habitats, often neglected in urban habitat management, are outlined as a main ecological niche in cities.

Artificial habitat provision can create transient spaces for diverse species creating spaces of rest and connectivity. It can support taxonomically and functionally diverse insect communities even in highly urbanised areas, with material and cavity diversity being key drivers of colonization. Drapeau Picard, Mlynarek, Boislard, Normandin, & Saint-Germain, (2023) note that while making artificial habitat spaces attractive for wild insect species is not well understood, these spaces can play complementary ecological roles. Additionally, it is pointed out that insect nesting boxes, often marketed for pollinators, are also used by predators and parasites, diversifying trophic interactions.

The quality of artificial habitat and space creation is often more critical than its extent. Functional connectivity for foraging, mating, resting, and nesting opportunities must align with essential resource requirements, intrinsic traits, and population dynamics while limiting adverse drivers such as pollution

(Samways et al., 2020). This aligns with the goal of habitat management for insects: to increase pollinator and beneficial arthropod visitation, thereby enhancing pollination, and biological control, and ultimately contributing to increased biodiversity within an area. Habitat management offers insects overwintering or nesting sites, alternative hosts, and pollen and nectar resources (Harris, Poole, Braman, & Pennisi, 2021). Green infrastructure increasingly provides space in urban areas, but the challenge lies in the design and management of these features (Samways et al., 2020).

Assessing habitat systems is crucial for targeting species' comfort and increasing visitation. Assessment can be carried out by targeting factors such as ecological niches, facade orientation, building environment (soil, water, plant proximity, air quality), and climatic conditions (temperature, humidity, wind speed, and pollution levels), which can all be simulated and evaluated. Meier, Raps, & Listen (2019) emphasise the need for the building of physical investigations of comfort needs for different species in habitat systems through integrated habitat studies, field studies and controlled simulated studies to investigate the comfort needs of different species.

Ultimately, the quality of habitat creation and provision for transient spaces that create connectivity depend largely on local patch characteristics. Material and cavity diversity, microclimatic conditions such as temperature, vegetation quality and variability are seen as considerations driving colonisation rates of green spaces by insects. These aspects are considered in the articulation of the design by incorporating spaces for insect nesting, bird nesting and plant species to create attractive characteristics.

5.3 DESIGN CRITERIA

This section presents the research foundation for establishing design criteria for each group (insects, birds, plants) and their dedicated living wall elements. It outlines the specific parameters and key features of each element, ensuring a comprehensive understanding of their importance and functionality.

5.3.1 INSECTS

To identify the essential elements for insect nesting, a review of resources, including scientific papers, iNaturalist, online articles, and multispecies design projects, was conducted. This review led to an outline of nesting behaviours, followed by innovative and artistic renditions of insect nesting spaces. This research provided both evidence-based insights and creative inspiration for the dedicated elements.

Sane, Ramaswamy, & Raja (2020) investigate insect architecture, structural diversity and behavioural principles to inform design and architecture. Insect-building behaviours are discussed in terms of materials and geometries, noting that materials used for nest building are typically gathered from the surroundings or secreted by the organisms themselves. Examples include honey bees secreting wax, wasps using wood fibres to create paper with saliva, and various insects producing silken threads. This diversity in material use and construction methods suggests that catering to all needs is impractical. Therefore, the aim is to target general needs based on groups of organisms, similar to conventional insect hotels, to facilitate access for many species. Excavators, cavity nesters, burrowers, spit and cocoon type insects, allied species, solitary nest builders pollinator species, social pollinators and communal nest builders are identified as the main nesting types to be considered. Based on these essential needs are outlined to find commonalities and define the design criteria. Table 1. systematically summarises these findings.

INSECT NESTING TYPE	MATERIAL USE	DESIGN CRITERIA
Excavators	Wood (rotten/intact) Excavation media Ready-made holes Mud, leaves, dead plant matter and twigs	Ready-made cavities, holes, tunnels Excavation media Material availability Proximity to plants
Cavity nesters	Wood (rotten/intact) Burrowing media Ready-made holes Mud, leaves, dead plant matter and twigs	Ready-made cavities, holes, tunnels (opening 4-15mm, depths 80-300mm) Material availability Proximity to plants
Spit and Cacoon type Insects	Mud, leaves, dead plant matter and twigs Detritius material (including animal matter)	Material availability Proximity to bird nesting
Burrowers	Wood (rotten/intact) Burrowing media Ready-made holes Mud, leaves, dead plant matter and twigs	Ready-made cavities, holes, tunnels Excavation media Material availability Proximity to plants
Overwintering Allied Species	Mud, leaves, dead plant matter and twigs Detritius material (including animal matter)	Material availability Proximity to bird nesting
Solitary Nest Builder Pollinator Species	Wood (rotten/intact) Ready-made holes Mud, leaves, dead plant matter and twigs Detritius material (including animal matter)	Ready-made cavities, holes, tunnels Material availability Proximity to plants
Social Pollinators and Communal Nest Builders	Wood (rotten/intact) Fixture post	Material availability Proximity to plants

Table 1. Summary of nesting behaviours and associated needs leading to the definition of design criteria. Excavators, cavity nesters, burrowers, and solitary nest-building pollinator species rely on cavities for resting, nesting, and shelter. These species often use detritus materials such as fallen leaves, mud, or flower petals to line

their tunnels, which are then filled with pollen and honey for optimal nursing conditions. Spit and cocoon spit-type insects use leaves or twigs mixed with spit to create cocoons, while allied species that overwinter in cocoon form hide among branches and detritus materials spun with silk. Social pollinators and communal nest builders use spit, wax, or other bodily materials mixed with wood fibre or detritus to build nests fixed to open support points. Vertebrate nesting sites also support diverse insect communities due to the ecological niches created by birds using varied materials for nest building (Collins, 1907; Harris, Poole, Braman, & Pennisi, 2021; Parker et al., 2023; Drapeau Picard, Mlynarek, Boislard, Normandin, & Saint-Germain, 2023; Westerfelt, Widenfalk, Lindelöw, Gustafsson, & Weslien, 2015; Bovyn, Lordon, Grecco, Leeper, & LaMontagne, 2018; Jaworski, Gryz, Krauze-Gryz, Plewa, Bystrowski, Dobosz, & Horák, 2022).

The main criteria to be integrated for insect elements are ready-made cavities, holes and tunnels; material infill for excavation and burrowing; material availability (mud, leaves, dead plant matter, detritus material); proximity to plants and bird nesting. To incorporate these features, inspiration is drawn from various works. Variability in cavity size and shape can be addressed in multiple ways. For instance, traditional insect hotels use materials such as drilled wood, ceramics, and tiles to cater mainly to pollinators. A different approach is an artwork by Marlene Huissoud, sculptural chairs, that create "seating" for insects in urban gardens, incorporating irregular cavities of varying openings, materials, and colours that attract insects. Similarly, OFL Architecture's open-air wooden pavilion features traditional drilled cavities, catering to insects while exploring human-insect relationships. Similarly, Mexico-based creative studio MaliArts designed a series of three structures, called Refugio, for solitary bees in urban environments. These structures provide shelter, food, and water to different species of solitary bees, fostering a closer relationship between human-centric cities and nature. These works initiate conversations around multispecies design and the importance of insects in urban life through interactive artworks. Despite their instrumental designs, building-scale applications are still scarce and need further exploration.

In response, the Indian School of Design and Innovation in Mumbai offers an eco-friendly alternative to concrete, allowing plants and insects to thrive on building surfaces. These bricks, made from soil, cement, charcoal, and organic luffa fibres, create an irregular interior geometry conducive to plant growth and insect nesting. Other innovative explorations of building-scale incorporation of other organisms include a prototype by British engineering company Buro Happold and American architecture studio CookFox Architects. This terracotta facade system is designed to house small wildlife, insects, birds, and plants. The modular system can be integrated into building facades and features pod attachments for different species. The prototype demonstrates the feasibility of using such modular systems to support biodiversity in urban environments.

The Graduation Design Thesis of Takuimu Samejima titled "The Tower of Insects" explores architecture as an environmental device in an extreme urban context. The project aims to recover marginalized insect populations by reconnecting separated ecosystems. The design incorporates void spaces such as alleyways, narrow spaces between and within buildings, and small balconies to maintain ecological habitats. "The Tower of Insects" adapts to the recovery of urban species, providing habitats through architectural form aiming to envision a new form of nature, reflecting the intersection of extreme urbanization and ecological activity.

By examining these works the elements dedicated to insects mimic natural nesting preferences. These elements create space for diverse infills that support nesting behaviours such as substrate for excavation and burrowing, and supporting building materials such as wood, soil and detritus (fallen leaves, petals, branches). Pollen and living plant sources are also incorporated throughout the structure to create structural heterogeneity and a variety of habitats.

Furthermore, varying-sized connecting cavities and tunnels, ranging between dimensions of 4-8 mm up to 15 mm in diameter and 80-300 mm in depth, are favoured by many species. These features are incorporated through ready-made tunnels similar to the organisation of insect hotels, and alternative options for creating cavities innovatively. Figure 6. Illustrates an infill structure that incorporates irregular cavities and tunnels that can be 3D printed, made from treated fabrics, or generated using other technologies and techniques. Additionally, the textured surfaces and varying topography of the structure provide numerous cavities outside of the dedicated space, further diversifying the possibilities inherent in the design.

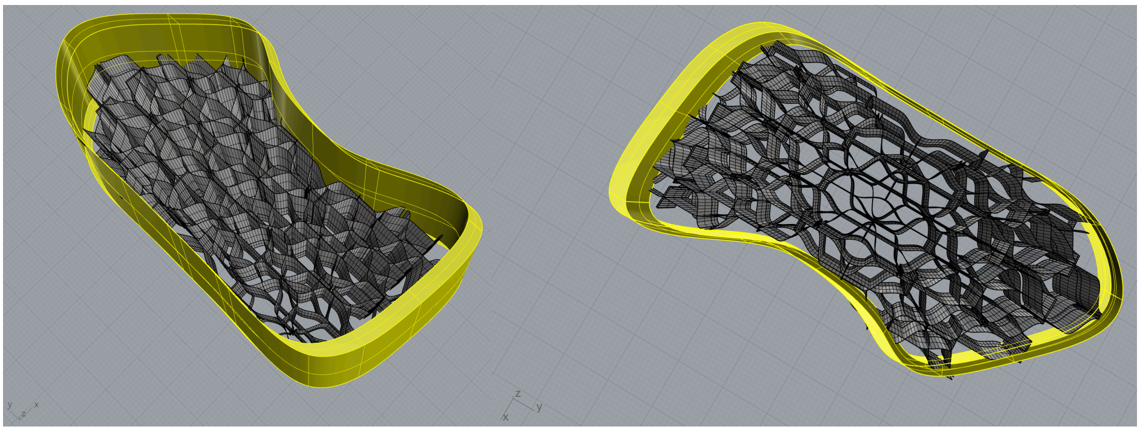


Figure 6. 3D Rhino model of the insect habitat element featuring preformed irregular tunnels and cavities.

Some concerns in connection with insect hotels are also considered. Human-made insect habitats are often in danger of promoting pathogens and parasites due to the sharing of condensed spaces between multiple species (Parker et al., 2023; Harris, Poole, Braman, & Pennisi, 2021). This is mitigated by spreading insect spaces throughout a larger structure and creating separate spaces for different insect needs (Figure 8.).

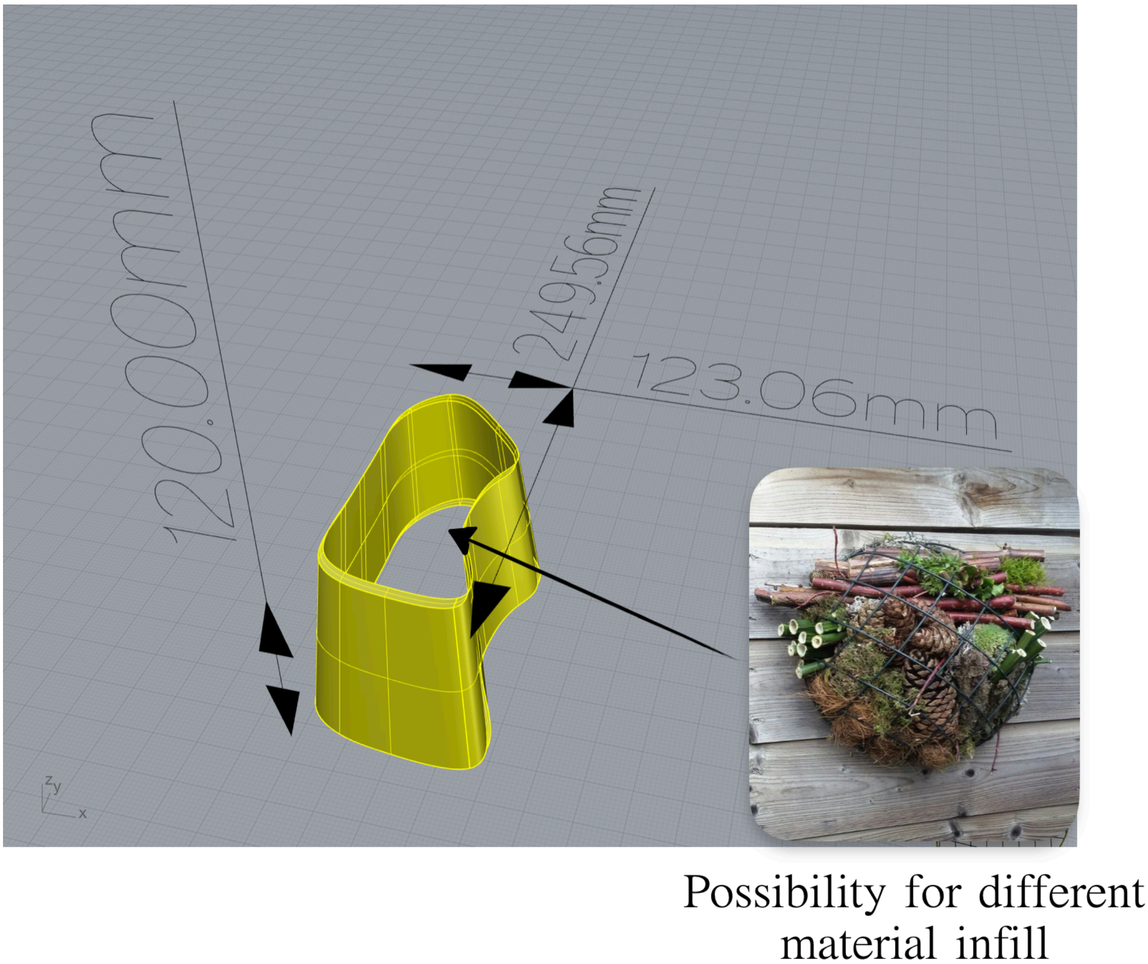


Figure 7. Dimensions and alternative infill materials for the design elements are depicted.

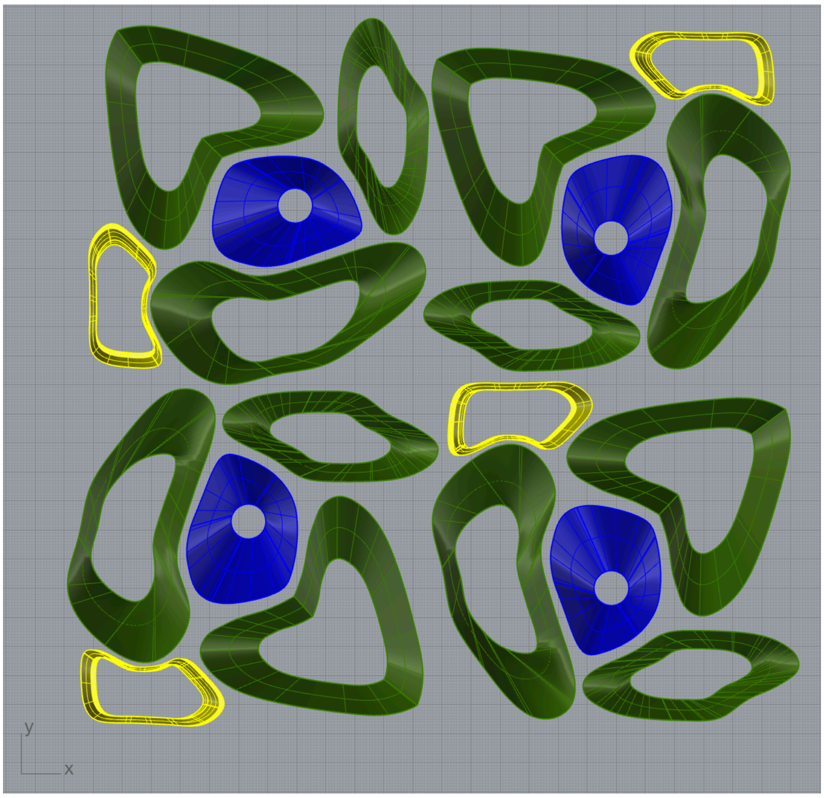


Figure 8. Represents organisation. Elements highlighted in yellow are dedicated to insects. Distance is created to minimise pathogen and parasite invasion.

5.3.2 BIRDS

Bird nesting design draws inspiration from natural habitats, urban adaptations of species, and research on the effectiveness of birdhouses. Urban environments require birds to adapt to novel food, water, and nesting resources while coping with anthropogenic disturbances and diverse stimuli such as vehicles, humans, pets, lights, and noise (Atwell et al., 2012). Birds demonstrate adaptability in urban environments and often develop flexibility in nesting and reproductive behaviour, for instance by using alternative nesting opportunities like building ledges, outdoor lamps, and building crevices (Bressler et al., 2023). Urban species also utilise a wider variety of nesting sites, incorporate anthropogenic materials into their nests, and demonstrate greater flexibility in nesting behaviour (Yeh, Hauber, & Price, 2007; Potvin, Opitz, Townsend, & Knutie, 2021; Wang, Chen, Jiang, & Ding, 2008). Additionally, Ciach, & Fröhlich, (2017) highlight the interseasonal species composition of wintering birds in urban areas and a positive correlation with urban greenery due to increased light (artificial light) and varying food availability.

However, urban environments often suffer from decreased nesting availability due to the removal of old trees, landscaping, and modern building materials and modernisation of buildings (sleek surfaces, steel, glass) (Dulisz, Stawicka, Knozowski, Diserens, & Nowakowski, 2022). Reynolds, Ibáñez-Álamo, Sumasgutner, & Mainwaring, (2019) highlight that, compared to other aspects of avian life, nesting biology is under-explored, particularly in urban contexts. Nest boxes are suggested as tools to address reduced nesting site availability, mostly when located in areas of high food abundance, sheltered from predators and extreme weather conditions to avoid acting as ecological traps (Dulisz, Stawicka, Knozowski, Diserens, & Nowakowski, 2022; Reynolds, Ibáñez-Álamo, Sumasgutner, & Mainwaring, 2019). Reynolds, Ibáñez-Álamo, Sumasgutner, & Mainwaring, (2019) also conclude that to mitigate the scarcity and homogeneity of nesting sites in urban areas, nest boxes, artificial platforms, and native vegetation availability can provide solutions when implemented on large scales.

Endangered species in European cities often exhibit cavity nesting behaviour, utilising building cavities for nesting purposes. This behaviour potentially supports population growth and the establishment of new breeding habitats within urban environments (Jokimäki et al., 2018). Therefore, Schaub et al., (2016) suggest that contemporary building designs should reflect the nesting requirements of cavity-nesting species to promote urban bird conservation efforts (Schaub et al., 2016). Chiquet, Dover, & Mitchell, (2013) found that vertical building surfaces colonised by vegetation provide forage, cover and nesting opportunities for birds and, therefore, can act as tools for promoting conservation efforts. However, the literature indicates both benefits and challenges associated with this, including issues related to predation management, maintenance, interactions between humans and birds, habitat requirements, and broader ecosystem implications (Reynolds, Ibáñez-Álamo, Sumasgutner, & Mainwaring, 2019). To integrate dedicated nesting spaces for birds on facades, the design should consider key characteristics such as microclimatic conditions, construction materials, ventilation, drainage, and predator considerations.

Dulisz et al. (2022) found that different bird species preferred boxes with specific dimensions, highlighting the importance of tailored designs. Additionally, Maziarz, Broughton, & Wesolowski (2017) emphasise the consideration of natural habitat conditions, comparing tree cavities and traditional nest boxes. Tree cavities generally provide cool, well-insulated and humid environments while nest boxes harbor generally drier, less insulated and warmer microclimates. As such, birdhouses that better mimic natural habitats and specifically cater to certain species are a preferred alternative. Additionally, employing these as a temporary intervention rather than a routine practice and opting for the retention of cavity-bearing trees is seen as a more sustainable, cost-effective and less disruptive measure (Maziarz, Broughton, & Wesolowski, 2017). Møller et al. (2014) discovered significant correlations between nest box material, nest floor area and reproductive success, with variations being more pronounced in certain species. This highlights the potential for unintended bias in design. Moreover, factors such as latitude, longitude, altitude, habitat type, level of urbanisation, and inter- and intraspecific interactions were identified as influential in this context (Møller et al., 2014).

Figure 9. intends to summarise the primary requirements of birds, incorporating common nesting habits that serve as aesthetic inspiration, and the dimensions most appealing to cavity-nesting species (Dulisz et al., 2022; Parkes, 2022). The figure also presents the resultant design dimensions derived from these considerations.

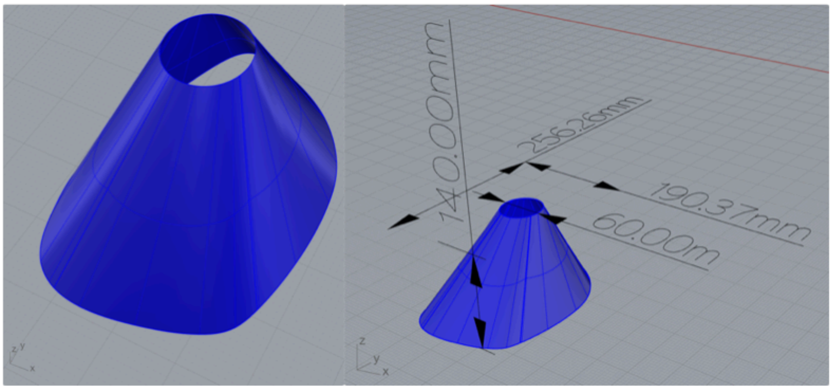
KEY CONSIDERATIONS
FOR NESTING

Microclimatic conditions
Construction material
Ventilation
Drainage
Protection (environment/predator)
Dimensions

NESTING HABITS

Dimensions	Nesting Box Parameters in Woods	Preferred Nesting Box Parameters for Small to Medium Species
Front Height (cm)	9 - 54	10 - 15
Back Height (cm)	14 - 54	10 - 15
Bottom Size (cm)	12x12 - 23x23	15 x 25
Hole Diameter (cm)	2 - 90	2 - 6
Distance from Hole to Bottom (cm)	9 - 27	10 - 12

3D MODEL



OUTCOME

Figure 9. Key considerations for bird nesting spaces encompass microclimatic conditions, construction materials, ventilation and drainage, predator and environmental risks, and nest dimensions. Drawing from the research of Dulisz et al. (2022), the preferred parameters for medium to small-sized bird species are identified for birdhouses. Consequently, the design employs the following specifications for this element: a height of 14 cm, a bottom size of 19 cm x 25 cm, and a hole diameter of 6 cm. These parameters can be adjusted in each design element dedicated to birds to accommodate different preferences.

5.3.3 PLANT

The elements dedicated to vegetation growth were outlined based on the work of Manso and Castro-Gomes (2015), and Tamási, & Dobszay, (2016) researching living wall systems.

Manso and Castro-Gomes (2015) distinguish between green facades and living walls to identify systematise main characteristics, technologies, composition, and construction methods. Living walls are characterised by integrating vegetation more uniformly through continuous or modular elements supporting in situ plant growth. Common system design elements include supporting structures, growing media, vegetation, drainage, and water supply.

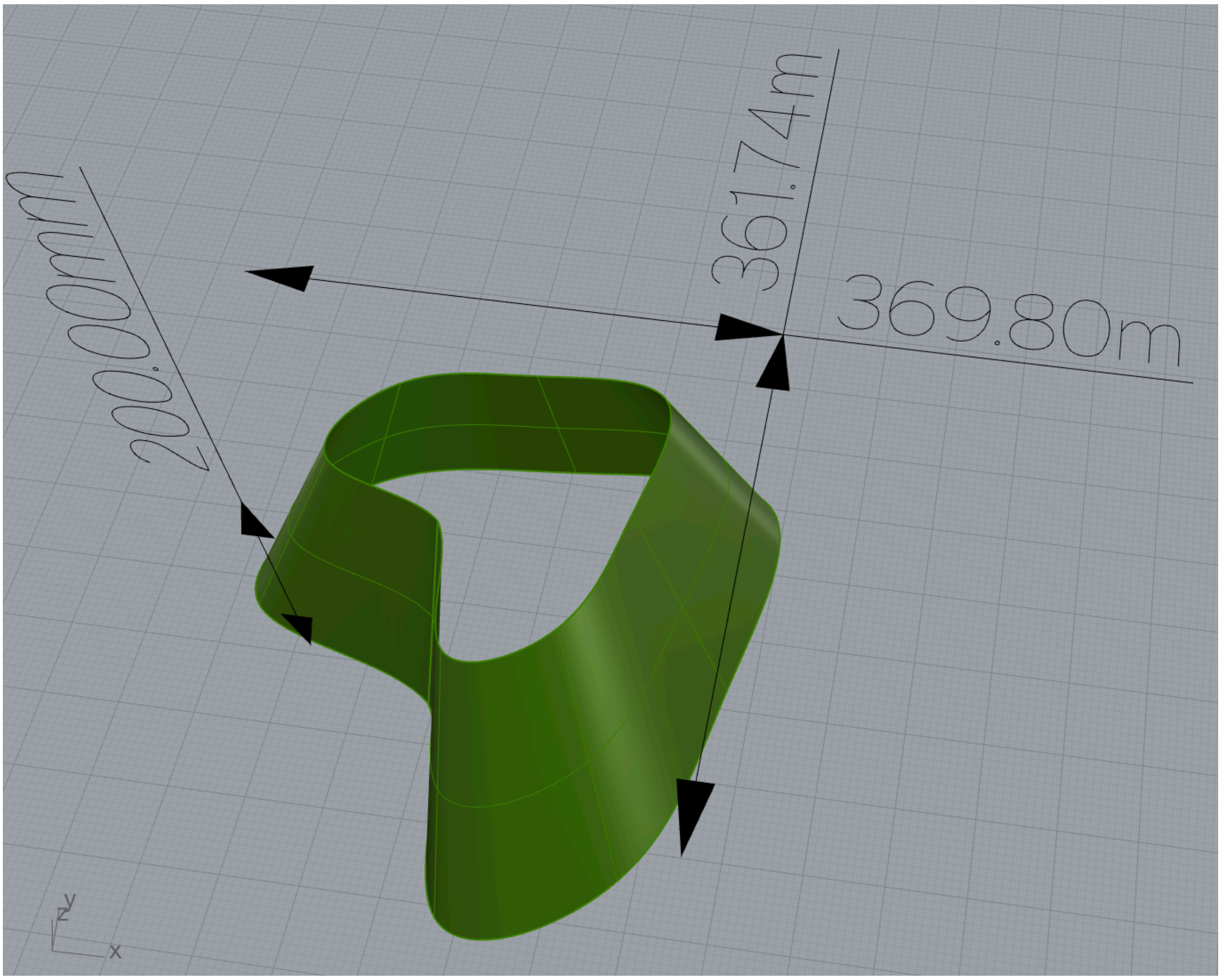
Modular systems, which are the basis for the current design, consist of lightweight materials that support plant weight and allow for the installation of a variety of plants on a surface. Growing media typically comprise a mixture of light substrate and granular materials to optimise water retention capacity. Irrigation needs are met through continuous irrigation tubes at the top of structures that encourage connectivity and build on the percolation of water through modular pieces, or customised systems that adapt output to plant water requirements, with strategies like rainwater recovery, system water recovery and sensor monitoring for optimisation. These systems can also incorporate improved water use and moisture access through the implementation of openings that contribute to better aeration. Considerations like nutrient availability, weather conditions and species-specific needs can further optimise vegetation development and vivacity (Manso, & Castro-Gomes, 2015).

Similarly, Tamási, & Dobszay, (2016) intend to provide a starting point for the design of living walls and identify water, nutrients, and light as the main needs of plants, focusing on soilless systems while acknowledging the benefits of soil in enhancing thermal characteristics and delivering other benefits associated with living walls. They also assess growing medium, planting layer thickness, and foliage density, showing that a mixture of organic and inorganic media with a planting layer thickness of 100-250 mm can achieve foliage density between 10-100 % depending on system type. Modular systems incorporating 100-200 mm organic and inorganic growing substrate combinations can produce between 30-100 % foliage density after installation.

Based on these studies, the design incorporates a modular living wall system with modules of varying sizes to achieve maximum foliage density. Table 2. summarises the parameters considered in this design, while Figure 10. presents the resulting modular pieces with their specific parameters.

BASIC NECCESITIES	INCREASED FOLIAGE DENSITY IN MODULAR SYSTEMS
Structural Integrity	Lightweight construction materials High loadbearing capacity
Growing Media	Mixture of light subtrate and granular materials Thickness of 100-200 mm planting layer thickness
Water Availabiltiy	Mixture of light subtrate and granular materials Irrigation system
Nutrients	Mixture of light subtrate and granular materials Irrigation system
Pollination	Proximity to pollinator organisms

Table 2. Summarises the strategies for meeting the basic needs of plants in living walls to achieve increased foliage density in a modular system (Manso & Castro-Gomes, 2015; Tamási & Dobszay, 2016).



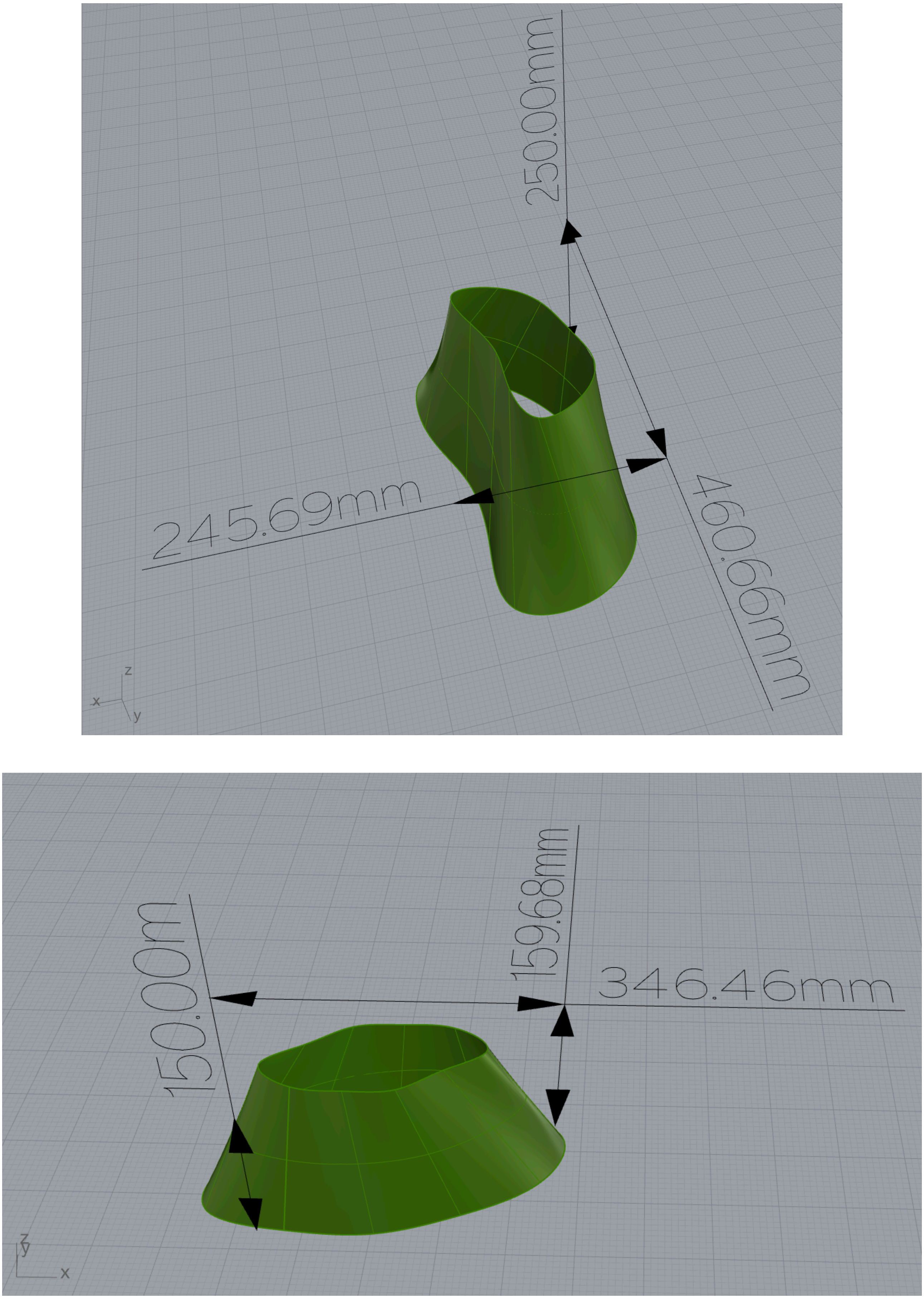


Figure 10. Modular pieces dedicated to plants with dimensions

6. FABRICATION AND RESULTS

This section outlines the fabrication process behind the creation of the 1:2 design model. Beginning with 3D modelling using Rhinoceros 3D and TFP path generation, followed by fine-tuning stitching parameters in EDO paths. Subsequently, machine handling and the fabrication of element components took place. Finally, the element pieces were combined into the 1:2 scale model of one element group that incorporates space for insects, birds and plants. The steps are described in more detail below.

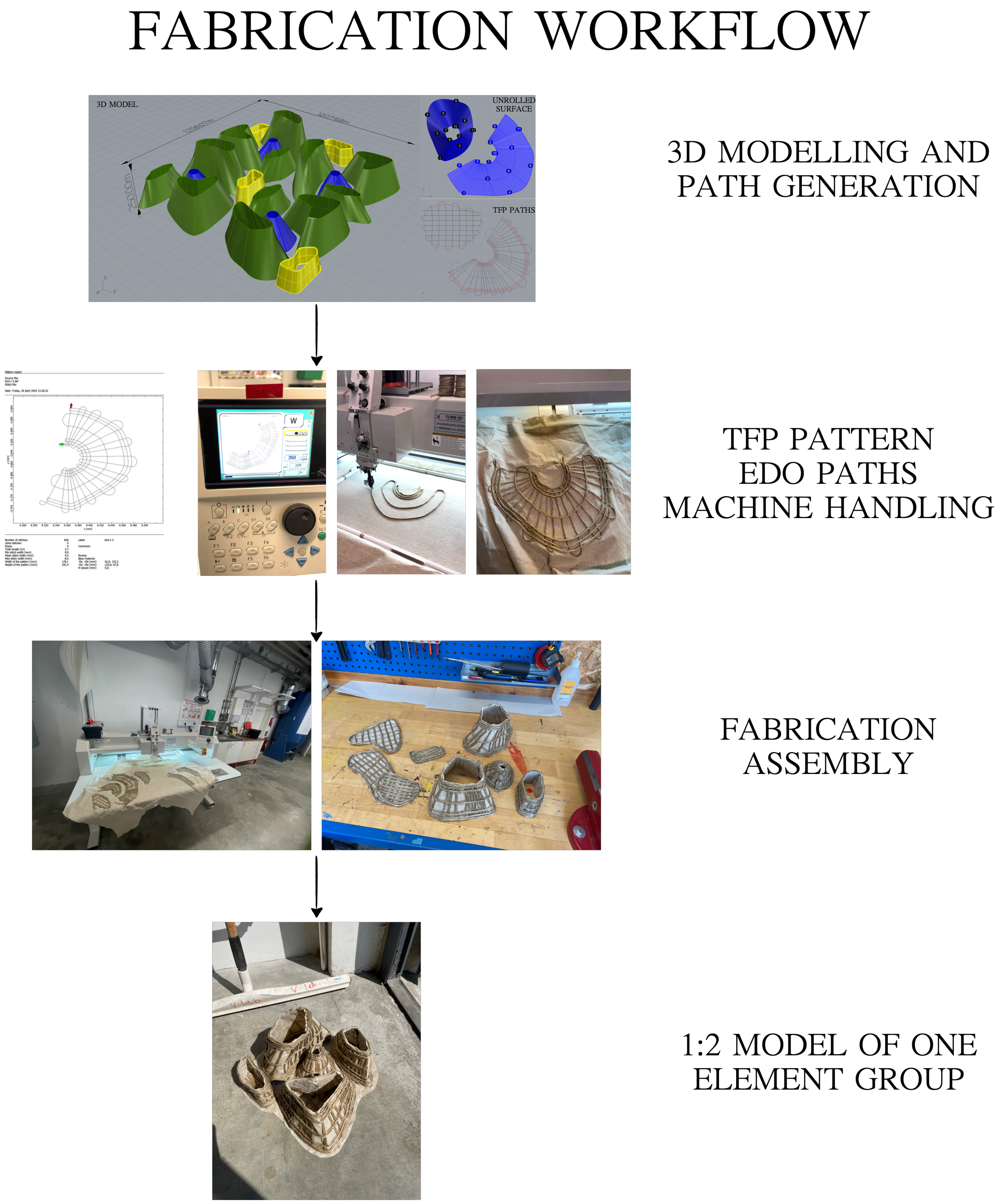


Figure 11. Fabrication Workflow

6.1 3D MODELLING

The 3D model in Figure 12. represents the living wall incorporating habitat elements, showcasing a tile-like design where four units integrate elements for insects (yellow), birds (blue) and plants (green). The design logic allows for easy modification of parameters within the different units to meet more targeted, species-specific habitat needs and create heterogeneity. The units made up of one insect, one bird and three plant elements, are repeated and rotated to create distance between insect elements and a more interesting visual experience. The 3D rendition (Figure 13.) showcases the varying dimensions of the components.

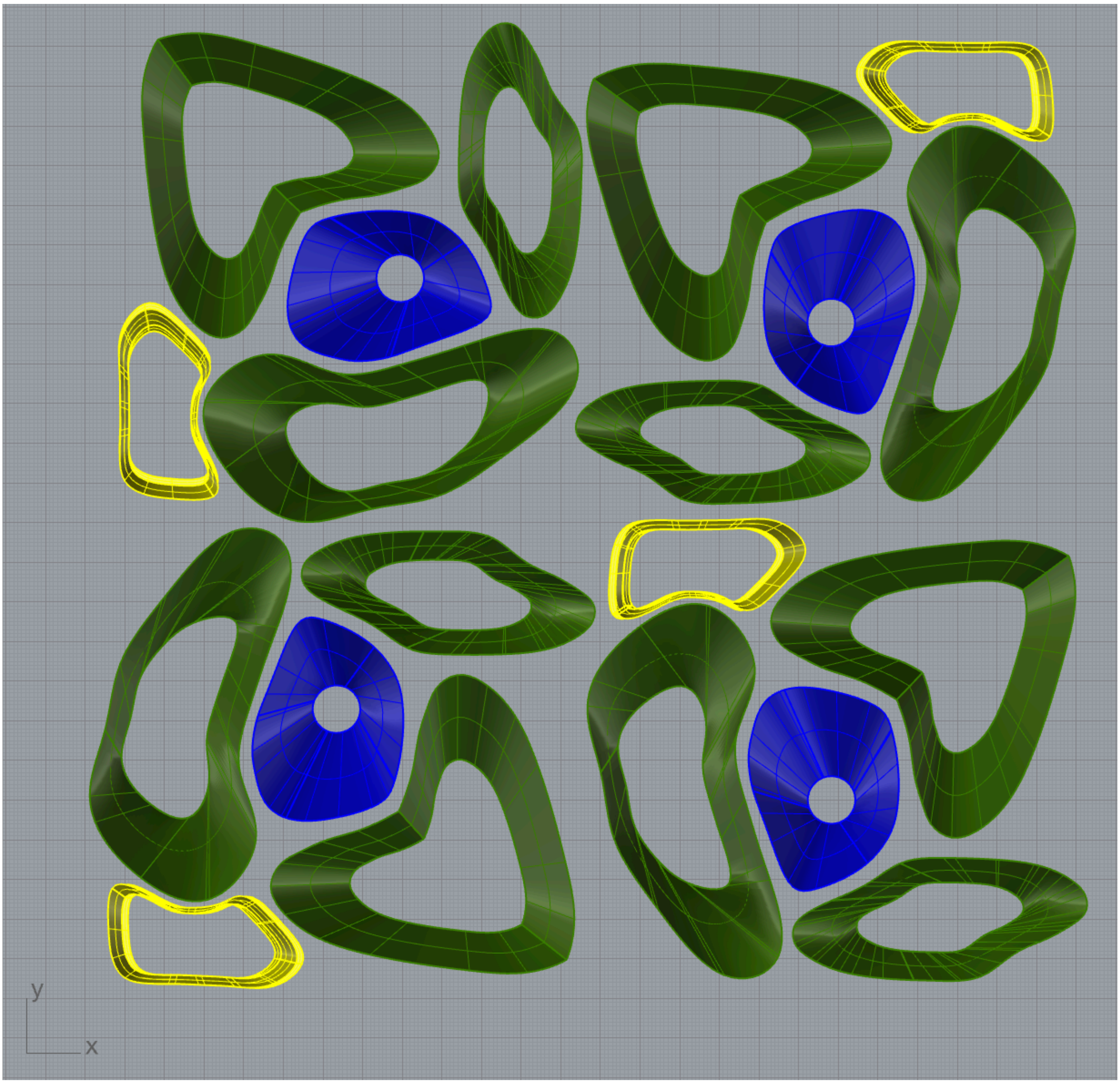


Figure 12. Top view of the model, illustrating the incorporation of identical element groups in various rotated positions. This arrangement is designed to create a distinct aesthetic experience and to introduce structural heterogeneity within the habitat system.

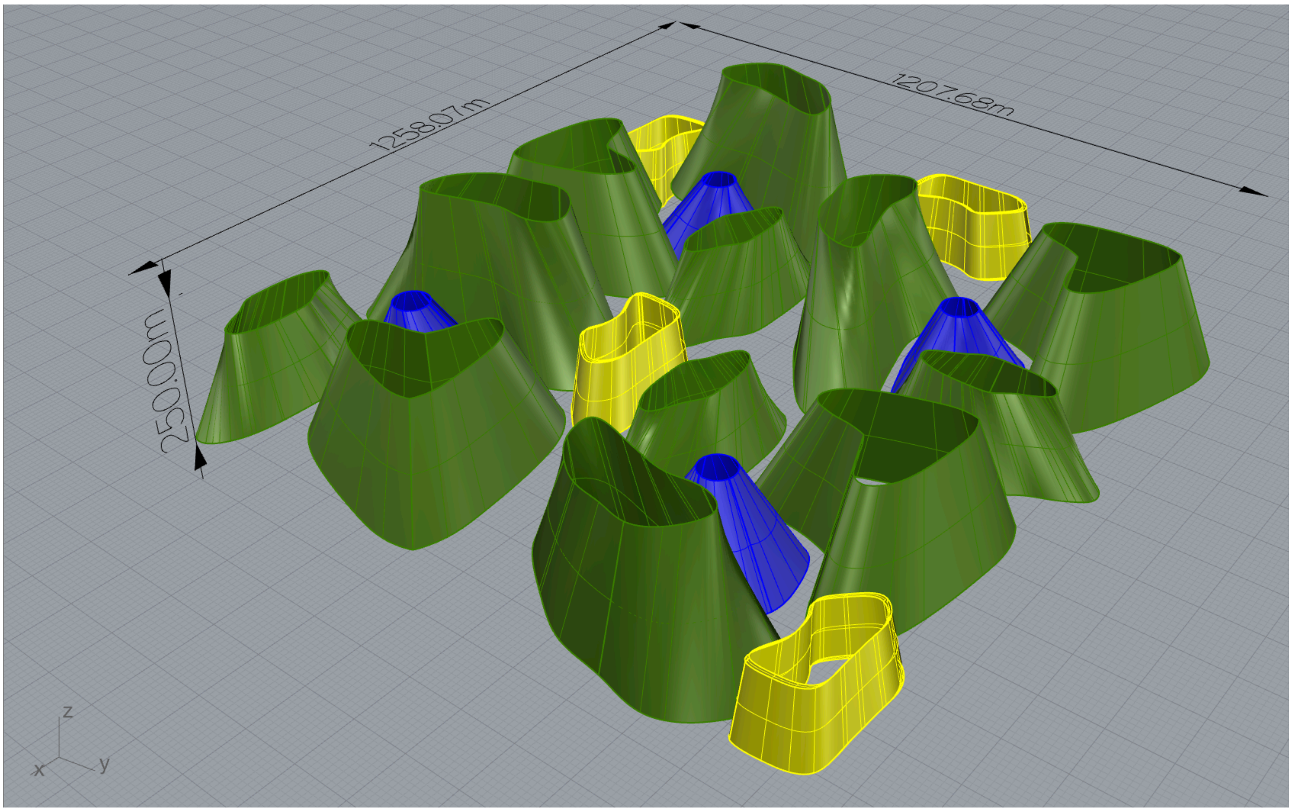


Figure 13. Perspective view of the model, demonstrating variations in height to generate topographical dimensions.

6.2 TFP PATHS

The TFP paths were derived from the 3D model by extracting the wireframe, unrolling the surface, and optimising the layout for areas requiring reinforcement based on stretching, load-bearing needs, robustness, and support. Connection points were also considered, necessitating additional fabric and path spacing. Ensuring a continuous 2D path was crucial to creating the stitching pattern accurately. Figure 14. illustrates this process for each element. It highlights the elements, with the unrolled surfaces in yellow for insects, blue for birds and green for plant elements. The TFP paths for each are also presented with the reinforcement areas

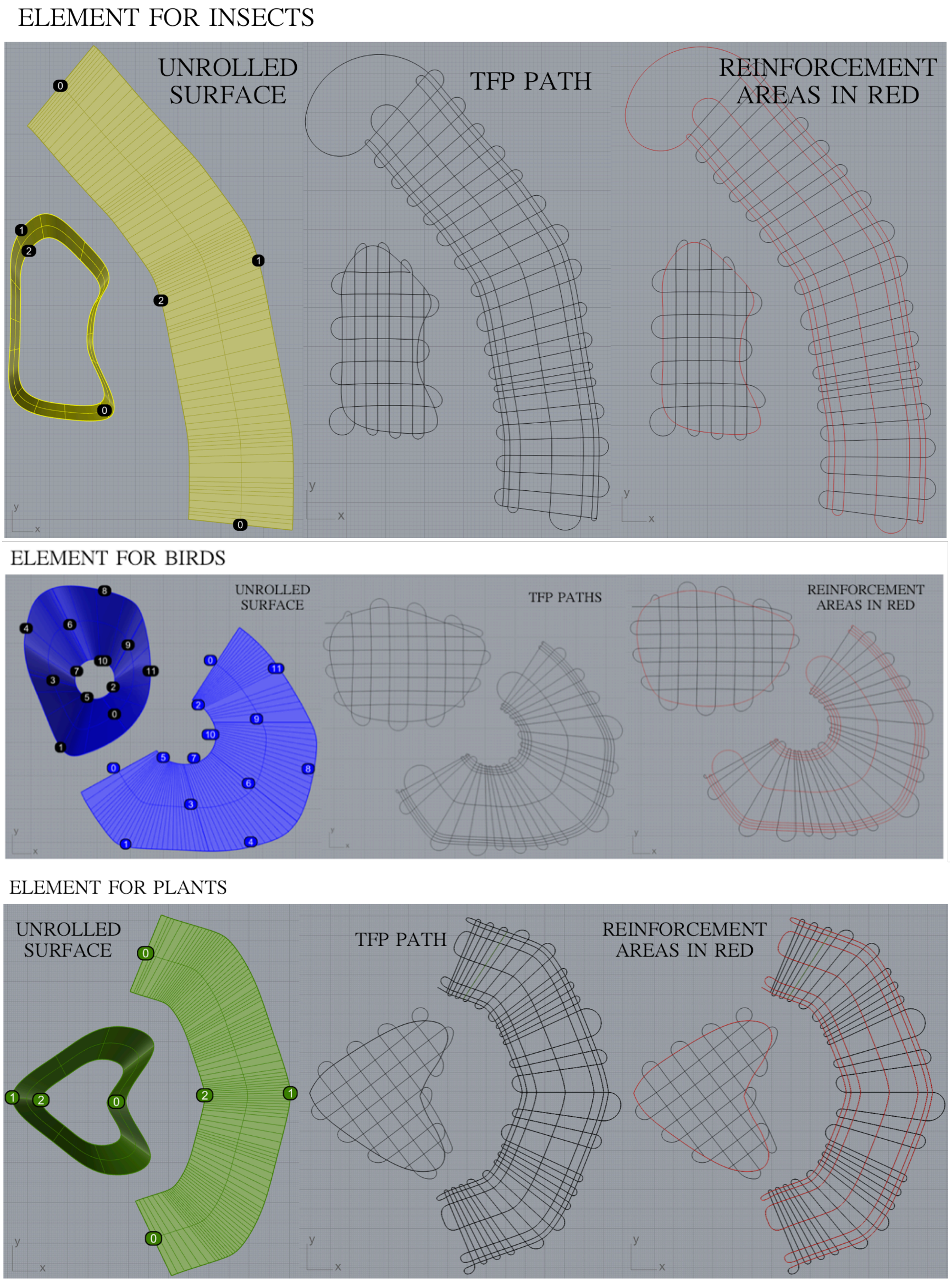
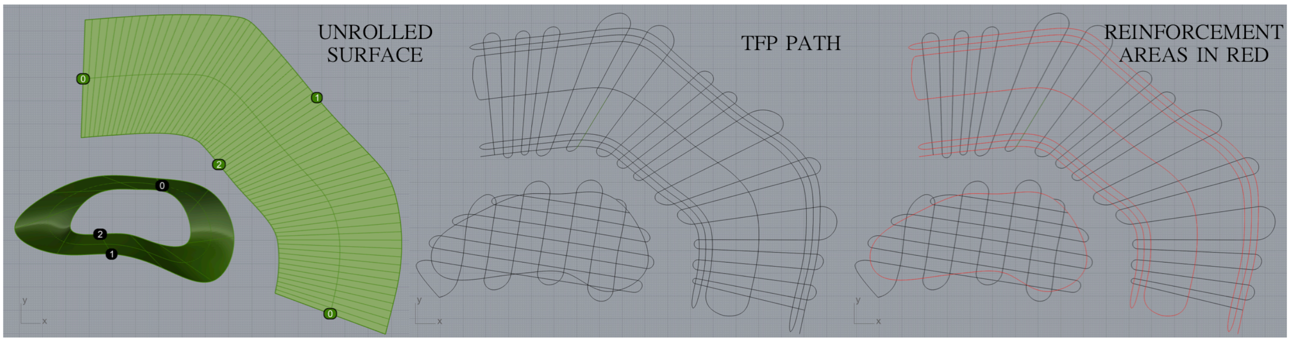


Figure 14. TFP Path generation process for each element

ELEMENT FOR PLANTS



ELEMENT FOR PLANTS

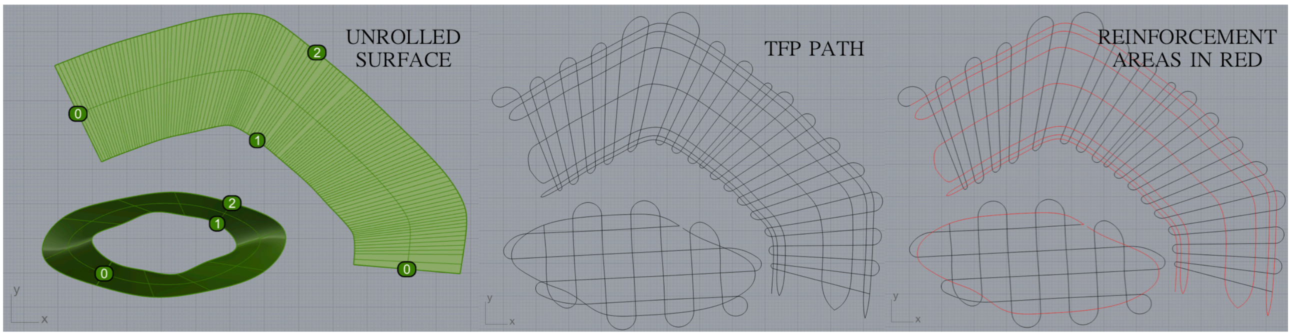


Figure 14. TFP Path generation process for each element

6.3 EDO PATHS

The EDO paths program was employed to generate the stitching pattern and optimise stitching diameters, particularly for tight turns, to minimise error areas, improve stitching precision, and enable precise reinforcement. Reinforcements with higher fibre volume were strategically applied on the horizontal plane, where elevated stress levels are anticipated, in connection and inlet regions. This was accomplished by commencing stitching on the horizontal plane and concluding it on the vertical plane. Such sequencing facilitated the seamless and accurate stitching of a second layer, whereby the pattern was halted before transitioning to the vertical plane in subsequent rounds. Consequently, the establishment of reinforcement zones was achieved without necessitating a distinct pattern input. Figure 15. Showcases the EDO paths document with the specific parameters for each design element.

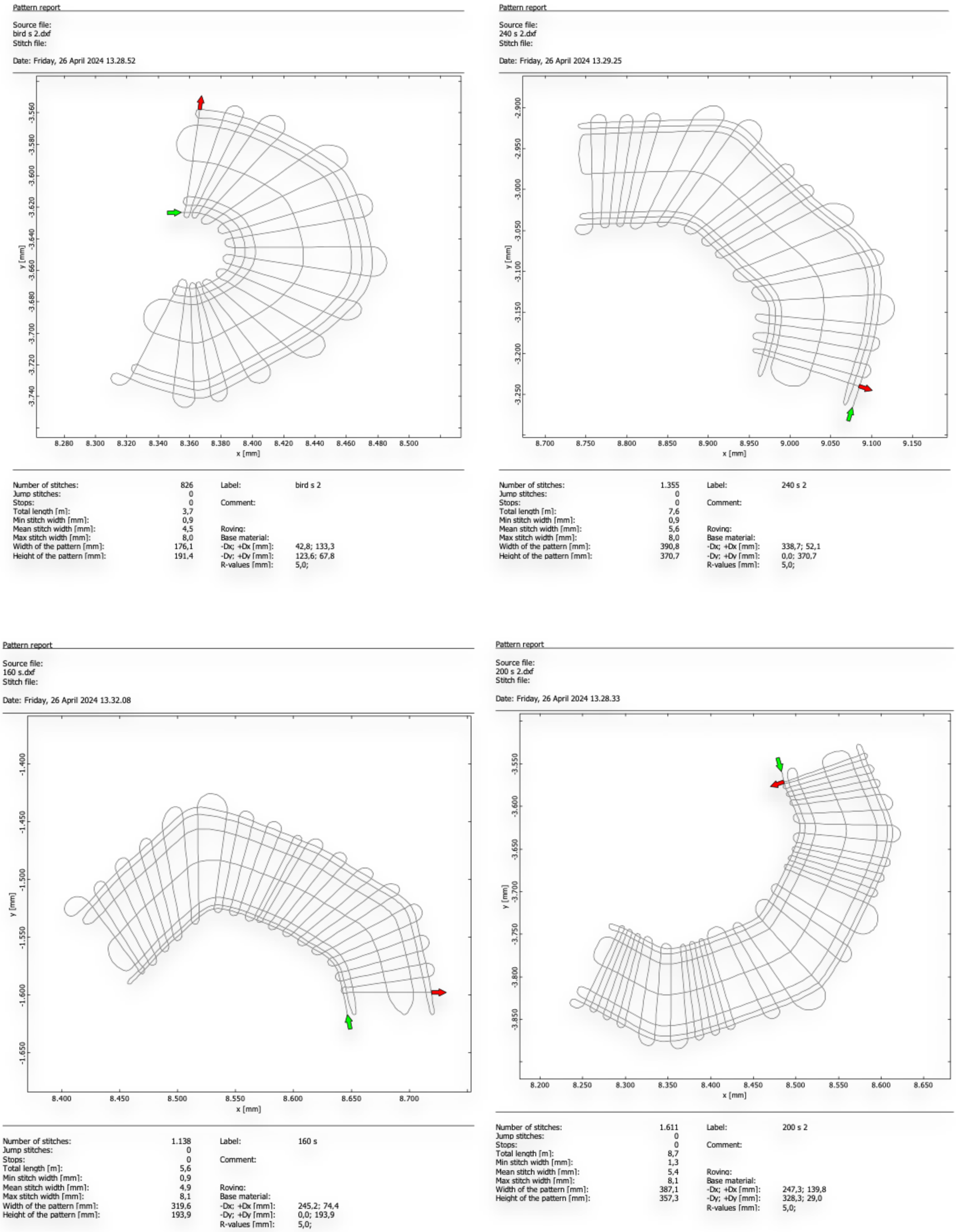


Figure 16. EDO paths, bird element (top-left), plant elements (top-right, bottom-left, bottom-right)

6.4 Assembly

The pieces for insects, birds, and plants were assembled through hand sewing. This assembly process could be further streamlined by combining the bottom and top pieces into a single pattern formation. The resultant 1:2 model (Figure 17.) encapsulates one mosaic piece that integrates elements for birds, insects and plants. The present model accurately showcases the geometries achievable purely through material properties and the fibre organisation. Additionally, it represents the role and value of TFP in the process.

Subsequently, treatment was intended to solidify the shape and enhance fibre matrix performance in terms of resistance to degradation, moisture absorption, and durability in external environments. Resin infusion is often preferred for this purpose for several reasons including adhesion and binding, flexibility, enhanced properties in terms of strength, stiffness and resistance, uniformity and curing control. Resin infusion is accomplished by drawing resin through a stack of dry fabric layers using a vacuum pump, followed by curing either in an oven or at room temperature with subsequent post-curing (Foulds, Carra, & Stokes, 2013). However, due to budgetary and facility constraints, alternative solutions were explored. Clay was identified as a viable alternative due to the mechanical properties it provides. It can create robust and relatively lightweight structures. Additionally, it is often employed in multispecies projects due to its high porosity and surface texture which is often beneficial for habitat creation for insects, plants and mycelium (Parker et al., 2023). Although a viable alternative to resin, clay necessitated facilities for kiln firing. Due to facility and budgetary constraints subsequent clay treatment was not carried out.

Figure 17. 1:2 model of element group incorporating space of insects, birds, and plants.

7. DISCUSSION

This study explores the application of Tailored Fibre Placement (TFP) using flax fibres, for a living facade that incorporates habitat elements for insects, birds and plants. It addresses the dual objectives of multispecies design and examines the applications of TFP in architectural design.

The 1:2 model demonstrates that TFP using flax fibres can effectively create geometries conducive to habitat creation within urban settings on a building level. These findings align with existing research, confirming the value of additive manufacturing technologies in creating structures that cater to the needs of various species by resembling natural habitats in terms of dimensions, materials, aesthetics, and environmental conditions. This work highlights a novel application of TFP for living wall design, leveraging the customisation and adaptability of flax materials through the methodology. The process showcases the technology's ability to consider shapes, sizes, hierarchical structures and material composition, instrumental in achieving geometries that resemble natural features. Additionally, the flexibility to modify composite components allows for moldless fabrication and shape-forming through material properties, creating a unified framework that can be customised for localised and species-specific targets. This customisation potential indicates the high adaptability of TFP for effectively mimicking natural habitats for building envelope applications.

Parker et al. (2022) demonstrate the value of computational approaches in addressing the limitations in designing, manufacturing, and deploying artificial cavities for wildlife habitats. By assessing and mapping natural habitats and their features, analysing the habitats of targeted species can improve the customisation of elements in the current design, potentially increasing their attractiveness to animals. Incorporating considerations such as human-nature interactions, co-design through dialogue, experimentation, and behavioural and methodological changes could transform the design into an open-ended process. This approach would serve as a means of communication, exploring and redefining relationships between humans, other species, and the environment, thereby creating an evolving system that fosters connectivity and complexity (Gatto & McCardle, 2019).

The design also emphasises the architectural potential of building envelopes for habitat creation, addressing the needs of various species and challenging anthropocentric perspectives. It supports a shift towards design paradigms such as multispecies and more-than-human design. The design concept follows an evidence-based process and workflow, adhering to multispecies design tendencies by considering human-nature relationships, embracing technical modifications to physical infrastructure that benefit other species, and encouraging broader societal narrative transformations. It aims to generate habitat continuity and encourages people to transform and interact with their surroundings, while also shaping animal experiences and their use of synthetic features in urban environments

(Grobman et al., 2023; McCardle, 2019; Weisser et al., 2023). Additionally, it leverages interdisciplinary insights from urban ecology and population management, aiming to support the natural functions and structures of urban ecosystems. This approach has the potential to shift narratives and encourage interdisciplinary engagement and experimentation.

However, there are challenges in applying multispecies design in architecture. This design concept demonstrates the value of evidence-based approaches but lacks contextualisation through observation, photography, visual diaries, videos, and sound research, which could provide a deeper understanding of how species use, interact with, and are affected by buildings and manmade features (Weisser et al., 2023; Metcalfe, 2015). While the present approach caters to the basic needs of various species, site-specific applications would necessitate these complementary methods to avoid misinterpretation of needs, which could encourage dependency and potentially pose risks (Metcalfe, 2015). Additionally, a gap in understanding behaviours, requirements, and the intricacy of ecosystem dynamics, and a conservation bias towards certain species, is revealed in line with previous research (Grobman et al., 2023). This bias creates difficulties in targeting other species present in urban contexts.

Another goal of multispecies design is to use design as a tool to promote empathy, inclusion, and relationality, rather than enforcing power relationships. Reflecting on the process, the design organises the activity of organisms in a human-centric way, structuring and ordering interactions, which is not characteristic of natural habitats. This limitation stems from the fundamental anthropocentric organisation of the human world and the fact that understanding the complexity and ever-changing nature of ecosystems is challenging (Ljokkoi, 2023).

Altogether, the strength of this design concept lies in integrating innovative fabrication methodology that highlights its potential for architectural elements supporting diverse species. The findings also underscore the need for a better understanding of non-human behaviours and requirements for developing more effective design solutions. Additionally, they highlight the necessity of establishing effective evaluation tools to assess the impact of these features within a broader ecological and urban context.

8. CONCLUSION

This paper demonstrates the application of Tailored Fibre Placement (TFP) using flax fibres for a living facade incorporating habitat elements for insects, birds, and plants, showcasing a novel application of the technology for architectural purposes and mimicking natural habitat conditions. While further development and evaluation are necessary, the research effectively articulates a design concept rooted in ecological research, exploring the value of TFP in this context. The 1:2 model provides a scalable solution for integrating multispecies habitats into facade elements, easily tailored for site and species-specific requirements. This advances knowledge in urban development by providing insights into the use of biobased materials and advanced manufacturing techniques for ecological design. Additionally, The employment of TFP in a multispecies context addresses a gap in the literature that, based on this design concept shows premise.

Future research on the concept should incorporate modelling natural habitats, conducting site observations, and employing co-design methodologies to refine the design. Evaluation and assessment of long-term ecological impacts and practical challenges would further validate its efficiency. Additionally, to create design criteria effectively for multispecies endeavours, future research should focus on detailed studies of the specific needs and behaviours of various organisms in natural and urban settings. Developing more inclusive and comprehensive methodologies, incorporating interdisciplinary collaboration, robust ecological data, and field research, could improve the accuracy and effectiveness of design solutions. Exploring the long-term environmental, social and species-level impacts of these is also important to create a holistic picture. Moreover, investigating other biobased materials and advanced manufacturing techniques could play a crucial role in a paradigm shift. Continued exploration and refinement of these concepts are conducive to the development of more resilient and inclusive cities that support diverse forms of life.

Overall, the research presented in this thesis underscores the potential of integrating multispecies design principles and advanced manufacturing techniques to foster more sustainable and inclusive architectural practices. By exploring the application of Tailored Fibre Placement and biocomposite materials, innovative ways to create living facades that support diverse ecological habitats are highlighted. The findings of this study pave the way for future advancements in urban development, encouraging a paradigm shift towards designs that harmonise human and non-human interactions.

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