TT Professorship Digital Fabrication
Department of Architecture
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Animal-inclusive design for digitally fabricated facades in Munich’s buildings renovation

Master Thesis
Department of Architecture
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Abstract

Motivated by the need to change the situation with biodiversity loss in the cities, the idea of human-animal harmonic co-existence in urban conditions is the central topic of the thesis. To do so, new envelopes with integration of the small animals, namely birds and bats for existing buildings were developed. Work explores the possibilities of new technologies in architecture, such as parametric design tools and digital fabrication, namely, additive manufacturing, in connection to the animal inclusive design. With the creation of the new building envelopes thesis covers topical problems of buildings' renovation and climate change.

To address the problem a case-study project within Munich urban area was developed. On the example of a student dormitories – a building that demands renovation – with the help of parametric tools and based on certain parameters, such as species and human needs, climate parameters, new façades elements were developed. Design of the façade elements is based on the existing ventilated façade system. To produce the elements, additive manufacturing with clay was used. Parametric tools were used to create a climate performative distribution of the elements on the façade and to verify the assumption of climatic performance through simulations. Façade fragment as a final prototype in 1:1 scale was built.

This work presents a new approach to the integration of species into building envelopes, based on theoretical knowledge and simulation. Thesis explores a possibilities of parametric design tools and additive manufacturing with clay in terms of animal inclusive design and provides a solid basis for further research in this area.

Kurzzusammenfassung

Motiviert durch die Notwendigkeit, die Situation des Biodiversitätsverlustes in den Städten zu ändern, ist die Idee einer harmonischen Koexistenz von Menschen und Tieren unter städtischen Bedingungen das zentrale Thema der Arbeit. Dazu wurden neue Gebäudehüllen mit Integration der Kleintiere, wie Vögel und Fledermäuse, für bestehende Gebäude entwickelt. Die Arbeit erforscht die Möglichkeiten neuer Technologien in der Architektur, wie parametrische Entwurfswerkzeuge und digitale Fabrikation, namentlich, additive Fertigung, im Zusammenhang mit dem tierintegrativen Design. Mit der Schaffung der neuen Gebäudehüllen deckt die Arbeit aktuelle Probleme der Gebäuderenovierung und des Klimawandels ab.

Zur Bearbeitung der Problematik wurde ein Fallstudienprojekt im Stadtgebiet von München entwickelt. Am Beispiel eines sanierungsbedürftigen Studentenwohnheims wurden mit Hilfe von parametrischen Werkzeugen und unter Berücksichtigung bestimmter Parameter, wie z.B. Bedürfnisse von Tieren und Menschen, Klimaparameter, neue Fassadenelemente entwickelt. Das Design der Fassadenelemente basiert auf dem bestehenden System der hinterlüfteten Fassade. Für die Herstellung der Elemente wurde die additive Fertigung mit Ton verwendet. Mit Hilfe von parametrischen Werkzeugen wurde eine klimatechnische Verteilung der Elemente auf der Fassade erstellt und die Annahme der Klimaleistung durch Simulationen verifiziert. Es wurde ein Fassadenfragment als endgültiger Demonstrator im 1:1 Maßstab gebaut.

Diese Arbeit stellt einen neuen Ansatz für die Integration von Arten in Gebäudeumgebungen vor, der auf theoretischem Wissen und Simulationen basiert. Die Arbeit untersucht die Möglichkeiten parametrischer Designwerkzeuge und der additiven Fertigung mit Ton im Hinblick auf die Integration von Tieren in das Design und bietet eine solide Grundlage für weitere Forschung in diesem Bereich.

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List of abbreviations

2D – Two Dimensional

3D – Three Dimensional

UHIE – Urban Heat Island Effect

AM – Additive Manufacturing

AAD – Animal-Aided Design

EPW map – Energy Plus Weather map

Glossary

Digital fabrication: A type of manufacturing process where the machine used is controlled by a computer.

Additive manufacturing: Process of producing three dimensional objects by depositing a material layer by layer. Can also be referred to as *3D printing, layered manufacturing, solid freeform fabrication* and others (Gardiner, 2011, p.41).

Animal-aided design: a design which integrates the presence of animals as part of the design (Weisser & Hauck, 2017).

Wildlife inclusive design: proactive design that develops new habitat opportunities for animals in the parts of the cities (Apfelbeck, et al, 2019)

Extrusion: a process of forcing plastic clay through a shaped mouth.

Ventilated facades: a system for the covering of the façade that allows the formation of an air chamber between the external wall of the building and the cladding.

Parametric design: a process based on algorithmic thinking that enables the expression of parameters and rules that, together, define, encode and clarify the relationship between design intent and design response.

Research through design: an approach to conducting scholarly research that employs the methods, practices, and processes of design practice with the intention of generation new knowledge.

Solar radiation: radiant energy emitted by the sun from a nuclear fusion reaction that creates electromagnetic energy

Wind façade pressure: The pressure on a façade structure due to wind. Can also be referred to as *façade pressure*.

1. Introduction

1.1. Motivation

Urbanisation, which displaces native wildlife and replaces it with impermeable surfaces, is one of the most significant contributors to environmental change. Paved areas, lack of greenery, and significant resource consumption (buildings being one of the largest energy consumers) are all factors in cities that have a negative influence on biodiversity (McDonald et al.,2013). Biodiversity is an important component of the ecology, moreover, juxtaposition of living spaces with animals could cause positive psychological effects on humans (Sandifer et al., 2015). Degradation of biodiversity also leads to the domination of species capable of surviving harsh conditions, such as rats, pigeons, cockroaches, etc. – which causes a proportional misbalance of one species in comparison to others, and consequently increases the spread of diseases, which are potentially dangerous for people (Newbold et al., 2018). The way in which cities and humans/animals interact now evokes researchers to create the future city vision, where the whole space is organised according to the needs of not only humans, but all living organisms, and possible interactions are planned (Villarreal et al., 2020) (Fig.1). Nevertheless, the current functions of building envelopes are mostly tailored to apparent human needs (including but not limited to division of space, insulation, and aesthetics) and presented as hostile to nature.

The other problem that most cities now deal with is the ageing of the buildings; many of them no longer satisfy modern ecological, energy-efficiency, and comfort requirements. According to the European Commission report, building renovation rates in the European Union will be doubled by 2030, resulting in 35 million buildings renovated by 2030 and maintained after in order to achieve European Union climate neutrality by 2050. Among others, energy-efficiency, decarbonisation, and life-cycle thinking were named as the most important principles of renovation (European Union, 2020) These fundamentals could be seen as an opportunity to rethink the approach to renovation, shifting towards sustainability and integrating new solutions into existing urban structure, thus improving the conditions in city centres with the minimum intervention. Creating new envelopes for these buildings could be a chance to rethink and redesign the façades towards inclusivity of different species in the envelopes: small animals, birds or insects. Emerging digital technologies could provide a new way to create site-specific solutions and to expand the habitual architectural tools, helping to bring architecture and nature together through the creation of building envelopes that will host nesting aids for selected species. Particularly, this work provides the opportunity for technological innovation in the field of non-standardised façade elements for breeding and protecting animals, by linking the expertise in the fields of architecture, digital fabrication, and terrestrial ecology.

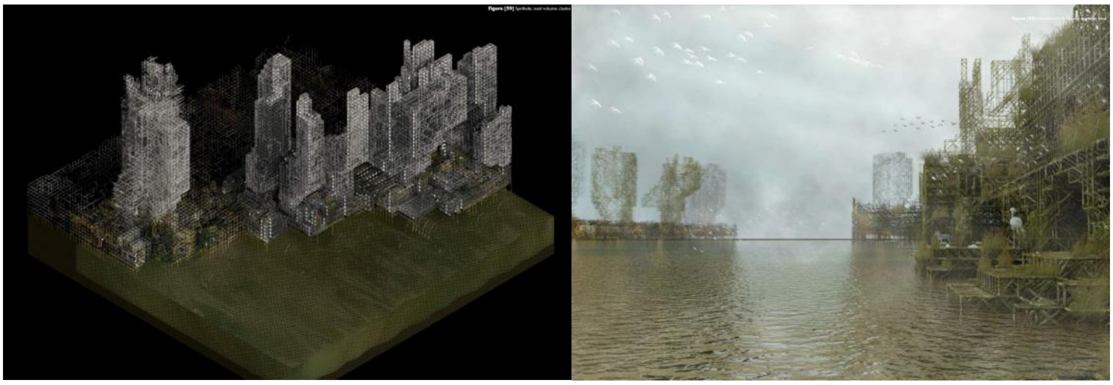


Figure 1: Biocoenosis Nest: A City Woven by Collective Intelligences, Villarreal O.

1.2. Research idea

Since a building renovation process arose in the European Union in recent years, there are already several approaches dealing very effectively, in terms of energy- and cost-efficiency, in providing feasible and rapid solutions. Still, buildings that go beyond energy-efficiency, and include aspects such as life-cycle thinking, integration of renewables, and integration of greenery or species, appear rather rarely and presented by unique objects. A typical façade renovation project consists of adding a new layer of insulation beyond an existing finishing layer of the building, and then to close the insulation with a new finish surface, which is commonly High-Pressure Laminate (HPL) panels or similar technologies. Examples of economically efficient, but aesthetically displeasing and unsustainable, solutions can be found in the centres of European cities (fig.2).

Figure 2: Renovated building in Moscow, Russia – before and after

To change this approach to be more sustainable and qualitative, new design solutions and methods need to be developed. Integration of the greenery is not a new topic in architecture, however, wild-life-inclusive design is not yet widespread, though it has a lot of potential for biodiversity improvement in the cities (the more detailed analysis of animal-inclusive design theory and projects presented in chapter 2, State of the Art). Improvement of microclimates and reduction of heat stress are other aspects to be considered that can contribute both to human and species well-being.
Modern design tools and building technologies help to realise complex solutions and geometries and to create a data driven design, which helps to operate with large amounts of input parameters. Therefore, the idea of the research is to create an animal-human coexistence possible and to bring new architectural and aesthetical qualities to the façade renovation through the creation of façade elements with the help of parametrical design tools and digital fabrication.

1.3. Aims and objectives

The research topic covers a wide spectrum of immediately relevant topics in architecture: sustainable façades with species integrations, microclimates, renovation, and application of digital fabrication, namely, additive manufacturing with clay. In order to address all of the topics in a short term of a master thesis project, focus was on exploring the potential of digital fabrication and computational design as integrative tools for wild-life inclusive design, as well as façades renovation potential as exemplified by chosen case study building to be renovated within the Munich urban area (Fig.3). To address the problem on all scales, the design of one façade element as well as a design of a whole façade pattern and system have been created. The research goals of this thesis are summarised by following objectives:

- To create a vision of harmonic and well-controlled coexistence of humans and animals in the existing urban conditions of the case study project.
- To develop a feasible analytic-based approach for integration of the species needs into design solutions.
- To investigate wild-life inclusive, data-driven design in terms of possibility and feasibility for renovation needs.
- To address a climate change with the improvement of the microclimate and reducing heat stress with a performative façade design.
- To explore the possibilities and limitations of parametric-based design and digital fabrication, namely, extrusion based additive manufacturing with clay, in terms of animal-inclusive design.
- To verify the feasibility of the solution by fabricating a final mock-up.

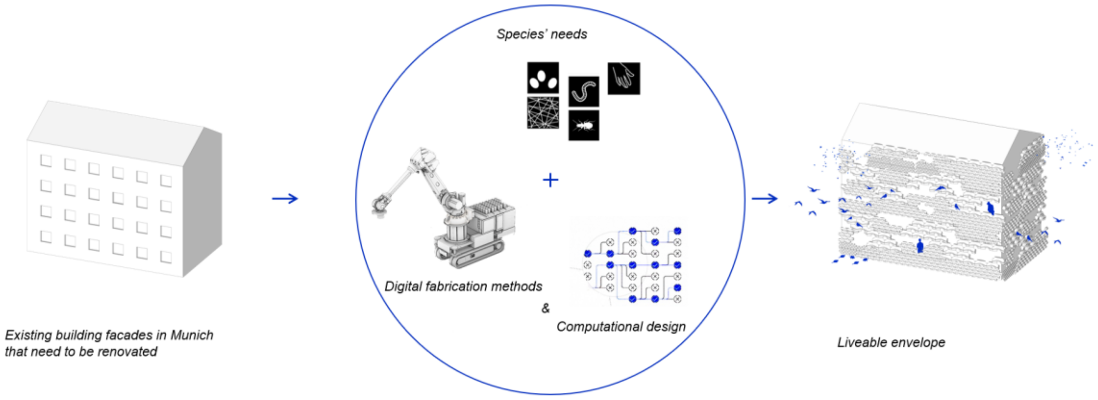


Figure 3: Research objectives

1.4. Methods

Analyses of reference build and unbuild projects that deal with animal-inclusive-design and digital fabrication, together with a literature review are used to contextualise this thesis in State-of-the-Art research and define a design and research approaches that allow basis of design studies on theoretical ground. In order to examine an assumption and verify it through design studies, the decision was made to create a case study design project in an urban context within the Munich city urban area. This method could be named as research through design.

Three species for the region were chosen with the help of a terrestrial ecology specialist – house sparrow, black redstart, and common pipistrelle. Based on research of literature and thematic projects, certain design criteria, such as species and human needs, structural feasibility, and fabrication methods were determined to set boundary conditions for the project. Certain design parameters were developed inside each of criteria and used as a base for parametric design.

A design approach could also be named as retrofitting: the decision was made to conduct design research based on existing façade systems in order to investigate possible application of digitally fabricated pieces within a standard system, ultimately inventing an economically viable solution. Existing ventilated systems for ceramic façades were chosen as a basis for the development of façade elements.

Additive manufacturing allows expansion of an application of well-known materials, for example, such as clay, concrete and plastics, to realise complex geometries and integrate multiple parameters into production, within that creating a new architectural language. Clay, as a biodegradable and reusable material, is attractive both in terms of sustainable architecture and safety for animals and was therefore chosen as a material for design investigations.

Moreover, research and case study design characterised with the work on different scales – from a macro scale (detailed design of a single façade element) to an urban scale (overall façade design).

2. Fundamentals

With the goal of contextualising the project, existing State of the Art projects and research were analysed. They were divided into two thematic chapters: Animal-Inclusive Design and Digital Fabrication.

2.1. Liveable building facades – Animal-aided design

Inhabitable building envelopes are not a new topic in architecture, however, the conscious inclusion of animals and insects as a goal of focus and not only as a side effect has only gained attention in recent years. In the research of Dr. Thomas E. Hauck (University of Kassel) and Prof. Wolfgang W. Weisser (Technical University of Munich), the concept of “Animal-aided design” (AAD) was developed. Their concept focuses on attracting and permanently keeping animals in urban environments. It provides planning strategies and techniques that outline approaches to include nature in urban areas. An especially important point of the animal-aided design strategy is that all parts of the project, such as choice of the target species, landscapes and open spaces design, and architectural solutions are planned as a united system, where all components are aligned with each other and have their own specific functions (Weisser & Hauck, 2017). In that case, building envelopes are not serving as a separate solution of ecological problems but as part of the carefully designed system, providing not only the traditional protection function for people, but also fulfilling species’ requirements, for example, such as integrated bird’s nests (fig.4). One built example is the residential building in Munich, Laim, a project for re-densification and retrofitting that is already applying AAD’s principles in practice (fig.5).

Figure 4: Integration of nests into buildings’ facades, Weisser & Hauck

Figure 5: Integration of nests into buildings' facades, Weisser & Hauck

The interest to build inclusively for wildlife is starting to gain commercial demand. Innovative products such as nesting elements for birds and bats for outdoor use as well as for implementation in building façades are available from the Schwegler company in the German market (fig.6) The design of the elements is kept functional and simple; thus, they can be easily integrated into a standard façade construction.

Figure 6: Nesting build-in elements, https://www.schwegler-natur.de

Another built project is "Sloterdijk Kavel N1 N3" (2017 – under construction) in Amsterdam, the Netherlands, designed by NL Architects + Space Encounters, Studio Donna van Milligen Bielke, and Chris Collaris Architects. The building envelope of this high-rise residential building is designed to provide habitats for vegetation, animals, and bird species. It is treated as rock or cliff that has integrated different types of openings or niches to serve as nests or shelters for animals and insects (Apfelbeck et al., 2020). Therefore, the diverse species easily adopt to their preferred building height based on their individual conditions (fig.7). The building envelope has a standard geometry and construction method, nevertheless integration of the animals' and insects' accommodations was possible without complex architectural. However, conflicts between functions and nature occurred and nature was not a priority in comparison with other requirements such as lightning (Apfelbeck et al., 2020). This proves the importance of an integrative approach from the very early-stage design process where species' needs must also have significant value and design is wisely planned to be on par with other requirements. It also shows that usual architectural solutions are not always successful in integrating all the necessary functions.

Figure 7: Wild-life inclusive facades of Sloterdijk Kavel N1 N3, NL Architects

The conscious selection of target species is an essential part of the wildlife inclusive design approach; socio-cultural, ecological, and design aspects should be examined and considered (Apfelbeck et al., 2019). Without wisely planned selection and control, construction could lead to disservices and potentially cause harm to people and the ecosystem (Dunn, 2010).

2.2. Digital Fabrication

Digital fabrication, in combination with parametric design, allows for expansion of the possibilities of architecture and even to create a new architectural language. Digitally fabricated façades have a lot of potential, such as geometric and material freedom and customisation possibilities, which allow integration of various functions, whereas computational design allows for creation of complex geometries, operation with different design parameters, and to test solutions through diverse simulations. Though digital fabrication on a largescale is not yet common practice, there are several projects that prove the legitimacy of this approach and show the potential for future development and potential applications for animal-inclusive designs.

A project that merges digitally fabricated façades and nature integration is “Cabin of curiosity” from Emerging Objects Studio. The front façade is composed of tiles hosting succulents which are typical plants of given climate, the tiles’ material is clay that is mixed with Portland cement, sawdust, and chardonnay pomace (Rael et al.,2018) (Fig.8). Thus, the façade represents the possibility of recycled materials inclusion into digital fabrication for vegetation-inclusive design. The side façades and roof are composed of ceramic rain screen tiles with a complex geometry (Fig.10). The combination of different types of tiles creates an expressional architectural image and joins several functions, such as creating shadows, rain protection, and accommodating vegetation in one object (Fig.11).

Figure 8: digitally fabricated clay facades with greenery integration of “Cabin of curiosity”, Emerging Objects Studio

The urban cabin summer house in Amsterdam by DUS has a fully 3D-printed building envelope, through which the complex façade geometry was realised (Fig.9).

Figure 9: 3D printed building envelop of urban cabin summer house, DUS Architects

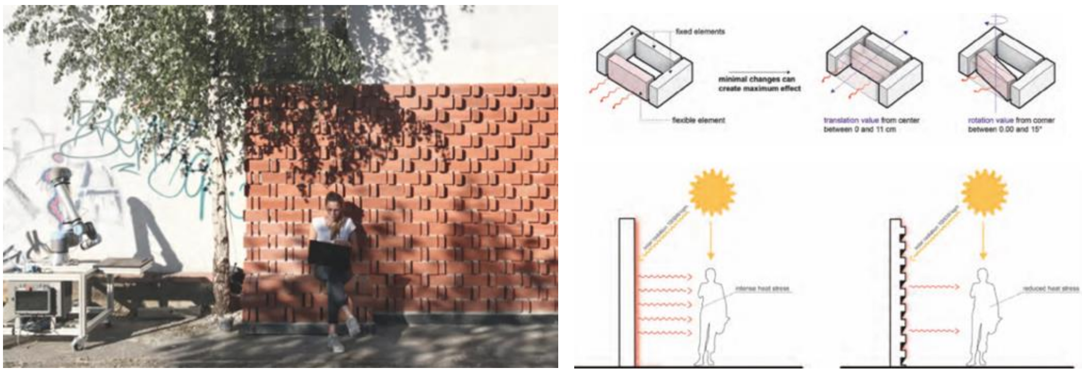


Figure 10: digitally fabricated brick facades, based on climatic simulation studies, Dörfler et al

A different digital fabrication approach was investigated in the “Climate Active Brick” project (Fig.10). The main idea of the project was to re-imagine classic brick rat-trap bond to reduce negative climate impact from the heated façade, exploring the potential of computational design and climatic simulation. The idea of the functions integration into the building envelope was inspired from Alberti's Palazzo Ruccelai in Florence with the integrated continuous stone bench (Dörfler et al., 2020). Thus, to achieve optimal façade shading and create a visual pattern, each brick in a front layer of bond has its' unique rotation angle. Parametric design tools were used for creating the shape and testing different options, such as brick rotations and simulating the environmental conditions, to achieve the best possible climatic solutions and integrate them into the design.

2.3. Building site

While aiming to develop a design solution, it was important to contextualise the project under a certain urban condition. Such criteria as: dense urban area (preferably not far from city center), available greenery in a close proximity, wall/windows ratio, and function of the building were important for the choice of the building site. Munich city was chosen as a city for placement a case-study project (fig.11).

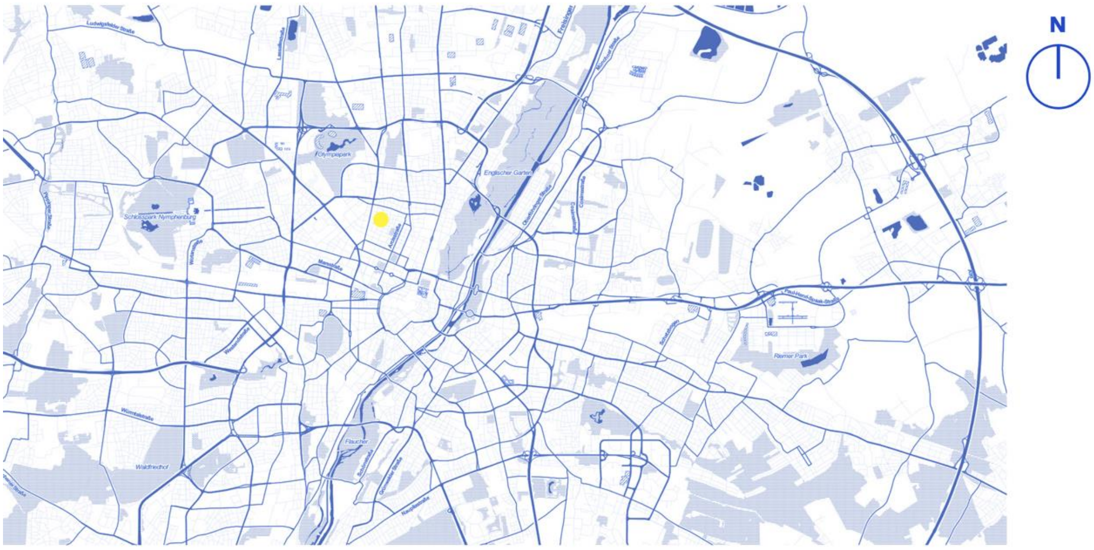


Figure 11: Munich map with a chosen building site spot

Urban area is significant in order to verify the assumption that animal-inclusive design can help to bring more diverse species into the city environment, as well as to improve the conditions within the city boundaries. Greenery near to the building is crucial, as animal inclusive architecture can provide sheltering and nesting facilities and potential food for animals because it is strongly connected with trees/ bushes and various grasses/ flowers. The wall/windows ratio was an important architectural parameter, as one of the main goals of this thesis was the creation of well-organised, which also means in that case well-separated, coexistence of humans and animals. Consequently, the decision was made to avoid placing nests directly under or too close to windows. The function of the building was considered as a social criterion. Therefore, the best choices for a case study to test feasibility of human-animal coexistence could be buildings where people reside temporarily, such as hotels and student dormitories, prior to expansion to residential units where people live permanently. Moreover, the building needed to demand a renovation. An excellent building site was found in the Maxvorstadt area of Munich – a student dormitory, with available east and north façade surfaces and in need of renovation (fig.12).

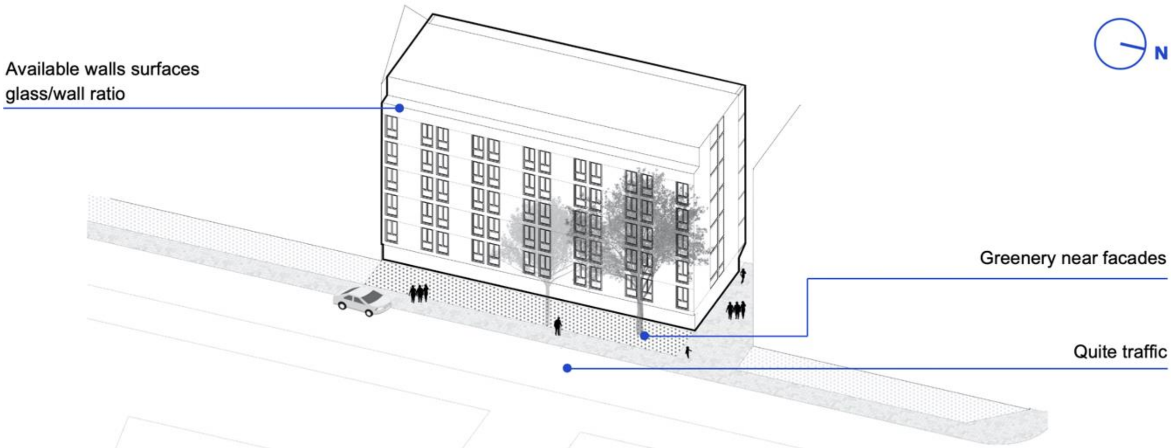


Figure 12: Axonometry of chosen building for a case-study project

3. Design criteria

Intending to base a design on certain parameters, which will influence the final geometry and architectural image, three main design criteria were determined: species and human needs (which also include microclimate improvement and heat stress reduction), façade structure, and fabrication (fig.13). Each criterion has its own set of parameters which were reviewed, analysed and contextualised before being merged and converted to design parameters.

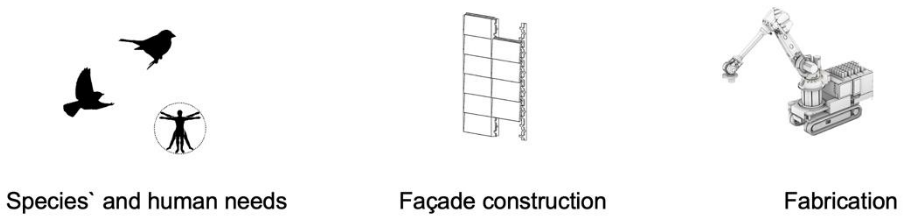


Figure 13: Design criteria

3.1. Species and human needs

To address both species and human needs with the design was an important goal of the case study project. In order to make design parameters clear and precise, main needs were defined (fig. 14) and afterwards carefully analysed.

Figure 14: Species and human needs parameters

As was mentioned, three main species were chosen to develop further design – the house sparrow, black redstart, and common pipistrelle. The analysis of the species' needs was mainly based on literature (based on Weisser & Hauck, 2017; Apfelbeck et al, 2020, Londono, 2007; Droz et al, 2015, Koryakina et al, 2018, Weggler et al, 2006) and experience of the Schwegler company (Papenfoth S. & Papenfoth G.,2014)). It is important to emphasise that most of the parameters should not be seen as a rigid set of rules, but rather as recommendations because not enough research was conducted to collect precise data. The research from University of Florida, for example, found an influence of temperature of nest on an incubation behavior (Londono et al, 2007), though a lot of information remains controversial. On the table 1 overview of species needs, a matrix could be seen, which includes various parameters such as height from the ground, preferable temperature, size of the nest, etc. Basically, all the parameters could be divided into two main groups: geometrical and microclimate.

Specie/ Parameter	Size of the specie	Height from ground	Number of nests	Distance between nests	Building Orientation	Avoid	other
House sparrow	15-17 cm	3-10 m	Colonies with 5 - 10 nests	min. 0,5 m.	West, North, East	Hot temperatures Strong wind	Nests need to be cleaned once in 2-3 years
Black redstart	13-15 cm	1-4 m Or 20-40 m	Prefer to live alone (in couples)		West, North, East	Hot temperatures Strong wind	Nests need to be cleaned once in 2-3 years
Common pipistrelle	3.5 - 5 cm	3-6 m	Groups from 3 to 5 caves near each other	min. 0,6 m.	South	Too cold temperatures Dry Strong wind	Nests could be self-cleaning

Table 1: Species needs matrix, based on literature analysis and experience of Schwegler company.

Geometrical factors such as size of the nest, height from the ground, and if the species prefers to live alone or near the neighbors could be addressed though geometry directly – with the correct position of nest on the façade, correct size of the nest, and correct size of the nest openings. Other factors, such as temperature and protection from the wind could be devoted to the microclimate parameters, which cannot be solved directly by geometry or placement on the façade. However, they could be influenced by creating a design that would reduce the amount of radiation or protect the nest from the wind, reducing the façade pressure.

Human needs could be addressed both from the side of microclimate improvements, namely, reduction of UHIE, and aesthetical qualities of the project.

3.1.1. Geometric parameters

Geometrical parameters could be characterised by certain sizes and shapes of the nests and their openings as well as by placing the nests on the façade within certain heights and distribution logic. On the figure 15 an overview of the geometrical parameters for chosen species could be seen.

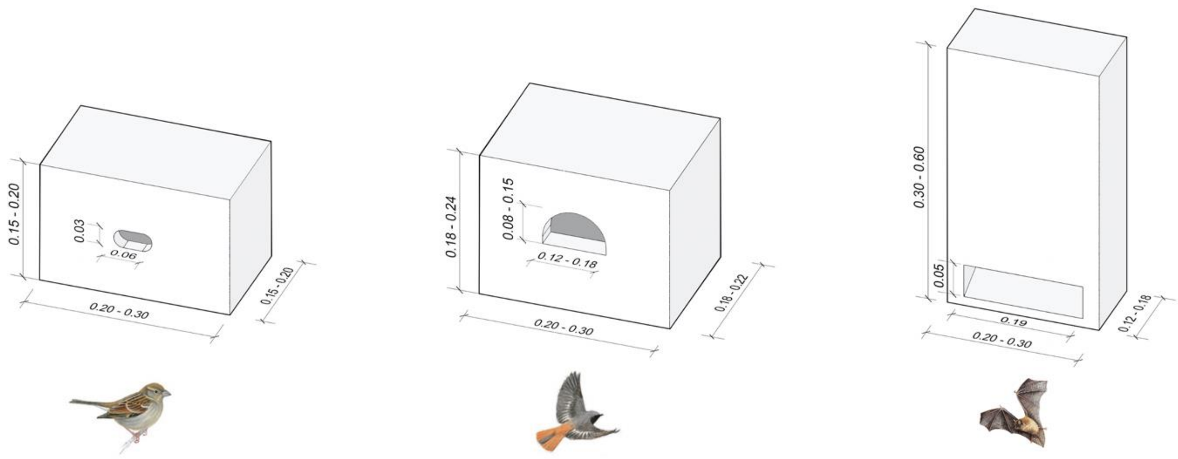


Figure 15: Geometric parameters – nests sizes and openings characters

For the bird species house sparrow and black redstart, the parameters of the nests are similar, the width is 20 to 40 cm, height from 15 to 20 cm for house sparrow and 20 cm for back redstart, and depth is minimum 15 cm for both house sparrow and black redstart. The main difference between the preferences of these two species is the character and size of the nest opening – for the house sparrow it should be no bigger than 5 cm in diameter or have dimensions larger than 4cm by 6cm to avoid seizure of the nests by bigger birds (Weisser &Hauck, 2017). For the black redstart, specifications are opposite – the entrance should be big and balcony-like so that the birds can observe an outside world from the inside, with a minimum width of 10 cm and height of 7 cm. For the common pipistrelle, parameters of the nest are different – the nest should have an oblong shape with a minimum of 40 cm of the height, however, 8-16 cm depth is sufficient. The required width of the height is similar with the birds' requirements – it is 20-35 cm, which makes it possible to unify the sizes of the tiles from the front surface. The preferable opening of the nest for common pipistrelle should also be oblong in shape but horizontally, occupying the whole width of the nest, with the modest height of about 5 cm. Another crucial geometrical parameter is a preferred height of the nest from the ground, which can be seen on the table 1. Inasmuch as different species reside on different heights it makes the distribution of the nests on the façade one of the important parameters of overall façade design. Another parameter that also contributes to the final façade image is the number of the nests that could be placed near to each other (scheme) – the house sparrow prefers to live in colonies of 5 -10 nests with 50 cm in between each nest, whereas black redstarts are more likely to settle alone, and the common pipistrelle in a small group of 3-5 nests.

3.1.2. Microclimate parameters

Although there are few data about preferable temperatures and humidity levels for some species, it is not always possible to find perfect conditions for placing nests and there is no statistic describing species preferences and ranking of importance. The Schwegler company has common recommendations for users, such as to place elements on a certain façade to avoid direct sun/overheating or weathering. The modern analytic tools make the choice process more precise and conscious and serves as a base to create a design that would help adjust given climate conditions. Within that, more suitable possible placements on the façade are gained, which is especially valuable in dense urban conditions when perfect conditions are not presented.

A microclimate is a complex term that depends on many factors such as humidity, climate, outside temperature, wind, etc. The decision was made to define certain parameters that could be influenced by geometry. Therefore, two parameters – amount of radiation and façade pressure were analysed, and their reduction was chosen as a basis for further design development.

Solar radiation. A reduction of solar radiation will not only help improve microclimate conditions for birds but can also serve the goal of reducing overall heat stress and creating more comfortable environments for human, thus, serving as a multipurpose design parameter.

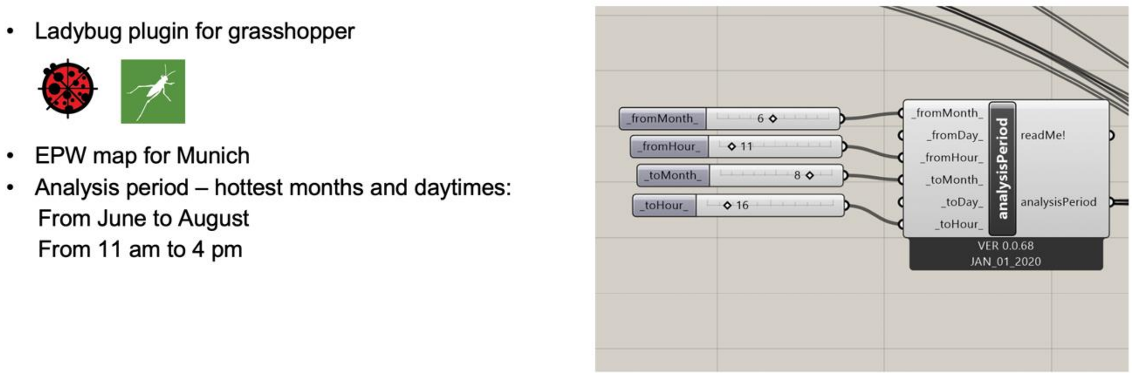


Figure 16: Solar radiation analysis tools and parameters

In order to reduce the solar radiation amount, first, the analysis of existing solar radiation was conducted. With the help of Rhino, Grasshopper, and ladybug plugin, based on the mesh geometries of building and surroundings, and EPW (energy-plus weather) map for Munich, the amount of the solar radiation of the hottest days and times were calculated (fig.16). The result of the analysis can be seen in figure 17.

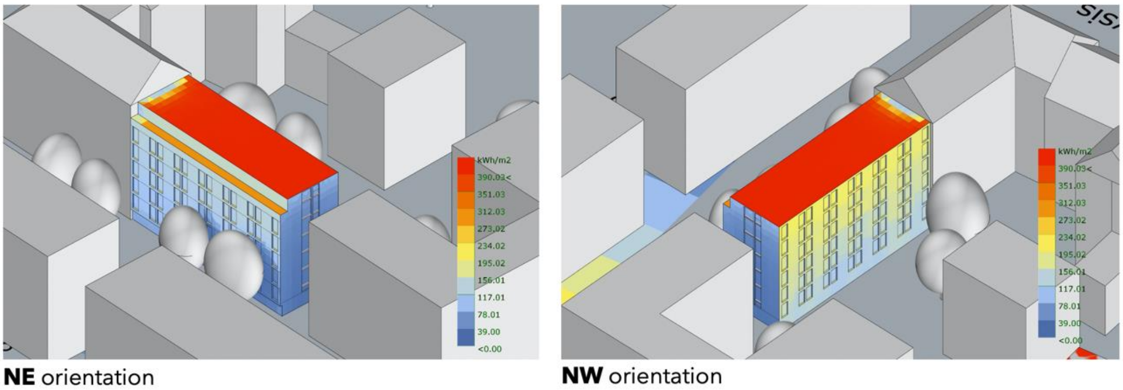


Figure 17: Solar radiation analysis

Wind façade pressure. As weathering is a possible threat for nests, it was decided to reduce wind façade pressure in order to protect the shelters. The analysis of the existing façade pressure was conducted with the help of Rhino, Grasshopper, and Eddy 3D plugin, for two main wind directions – North and West for the annual period. The analysis was based as well on the mesh geometries of building and surroundings, average wind speed, and EPW (energy-plus weather) map for Munich. Figure 18 depicts the results of a wind façade pressure analysis.

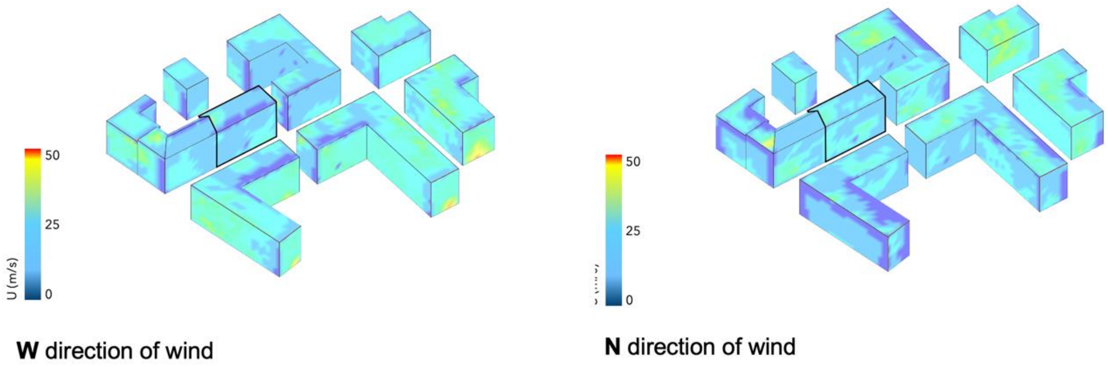


Figure 18: Wind façade pressure analysis

3.2. Façade structure

One of the ideas of the project is to fit the digitally fabricated tiles into an existing façade system in order to make elements easier for mounting and economically feasible. The experience in ceramic façade of TONALITY company was a base for the structural design of the unique elements.

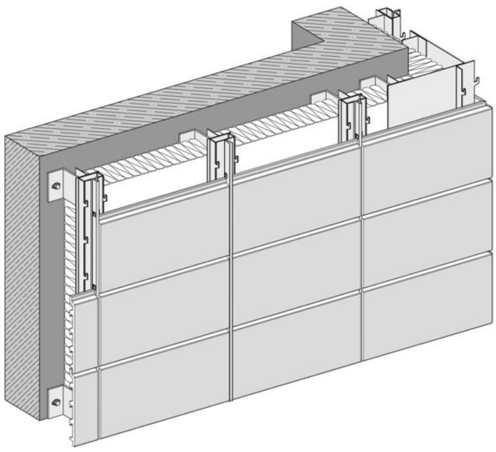


Figure 19: Adaptive ventilated façade system, TONALITY

A ventilated façade system (fig. 19) has an advantage of having additional air space between façade surface and insulation, which in the case of the project, is crucial, as this space has flexible sizes and potential to host a nest part of the tile behind façade surface.

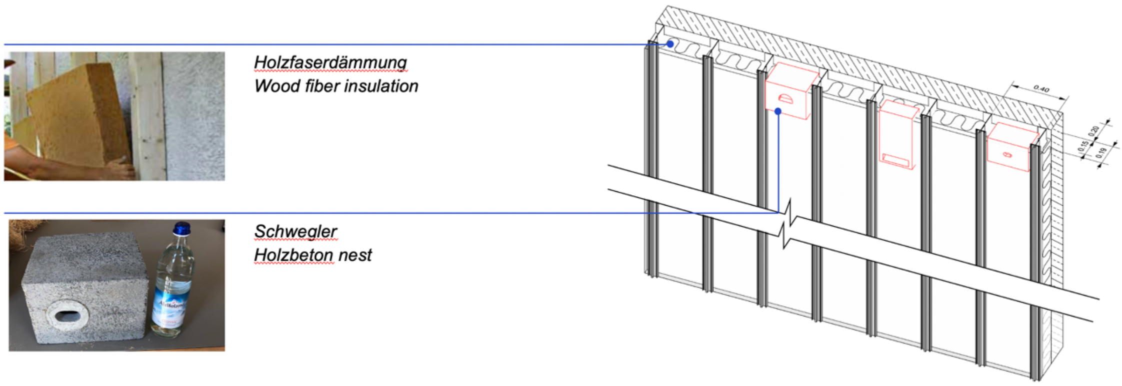


Figure 20: Retro-fitting design principle

The initial scheme of depicting an approach of retrofitting design principle in figure 20, is to fit the nests between the bearing metal elements of the facade structure, to hide them behind façade surface. As additive manufacturing allows for realisation of complex geometry, the front tile and nest will be merged into one to keep mounting and maintaining processes as easy as possible. As a part of the project, TONALITY company consulted for the thesis regarding substructure, firing process of tiles, and provided an adjusted substructure for final demonstrator object.

3.3. Fabrication – printability of the design

3D printing with clay allows for realisation of complex high-resolution geometries which are not possible with standard production processes such as extrusion, however, this method has certain boundary conditions which were important to note when creating the design. Limitations were defined based om literature review, experience of the chair of digital fabrication of Technical University of Munich and personal experience gained during printing tests. Following constraints of additive manufacturing influence design of the tile on par with species needs and fitting into substructure:

Printing continuously in layers. Robot goes continuously from starting point layer by layer creating the geometry, automatic interruptions of robot (for example to create an opening) are not possible, so providing an automatic process without manual interruptions of robot is necessary to plan openings on the upper layers or to add some auxiliary rigid parts.

Stability during printing and drying. Plastic clay mass is used for printing on the flat horizontal surface, so it is important that structure will be self-bearing to maintain the printing and drying processes without collapsing. A significant aspect is that cantilevered angles are confined by 30 degrees.

Soften edges. Extrusion nozzle of the robot is round and can have different diameters (In the possession of the chair of digital fabrication there are nozzles from 4 to 8 mm), this means that even if planned geometry (the path of the robot) has angles, in the reality all angles will be presented with fillets which gives certain visual qualities to the design. Careful planning of the elements is needed in order to fit fabricated tiles into rigid geometry of the metal substructure.

Printing path length. The maximum payload of the robot used is 12kg, therefore cartridges of 10kg were used for printing which corresponds to the path length of maximum 95 meters. The exchange of cartridge in the middle of the printing leads to the undesirable changes of the layer height which becomes obvious and interrupts the clearness of the shape. Hence, it was decided to set the maximum path length of 95 meters as one of the design parameters. It is important to mention, that the correlation between the payload and printing path length was determined only after first printing tests, due to the strong dependence of the printing path on the amount of the water in the clay mixture – the more water in the mixture, the easier and quicker the clay spent.

4. Design studies

4.1. Microscale

The idea of the design of an element is to mix standard flat tiles with climate performative ones (tiles which have geometry that allows for heat stress reduction and façade pressure reduction) and with tiles hosting nests (fig.21).

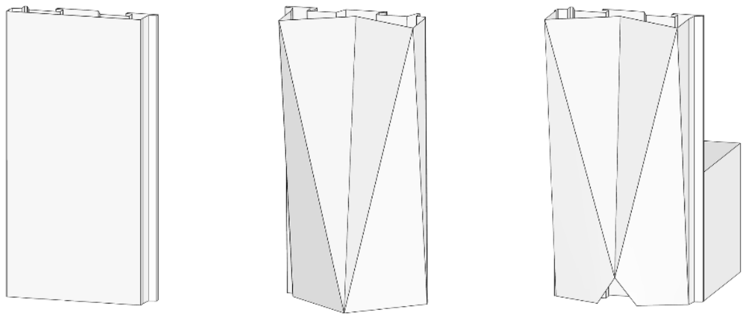


Figure 21: Types of the tiles

The design for 3D printed tiles was based on the shape and dimensions of a standard rectangular tile 20*40cm, since these dimensions could allow host nests for all three chosen species. However, after the first 3D simulations it was clear that because of the printing path length parameter, which was mentioned in the previous section, the feasible sizes for the final mock-up would be 20*35 cm, for the design schemes and façade design. However, the dimensions of 20*40 cm were used, in order to demonstrate multifunctionality of design.

The goal of the design was to keep the geometry clear and simple to gain maximum performance for the chosen parameters. The front surface of the tile was designed in order to meet individual species needs and printability design criteria. To reduce solar radiation and wind façade pressure, the climate performative tiles façade surface consists of bumps which create a self-shading effect and reduce the wind pressure. Vertical direction of bumps was chosen according to results provided in the work “Shape morphing wind-responsive facade systems realized with smart materials” (Lignarolo et al. 2019) that proved with simulations vertical texture of the façade is most efficient in terms of wind façade pressure reduction.

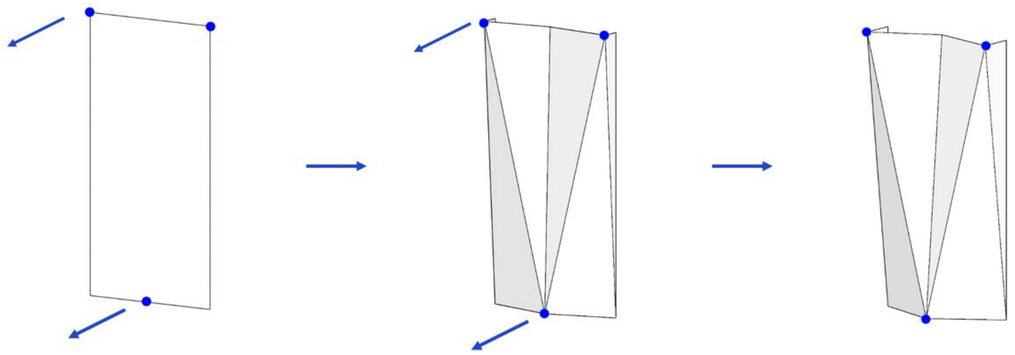


Figure 22: Climate reduction geometric principals

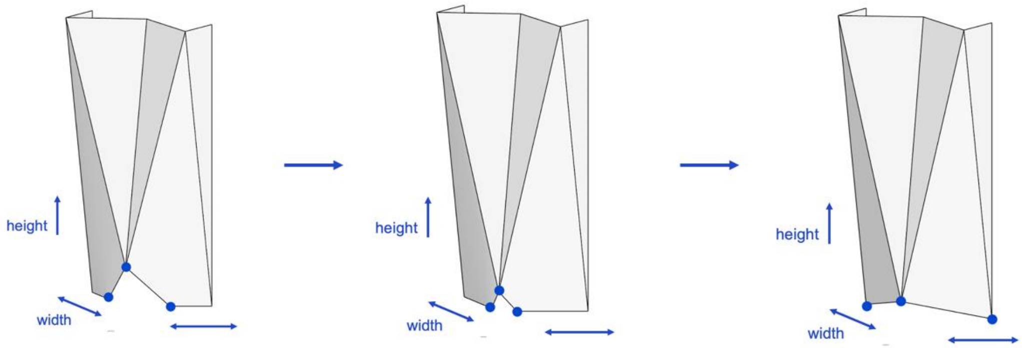


Figure 23: Flexible geometry of openings for different species

On figure 22 three control points of the tile could be seen. By moving these points back and forth, different depths of protrusion are gained, resulting in different intensities of shadowing and façade pressure reductions. The verification of the climate effectiveness can be found in the next section of this chapter – overall façade design. The span of the points movement is from 0 to 10cm, and the difference between upper and lower points could not be more than 2cm in order to keep *printability* criteria realised. For the tiles with nests, three more control points on the front surface of the tile were added to create a dynamic parameter for the entrance shapes and sizes(fig.23). A nest located on the back side of a tile, thus, together with the front surface the tile is presented as one unified element.

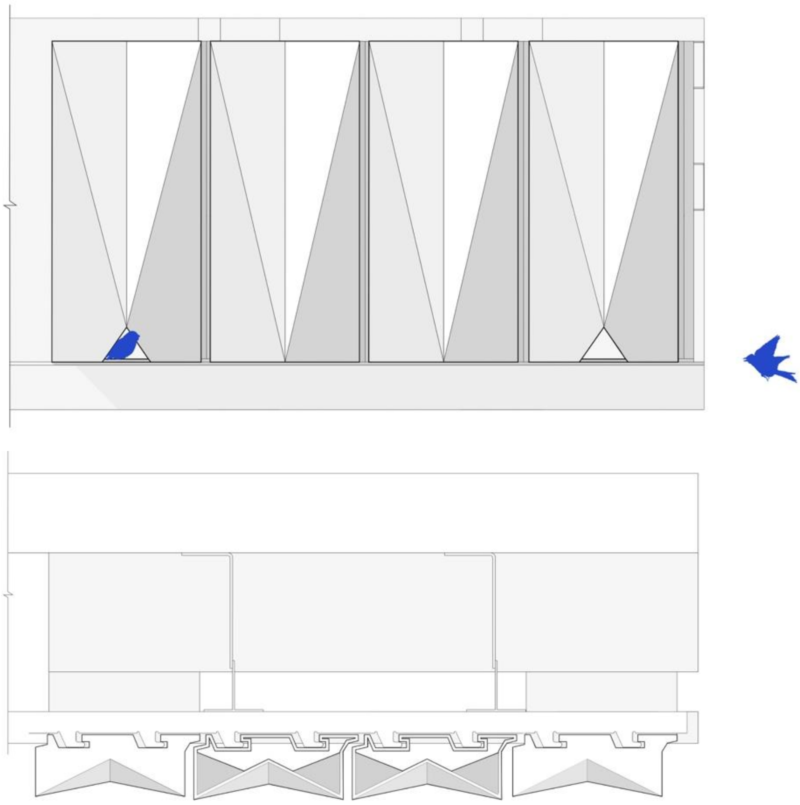


Figure 24: Drawing of the façade fragment façade and plan

Each tile has the same structural profile on the back side as the standard tiles from TONALITY systems to be easily mounted into substructure what can be seen on plan in the figure 24. In order to keep printability criteria fulfilled, vertical Adaptive system was chosen. In the figure 25 axonometry section of the tiles are presented. The tiles with nests have closed upper and lower parts to keep the inner façade systems protected from birds and litter invasion. The bottom of the nest is temporarily fixed but could be open. Another important design feature is that the façade system allows tiles to readily be taken off after mounting. This grants the possibility to clean the tiles with a nest not only through openings but by accessing the tile through the bottom of the nest.

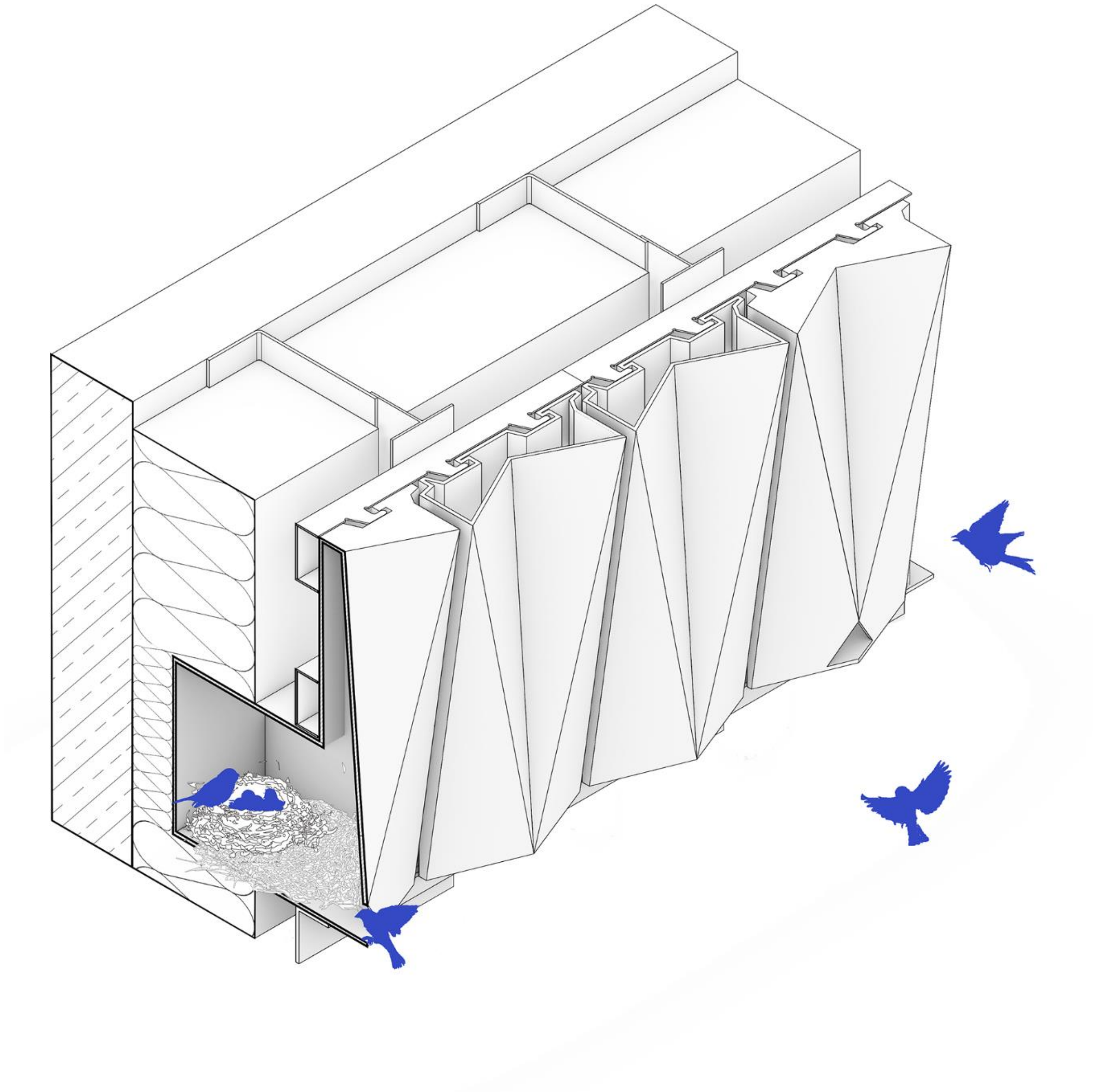


Figure 25: Axonometry section of the façade fragment

4.2. Façade scale

The overall façade design certainly corresponds with some of the design criteria, such as species and human needs and façade structure, however criteria such as overall architectural image, urban context, and the street view of the façade were also of importance. To distribute the tiles on the façade in the most performative way, it was essential to create façade maps defining where which elements are needed. In the figure 26 three of such façade maps are presented: radiation, façade pressure, and the scheme which depicts which height for which species are suitable.

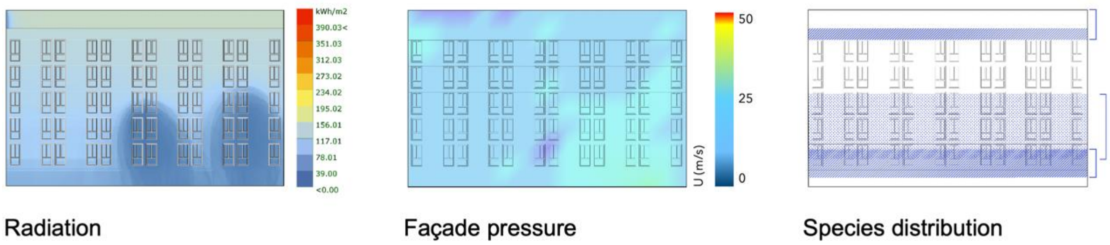


Figure 26: Façade maps

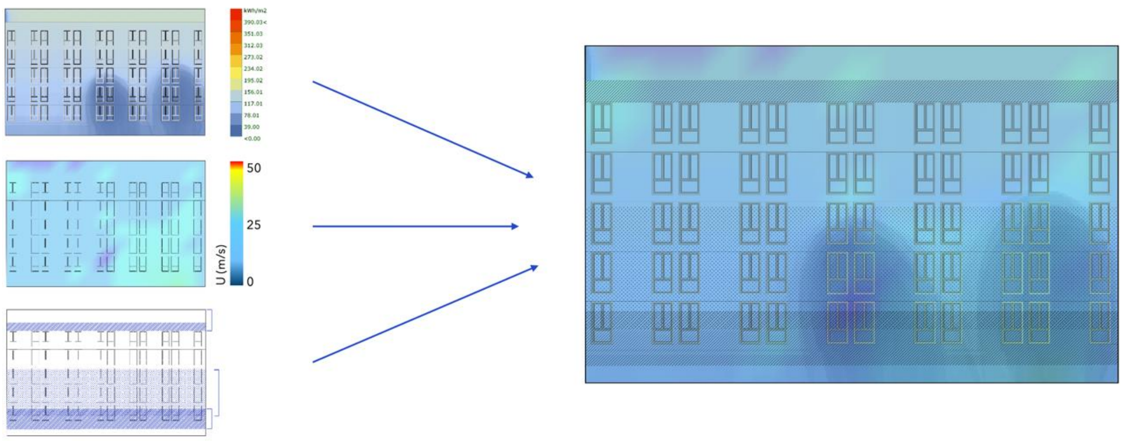


Figure 27: Three façade maps merged into one map for design basis

These three maps were merged into one façade map in order to make the distribution process easier. The lighter zones correspond higher amount of radiation and higher wind façade pressure, that means light zones require more performative tiles with higher protrusion/depth ratios. Dark zones depict lower level of radiation and wind pressure; thus, flat tiles could be used there (fig.27). One more parameter – not to place tiles with nests under windows was added. Based on this data with the help of parametric tools, different façade design pattern variations were created (fig. 28).

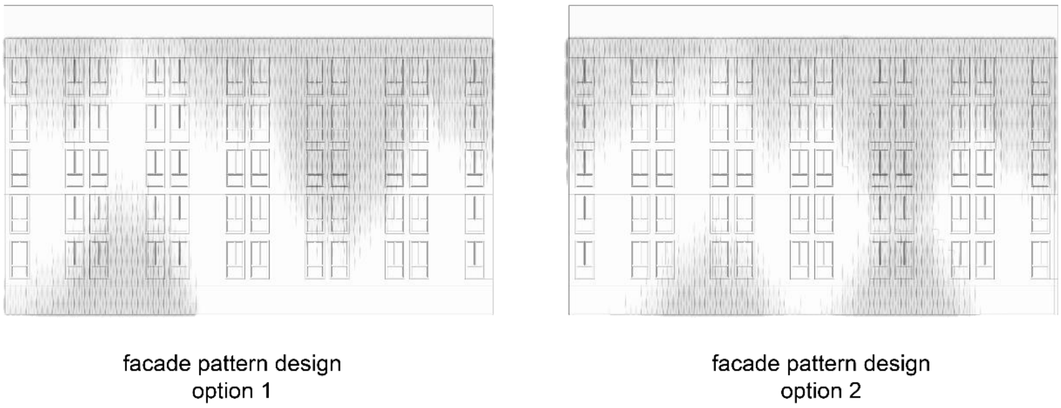


Figure 28: Façade pattern design variations

Nonetheless, these design variations could not be a final design, because they are not considering such important factors as urban context and architectural image, which cannot be converted into some calculable parameters. In order to meet these criteria, the parametrical distribution of the tiles was taken as a basis and further work was done manually, testing different design variations. The final design can be seen in figure 29. This is an example of how collaboration between an automatic and artistic process can lead to a valuable result. Figure 29 also depicts the idea of the concept of human-animal coexistence in an urban context. As could be seen, with the minimum intervention, it is possible to provide hosting elements for nests, improve the quality of architecture and energy-efficiency and microclimate conditions, within that to fit building into urban context.

Figure 29: Final façade design

In order to verify the assumption of climatic performance, namely, solar radiation reductive design, simulations with the fragment of façade were conducted. As can be seen in figure 30 with the help of tiles with bump geometry, solar radiation could be reduced up to 100%, especially performative are the tiles with the protrusion/depth ratio more than 7cm.

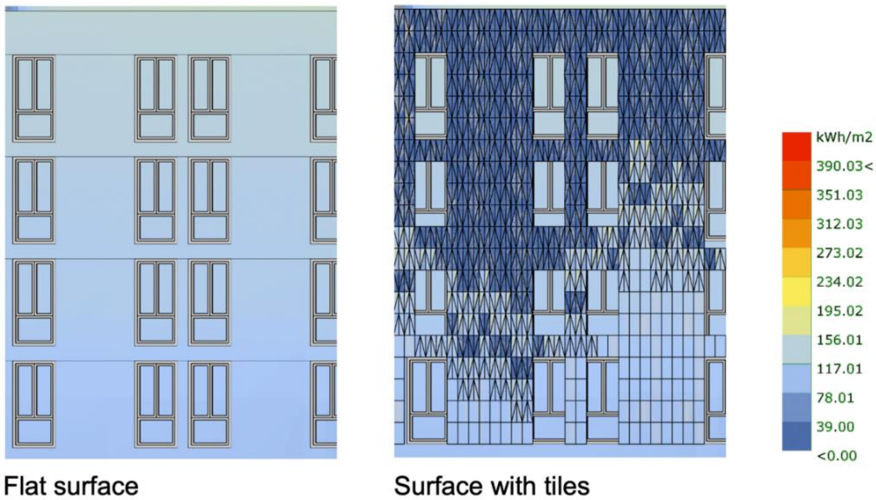


Figure 30: Solar reduction verification

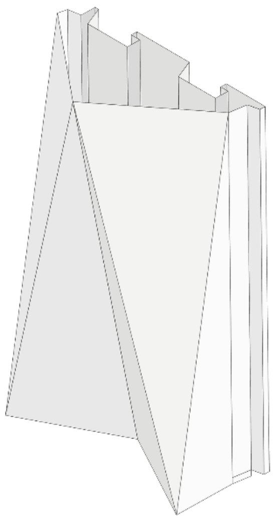
5. Fabrication

Fabrication of the clay tile could be described by following processes: printing setup, 3D printing, drying, and firing. First, in the printing setup, both files and materials should be properly prepared and calculated. Following the printing process is the drying process which is important and requires certain conditions and preparations. Afterwards, firing of the ceramic is needed to gain maximum strength properties and to allow elements to sustain the weather conditions.

5.1. Printing setup

The pressing process was selected as most suitable for gaining a planned result. Thus, with the nozzle diameter of 5 mm, the needed height of the layer was determined as 35 mm.

Files preparation. The initial geometry of the tile as developed in Rhino+Grasshopper is presented by polysurfaces geometries (fig.31). In order to print the geometry in layers, it was necessary to interpret it as a set of lines and then to derive extreme points, as a robot will use them as control points of printing path in the actual printing order.



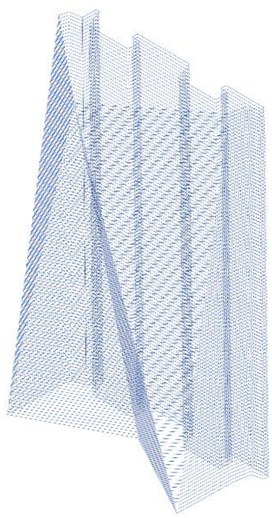


Figure 31: Polysurfaces geometry of climate performative tile

Figure 32: Printing path of climate performative tile

As a design of the tile could be expressed through straight lines, without curvature, no interpolation was needed. The edges of geometry serve as extreme points of each layer, hence, in order to build clean printing paths, the edges' lines were derived and divided into segments by points which were then connected into polylines. The order of connection of the points was turned afterwards into actual printing order and could be controlled manually at this point. The afterwards printing path is continuous, and the tile of the climate performative type could be printed without interruption (fig.32).

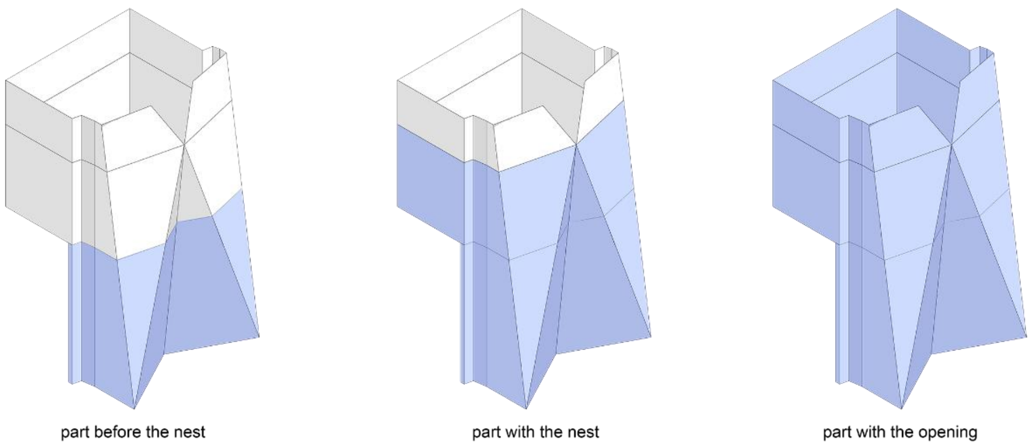


Figure 33: Printing sequence of the tile with the nest

For the tile with the nest, the main issues were creating an opening and integration of the nest into the continuous printing path. In order to solve these issues, the decision was made to print the tile upside down and break the printing into 3 parts: first, the part of the tile before the nest, then the part with the nest with the usage of the substructure, and afterwards – the upper part with the opening (fig. 33). Therefore, printing needs to be stopped 2 times – first, to place a substructure under the nest and second, to transit the nozzle from the backside to frontside to print an upper part with the opening. As the transition between layers is characterised by a short stop of the robot, at the end a geometric seam occurs because extrusion does not stop. To avoid it at the opening part, the whole upper part was printed in one layer. For the demonstrator object, standard flat tiles were also printed instead of using regular manufactured tiles, as long as the shrinkage and other factors of clay tiles behaviour was not fully predictable, and substructure will be suited for the printed tiles.

Material properties. Extrudability was a main criterion for material preparation. Witgert Ton S 11/111 sf 0 – 0.2 was used. Clay was already provided from distributor in a plastic state, however, was not soft enough for printing and additional water was needed. After first test printing, some collapsed due to excess water in the mix samples. From these examples, the suitable proportion between water and clay was determined. For a 10kg package it is 500ml (+/-100ml) of water, as a natural property of material is heterogeneous, the deviation of 100 ml occurred. Shrinkage was another significant issue, according to the Witgert information, the shrinkage after drying and burning at 1200 °C is 9,6%, so the original geometry was scaled up to 1.096 to gain a planned size after the end of full fabrication process. Clay was mixed with the help of industrial hand mixer and then pressed with the help of the machine in the cartridges. The material preparation process takes approximately 20-30 minutes for one cartridge.

5.2. Printing

The fundamentals of the printing process were described in chapter 3.3. As was mentioned, the pressing process occurs in layers, the printing time of one average layer is about 40 seconds which results in a printing time of around 70 minutes for one tile and allows production of about 3 tiles on average in 8 working hours. It could be sped up by having the tasks divided and done by different people. The base for the print has sizes 1m * 0.9 m that allow up to four tiles to be places in a row as they cannot be moved again until they gain stability with drying. In the figure 34 documentation of the 3D printing process of climate performative tile could be seen, on the figure 35 – documentation of the fabrication of a tile with a nest.

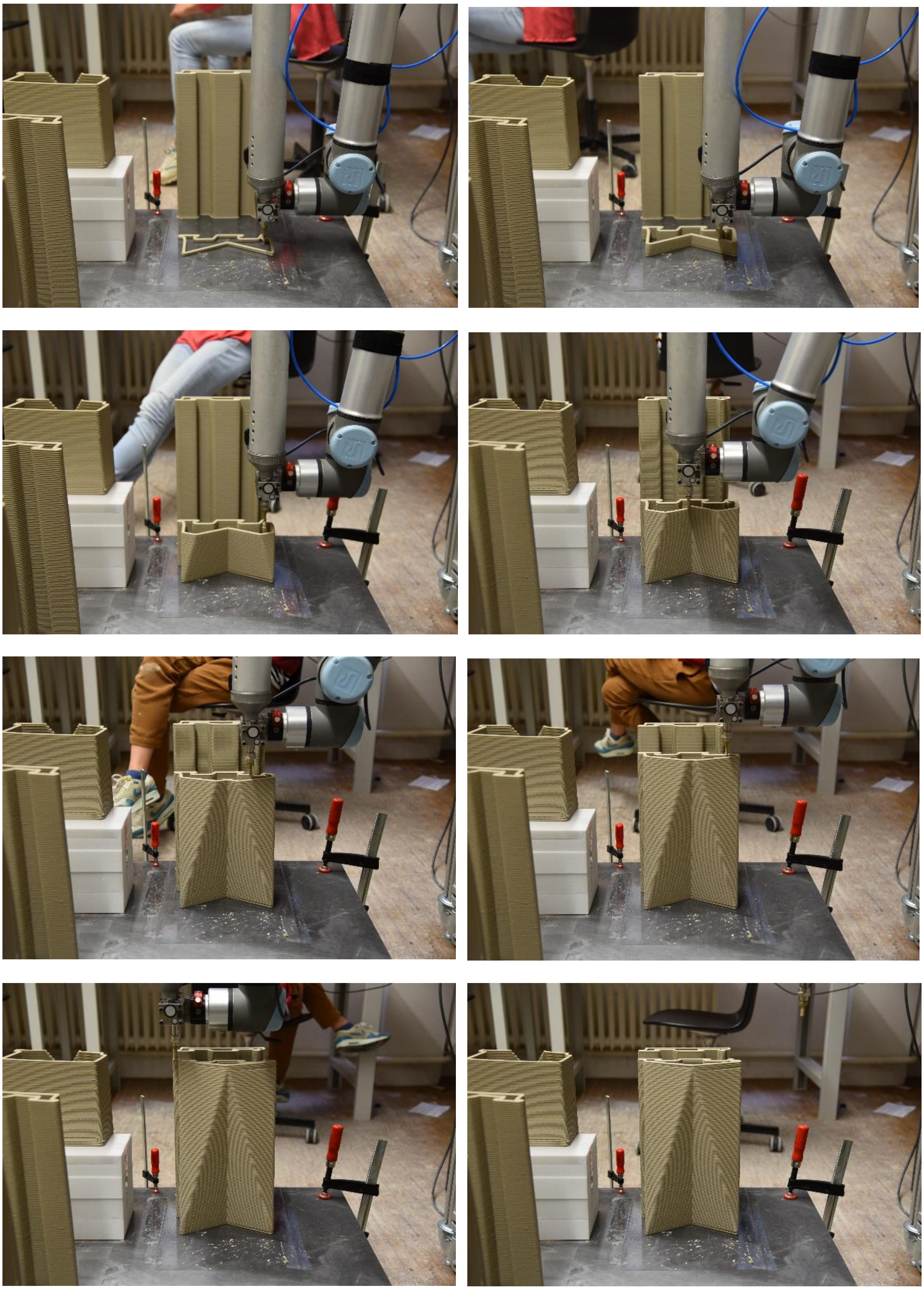


Figure 34: Documentation of 3D printing of the climate performative tile

Figure 35: **Documentation of 3D printing of the climate performative tile**

5.3. Drying

The drying process became a primary issue during the fabrication process. The University Lab at the Technical University of Munich with a humidity level around 50% was used for printing and drying, as pieces were not moveable until dry. The first problem determined was that the medium-density fibreboard (MDF) panel was used as a base for printing and drying on this base lead to its quick absorption of water. This resulted in a drying process that was too quick and heterogenous and afterwards there were significant deformations, especially twisting, of vertical elements which were more noticeable than flat elements. The deviations are 5% to 15% from the original shape could be seen on figure 36 in the middle. The next portion of elements were decidedly printed and then dried on the plastic base to prevent the MDF base from the absorption. This approach helps prevent absorption, however, elements started to stick to the plastic base what has prevented them from the natural movements of mass which typically occurs by drying and, because the issue with dry air was not solved, deformation and twisting continued occurring almost at the same rate. On the figure 36, right the tile which was printed on plastic base but dried half of the time horizontally, the left tile was printed with stiffness bridges and dried part of the time horizontally, however, deformations still occurred. The tiles with the nests were better balanced and fewer deformations occurred, however, some cracks appeared in the material. The optimal conditions for drying processes still requires to be found.

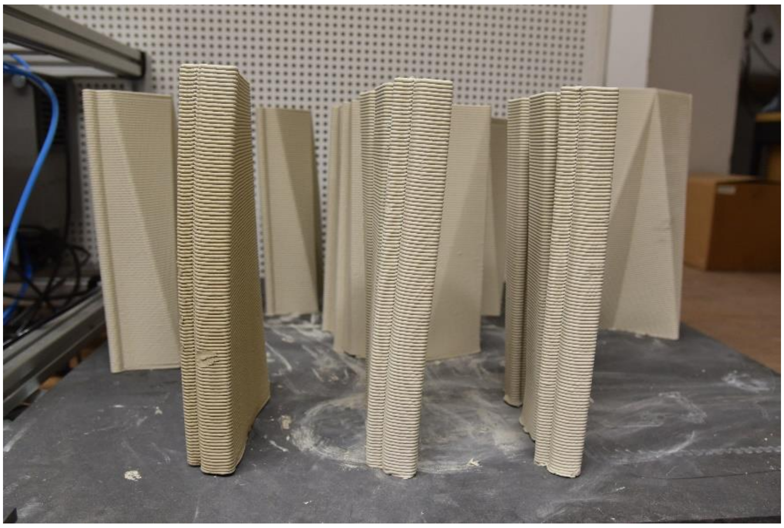


Figure 36 : **Deformation of flat tiles during drying process, tile with the stiffness bridges, dried half of the time horizontally(left); tile printed on MDF, dried only vertically (middle); tile printed on the plastic base, dried half of the time horizontally (right)**

5.4. Firing

One test element was bisque fired at around 900°C to harden the clay body, firing went without incidents – no cracks occurred. Other 3d-printed tiles will be fired at 900°C, glazed and fired one more time at 1200°C to achieve maximum durability of elements on the base of TONALITY manufacturing facilities. The transporting process from Technical University of Munich to the manufacture in Vatersdorf, however, showed extreme fragility of the elements, hence, there is a big possibility that some tiles for final demonstrator would be broken during firing process.

6. Results

6.1. Summary

The results of the thesis were reached on different scales, both in theory and practice. They could be summarised by the following:

- A possible concept of balanced coexistence between animals and humans in urban conditions was created and could be developed further with more details and applied with certain adjustment to the projects in similar conditions and pre-conditions.

- An analytical-based design approach, namely, the process of selecting reliable data and converting it into design parameters, was tested and verified.

- Wild-life-inclusive design has proven its feasibility and performative perspectives to be implemented on a real scale after further research and design investigations. Moreover, the approach promises to be feasible for renovation needs, as the maintenance of wild-life inclusive façades does not require large amounts of resources.

- Data-based design and simulations allowed for assumption of a positive performance of the façade elements in terms of microclimate improvement and heat stress reduction.

- Digital fabrication, namely additive manufacturing, has proven its' prospective possibilities in terms of animal-inclusive design. Certain limitations could be overcome by gaining more experience and through fabrication tests, which will be described in the next section

- Fragment prototype pieces in 1:1 scale were successfully fabricated and will be built into final mock-up in order to be presented and afterwards verified.

6.2. Fragment prototype in 1:1 Scale

Figure 37: **Photo of the tiles for final fragment prototype**

Fifteen tiles were printed during the fabrication process, nine of them were of the best quality and will become parts of a final demonstrator of 60cm* 108 cm that will be assembled after firing. In the figure 37 the dried tiles of the final fragment prototype in the right position but without substructure could be seen. Despite deformations, tiles could be still fitted near to each other creating clear geometric façade pattern. The glazing, firing, and substructure fabrication processes was overtaken by the TONALITY company. In case processes go well, the final mock-up will be delivered to the TUM in order to be presented at the final thesis defense. It would be significant to place the mock-up after presentation temporary in urban condition to verify the results on the small scale in the reality and to understand better possible improvements. In the collage a vision of possible implementation of the prototype on the façade could be seen (fig.38).

Figure 38: **Collage with the vision of prototype implementation**

7. Conclusion

This master thesis research aimed to address, in a short term, many topics such as of renovation, wild-live inclusive design, climate change problems. This research provides a first overview of analytic, design, and fabrication processes of wild-life inclusive façade designs. It also provides a new approach for the façade renovation which could result in further development and implementation in real projects.

As the case study project received support from the industrial side, it was possible to first test a real-scale mockup with all construction elements and to gain an understanding of economic viability and market demands. Nevertheless, exploration of a new topic that integrates several disciplines evokes a lot of questions and discussions about its further scientific development and possible practical application.

7.1. Discussion

As mentioned, research was conducted on different scales and further issues and discussion could be addressed regarding scales from urban to macro. These would involve main topics: sustainable façades (with new species integration), microclimate, renovation, and application of digital fabrication.

Urban scale.

- How could systematical wild-life inclusive design be organised in the city? It would be necessary to understand the possibility of species integration not only on the urban block level, but on the city planning level; meaning that urban strategies should include information and approaches to the topics of available and planned greenery and presented and planned species distribution. Such approaches would allow for conscious and systematic choice of species and also allow well-planned biodiversity expansion at the urban level. Indubitably, this approach would require involvement from urbanism and ecology specialists. Theoretical research, simulations, and integration planning on a city scale can facilitate more viable architectural solutions
- Is it possible to establish mass façade production with the wild-life inclusive design systems which meets the renovation rate? In order to address the biodiversity distinction problem on an urban level, design and fabrication process should be optimised and easily adaptable for different building types. Unique

solutions could be used for individual buildings; however, the final goal would be to make the design widely available and applicable to many types of buildings in need of renovation.

Macroscale.

- How can we define and become more precise about species preferences? Certain data about species needs and behaviour is available. Further research and tests are needed for better a design basis. It is crucial to test demonstrators on site and document the behaviour of a species as well as to verify the correlation between assumption and actual practice of nest use by the species of interest. After tests of the demonstrator and collection of the data, the design adjustment needs to be conducted, produced, and tested again. This cycle should presumably be run several times before applying certain a design solution on a larger scale.
- How can we improve the design process and make it better informed? Many design decisions in the case study project were based on the theoretical knowledge and design parameters were chosen based on assumptions derived from theoretical research. On-site climate analysis, comparison of presented and expected results, and further work on the research and different case studies allow for adjustment of the set of parameters and to verify their feasibility.
- How are the fabrication obstacles overcome? Additive manufacturing has certain limitations which did not prevent fabrication in the case study project. Nevertheless, the material clay has limitations as well. Those that were remarkable in the case study project included twisting and deformations during the drying process. In order to overcome this problem, further research will need to find out what caused it– the geometry itself or the drying conditions. Therefore, either geometry requires further adjustment, or the drying conditions need to be changed. Another possible direction for further research could be testing another material as an auxiliary method, for example, 3D printing of moulds for tiles with biodegradable plastics. Presumably, it would accelerate the production process, as moulds can be used hundreds of times after printing, thus saving time of the printing process.

7.2. Further work

A quantity of open questions shows not only the issues of a master thesis and case study, however, the potential of work and possible directions of further researches. To gain a deeper understanding and useful results, all of above-mentioned issues must be addressed. Further research would also combine theoretical and practical processes, concentrating on more case studies and moving towards exploration of new approaches, innovative design, fabrication solutions, and methods. With the support of industrial and academic partners, research promises to be relevant both as a theoretical work and as a commercial project.

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9. Table of figures

10. List of tables