Additively Manufactured Urban Multispecies Façades for Building Renovation

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Abstract

This research investigates the potential of additive manufacturing and digital planning tools for the creation of location-specific façade redesigns that can host cavity-dependent animal species and develops methods for their realization. The proposed approach is explored based on a case study of a student dormitory in need of renovation in the urban area of Munich. Based on theoretical knowledge and design experimentations that link the fields of architecture, climate-responsive design, terrestrial ecology, and digital fabrication, a set of design principles for the additive manufacturing of inhabitable ceramic tiles is conceived and transferred into a computational design tool. The conception of single tiles and the overall façade design are developed in terms of their positive climatic impact on both the animal species and humans, their nesting opportunities, their structural feasibility, and their integrability with standard ceramic façade systems. To verify the fabricability of the proposed design, a façade fragment was additively manufactured as a prototype in 1:1 scale. The initial findings presented in this paper provide a glimpse of how emerging digital technologies could provide new ways to expand current habitual architectural planning and fabrication tools, to enable the creation of site-specific solutions, and to bring together human and animal needs.

Keywords

Additive Manufacturing, Computational design, Climate-aware design, Terrestrial ecology, Building renovation

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1 INTRODUCTION

The preservation of biodiversity is considered one of the key factors in mitigating climate change. Urbanization, which displaces native wildlife and replaces it with impermeable surfaces, is one of the most significant contributors to the global decrease in biodiversity. Paved areas, lack of greenery, and significant resource consumption – buildings being one of the largest energy consumers (Bauer et al., 2013) – are all factors in cities that have a negative influence on biodiversity and, hence, the global climate (McDonald et al., 2013). Beyond the positive impact of biodiverse environments on the climate, juxtaposing human habitats with animals' can also have positive psychological impacts on humans (Sandifer et al., 2015). However, the human relationship with non-humans throughout human history has often been one of fighting against or even conquering nature (Tsing et al., 2017). This approach is reflected in the built urban context through infrastructure and buildings that are primarily tailored to overt human needs; that is, today's building envelopes consider attributes that serve human requirements, such as spatial organization, insulation, and aesthetics, and present themselves as hostile to the requirements of native wildlife. Another problem that most cities deal with today is the ageing of the buildings; many of them no longer satisfy modern ecological, energy-efficiency, or comfort requirements. In 2020, 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 will maintain at this level after achieving European Union climate neutrality by 2050. Among others, energy efficiency, decarbonization, and life-cycle thinking are named the main principles of renovation (European Commission, 2020). These foundations could be seen as an opportunity to rethink the approach to urban renewal and to integrate new solutions into the existing urban fabric, enabling a shift towards a harmonious relationship with nature and the coexistence of humans with non-humans. Creating new envelopes for buildings needing renovation could be a chance to rethink and redesign façades toward the inclusivity of different species in the envelopes: small animals and birds, and the creation of positive microclimate conditions with the help of the surface design, for the wellbeing of both humans and other species. In this context, this research proposes to explore whether digital technologies could be used as a powerful tool to help build – literally and figuratively – a new way of co-habitation. It addresses the question of whether digital technologies could provide the necessary tools to extend the usual architectural tools for creating human habitats to create animal-friendly habitats, with the particular focus of this research being the development of such tools to accommodate nesting sites for selected species within building envelopes.

As such, the presented research provides initial findings of exploring an integrative approach that combines expertise in architecture, digital fabrication, climate-responsive design, and terrestrial ecology to redesign and transform building envelopes to host, breed, and protect cavity-dependent wildlife species in the urban context. In particular, the integration of microclimate performance and animal inclusion within a bespoke façade redesign using the possibilities of digital technologies and additive manufacturing is explored. Departing from a standard ceramic façade system, a digital design tool is developed, which allows for individually adapting the standard façade tiles towards a context-specific geometry, aimed at incorporating cavities for both self-shading effects and animal housing. The tool also enables the analysis of the static feasibility and its climatic performance through simulations. A functional prototype, at 1:1 scale, was produced with robotic extrusion 3D printing using clay and ceramic firing to test the fabricability of the proposed design principles. This research aims to create and demonstrate a preliminary design approach for a site-specific, wildlife-inclusive, and climate-performative urban façade design, as part of a global ecosystem that could be adapted and reproduced in different contexts using digital design and fabrication technologies.

The main body of this paper is organized by presenting the main stages of the research: Section 2 gives an overview of the research method; Section 3 contains the analysis, which contextualizes this research and provides an overview of the project's origins; Section 4 presents the design studies, which explain the development of the design tool (Section 4.1), details of the design explorations and their results (Section 4.2), and the validation of the proposed fabrication process, which documents the process, its limitations, and result (Section 4.3). Section 5 gives an evaluation of the proposed research method and process and discusses the design framework. Finally, Section 6 highlights the perspective of future work.

2 METHOD

To investigate the feasibility of wildlife-friendly and climate-conscious design for façade renovation, we apply a Research through Design (RtD) methodology, defined as "the possibility for design to be based on design practice, i.e., through artistic and creative design objects, interventions, and processes, to gain insights" (Bang et al., 2012) (Fig. 1), and an experimental case study based methodology by experimentally testing and validating aspects of the proposed method for a specific location in the urban context of Munich.

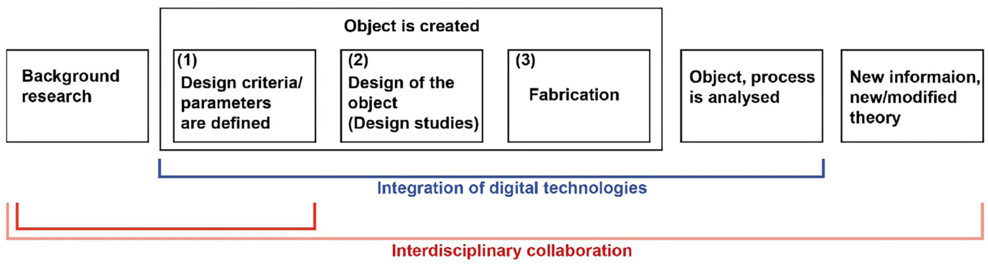


FIG. 1 Research through Design (RtD) method, as defined by (Herriott R., 2019), expanded by (1) the determination of design criteria, parameters, design systems, and fabrication methods and their primary analysis and evaluation; (2) the design of the object, including various parameter studies on different scales; and (3), the fabrication process, where the object is realised in real-scale to testify the legitimacy of the design solutions and the proposed fabrication process.

The interdisciplinary collaboration between architects, ecologists, and façade specialists is crucial to address the multiple aspects that define the scope of this research, comprising the topics of cavity-dependent species integration, microclimate considerations, as well as the application of clay extrusion 3D printing for custom ceramic tiles. The background research, referred to in the case of this project as "State of the Art" (Section 3), includes a literature review and the study of similar projects and research in this field, which forms a basis for the design process, in particular for the definition of sub-criteria and parameters. The practical experience and theoretical knowledge of the specialists from the research areas involved also formed a solid basis for the experimental research method of the project (Whitelaw et al., 2021).
To conduct the proposed RtD process, the experimental case study is set in a specific urban context – a student residence in Munich, Germany. Provided by the terrestrial ecology research (see Section 3), three main target species for the selected urban context are chosen: the bird species House Sparrow and Black Redstart, and the bat species Common Pipistrelle. The species' specific needs set the main boundary conditions for the project, which we have consecutively converted into parameters for the conception of design principles and the generation of design proposals.

In line with Multi-Objective Optimization techniques (Bertagna et al., 2021, Brown & Mueller, 2017), digital technologies are implemented at all design stages to guide the design process (Fig. 1). This technique allows evaluation, re-evaluation, and adjustment processes to be integrated into all design stages and to provide an optimal choice of sub-options. To fundamentally address the problem at various scales, the design of the single façade element and the design of the whole façade pattern are conceived and evaluated in terms of climate efficiency and fabricatability with the help of simulations. For the purpose of renovation, a retrofitting design approach is used – the elements are designed to fit into existing ventilated façade systems such that standard-sized tiles can be replaced with bespoke tiles of added functions at required locations. Additive manufacturing with clay was chosen for the realization of bespoke tiles, which have the ability to realize complex, high-resolution geometries. In addition, clay was considered the best option for initial investigations as a robust and potentially species-innocuous material. To verify the design for realization feasibility, i.e., to verify its fabricatability and evaluate the limitations and prospective of the selected digital fabrication method, a set of ceramic tiles are additively manufactured, fired, and assembled into a façade fragment prototype at 1:1 scale.

3 STATE OF THE ART

3.1 ARTIFICIAL HABITS IN THE BUILT ENVIRONMENT

The focus on inhabitable building envelopes, such as previously shown with the concept of Animal Aided Design (AAD) (Hauck & Weisser, 2015), has received increasing attention in recent years. Key objectives of AAD link urban planning disciplines with technical solutions to permanently keep and protect urban wildlife (Weisser & Hauck, 2015). Wildlife inclusive design strategies are characterized by a multidisciplinary approach, in which all aspects of the project, such as the choice of target species, landscape, and open spaces design, are planned as a united system and aligned with each other in architectural solutions (Apfelbeck et al., 2020). Built examples such as the social residential housing with integrated children's facilities in Laim – Germany, designed by the Munich architects bogevisches buero (bogevisches buero & GEWOFAG Projektgesellschaft mbH, 2019) in collaboration with Prof. Weisser and Prof. Hauck, already show this interdisciplinary approach of carefully designed habitats for hedgehogs, house sparrows, green woodpeckers, and pygmy bats (Figure 2) (Apfelbeck et al., 2019).

FIG. 2 Integration of nests into buildings' facades, Weisser & Hauck, bogevischs buero architects, 2015.

The design of the project focused on the wall's built-in elements to fulfil a single function: to provide shelter for birds. However, the design does not offer any additional visual or climate performative qualities. Moreover, the built-in elements cannot be temporarily removed from the façade, making cleaning and revising processes difficult. Therefore, in the experimental design study presented, we aim to extend the currently deployed solution with a multifunctional approach that includes multiple functions at the level of the single element, making this element the starting point of architectural explorations.

3.2 ADDITIVE MANUFACTURING PROCESSES FOR WILDLIFE INCLUSIVE DESIGN

Additive Manufacturing (AM) technology has been increasingly promoted as a sustainable production technology over the past decade (Jiang et al., 2018). Its potential for waste-free production, great material variety, and design freedom are now becoming increasingly prominent in the construction sector (Willmann et al., 2018). The production process of AM building elements typically occurs through the digitally controlled layer-by-layer application of material, providing a high degree of individualization and reducing material waste (Kloft et al., 2021). In combination with computational design and simulation, AM allows for the expansion of architectural possibilities, enabling the integration and customization of multiple functions through geometric and material freedom on a par (Dunn, 2012). Ceramic materials, due to their robustness, recyclability, and implementation in the building industry in the form of handy components for façade constructions, are particularly attractive in terms of their potential for AM (Wolf et al., 2022). In this context, the project Cabin of Curiosity has demonstrated the production of bespoke geometries of varying façade elements produced with clay extrusion 3D printing (Rael et al., n.d.). Each of the three typologies of elements incorporates a different mounting principle; moreover, each element integrates several functions: hosting vegetation, rain protection, and shade – made possible through the application of computer-aided technologies combining design with fabrication. The research defining framework for computer-aided design and manufacturing of habitat structure for cavity-dependent animals (Parker et al., 2022) explores an interdisciplinary approach on par with the possibilities of generative design and 3D Printing in terms of creating artificial cavities. In the case study of the owl (Parker et al., 2022), researchers tested several generative design variations and evaluated them before fabrication. The final selected geometry was adjusted for the owls' and stakeholders' needs. Modular components were produced in different manufacturing techniques: 3D Printing with wood and CNC cutting. This study presents the potential of digital technologies in terms of conservation initiatives. The research explores hanging nest structures, however, in cities or dense urban conditions, there is a limit of free available trees for placing the nests. Therefore, possible development of this idea could be expanding structural variety for placing the nests in diverse urban contexts.

3.3 DESIGN STRATEGIES FOR CLIMATE-RESILIENT URBAN FAÇADES

Urban climate phenomena, such as the Urban Heat Island Effect (UHIE), are strongly related to and amplified by the built environment (Roesler & Kobi, 2018). Materiality, shape, and morphology of buildings, greenery, global radiation, and evaporative cooling are parameters that influence the outdoor climate (Perini et al., 2017). By precisely controlling and planning such parameters, the outdoor climate comfort could be positively influenced with the help of computational design and fabrication. For example, the Climate Active Brick project (Fleckenstein et al., 2022) has investigated possibilities to reduce solar exposure and, hence, solar radiation, by integrating self-shading patterns into the classic rat-trap bonded brickwork. With the help of climate simulations, the optimal context-specific self-shading brick pattern was found, characterized by differentiated frontal brick rotations. The fabrication of the brick assemblies' customized pattern was then achieved with the help of a robotic arm. The focus of the current approaches lies on creating better microclimate conditions for humans; therefore, to improve biodiversity, it is important to include the needs of species in microclimate design.

4 EXPERIMENT - CASE STUDY PROJECT

4.1 SELECTION OF THE LOCATION

As defined by Apfelbeck et al. (2020), the choice of the urban context and a systematic approach are significant components of a successful wildlife-inclusive design. Therefore, the search for a suitable building was the first step in the research project development. The criteria for the building choice for the experimental project within the Munich urban area were defined based on the background research and desired goals: the building should be located in a dense urban zone to study the possibility of improving biodiversity/microclimate in dense urban conditions through the envelope design, with available greenery in proximity needed for nurturing the selected species, and a minimum of 40% wall-to-window-ratio, since glass façades are not suitable for integrating nests. A suitable prototypical site influenced by UHIE was found in the Maxvorstadt area of Munich based on UHIE study provided by Funk, et al. (2014), a student dormitory with available east and north façade surfaces and in need of renovation.

4.2 DEFINITION OF DESIGN CRITERIA

In a preliminary design phase, based on the state-of-the-art research and project goals, the following main design criteria that can influence the geometric differentiation and architectural idea are being determined: species requirements, including the microclimatic improvements for the selected species and humans, the façade system and structure, and fabricatability. Each criterion has its own set of parameters which are reviewed, analyzed, and contextualized before being merged and converted to design parameters, as described below.

4.2.1 Species Needs

As land-use modification pushes many bird species away from land areas, many species, such as the Common Redstart, are now located in urban environments (Droz et al., 2008). Wildlife-inclusive architectural design could help to provide species in the cities with suitable conditions within the built fabric. Some factors for the nests, such as the size of the nest, the height from the ground, and if the species prefer to live alone or near their neighbours, could be addressed directly through geometry – with the correct position of a nest on the façade, the right 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.

TABLE 1 **Selected species need matrix (Larikova I., 2021)**

	Species	Size of the species	Height of the nest from the 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	W, N, E	High tempera-ture, strong wind	Nests need to be cleaned once in 2-3 years
	**Black redstart**	13-15 cm	1-4 m	Prefer to live alone (or in couples)	-	W, N, E	High tempera-ture, 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	Min 0,6 m	S	Too low tem-perature, dryness, strong wind	Nests could be self-clean-ing

TABLE 2 **Geometrical requirements of the nests**

	Species	The shape of the nest	Size of the nest	The shape of the entrance	Size of the entrance
	**House Sparrow**	Sphere or rectangular	20-30 cm * 15-20 cm *15-20 cm	Round or rounded rectangular	D = 3-6 cm
	**Black redstart**	Sphere or rectangular	20-30 cm * 18-24 cm *18-22 cm	Oblong, balcony-like	W = 12-18 cm, H = 8-15 cm
	**Common Pipistrelle**	Oblong and narrow parallelogram	20-30 cm * 30-60 cm *12-18 cm	Oblong and narrow	W = 18-20 cm, H = 5 -7 cm

Based on the data collected by researchers in the field of ecology (Bischer et al., 2017.; Droz et al., 2008; Koryakina, 2018; Londoño, 2007; Weggler, 2006), and the direct consultations with specialists and industry professionals, the most important criteria for three selected species – the Black Redstart, the House Sparrow, and the Common Pipistrelle - are defined and summarised in Table 1, whereas geometric requirements for the nests are summarised in Table 2.

4.2.2 Microclimate Improvements for Species and Humans.

Although there is some data on preferred temperatures and humidity levels for the selected species, finding the perfect conditions for nest placement in dense urban environments is not straightforward. Digital analytical tools implemented from the early design stages make the decision-making process more precise and conscious and also serve as a base to create a design that would help to improve given climate conditions toward the species' requirements and needs.

However, to model and quantify the contribution and effects of every single parameter, both in the site selection and façade design process, several detailed computational models would be required. To reduce the computational complexity and focus on the geometry-driven parameters, two main environmental forces are selected to be simulated in this project. First, the amount of radiation incident on the building influences the microclimatic conditions of the façade. In general, this radiation should be reduced, both to protect the built-in nests from overheating and to avoid general overheating of the façade, to contribute to a well-designed microclimate for humans. Second, the wind façade pressure incident on the building influences parameters such as weathering. Here, too, the wind pressure should generally be reduced in habitable areas.

To address the selected microclimate parameters, the reduction factor is used as a basis for subsequent design developments. To proceed with developing and exploring a site-specific design solution, first, the existing state of solar radiation and the wind façade pressure are analyzed with the help of computational tools: The Ladybug plugin for solar radiation and Eddy 3D plugin for façade wind pressure are used within the architectural design environment Rhino (McNeel & Associates, n.d.) and Grasshopper, using the EPW (energy-plus) map for Munich. The simulations are done for the time frame of June to August, between 11am to 4pm, as the potentially hottest temperature possible in that time frame. The focus of the analysis is made on the west façade, as it is the street façade, which provides a higher potential for exploring visual qualities of wildlife-inclusive design in the urban context.

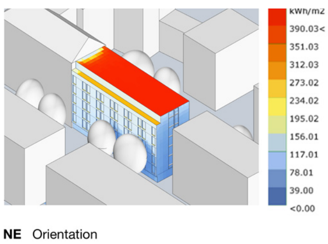


FIG. 3 Solar radiation analysis, June-August; 11am – 4 pm (Larikova I., 2021)

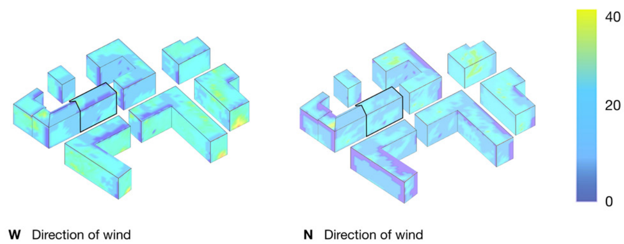


FIG. 4 Wind facade pressure analysis, west and north directions of wind, June-August; 11am – 4 pm(Larikova I., 2021)

Figure 3 depicts the output of the solar radiation analysis, in which dark blue zones receive little or no solar radiation while red zones are significantly affected. As the simulation shows, the vertical façade surface exhibits a progression from blue to green from the lower to the upper part of the façade, greenish especially in the higher areas, which would be ideal for the placement of nests due to their height and orientation. These green zones, indicating a high level of solar exposure, therefore need solutions that can reduce the amount of solar radiation for better comfort of the species to be housed and for better microclimate comfort for humans. Figure 4 shows the result of wind simulation for north and west winds. Dark blue zones depict areas with no or low wind façade pressure, whereas yellow zones show high levels of this pressure; hence, they would need to be adjusted to host nests. In sum, the analysis serves to detect façade areas which are directly suitable for placing nests for the selected species and areas which need microclimate improvement. Areas that are highly affected by wind or solar exposure are locally improved with the help of the design of the single façade elements and conscious elements' distribution (see Section 4.3).

4.2.3 Façade System

Based on background research, a Ventilated Façade Systems (VFS) with ceramic wall elements was selected. Though External Thermal Insulation Composite Systems (ETICS) are the most common systems in renovation projects in Europe, particularly in Germany (Asam, 2017) VFS have high efficiency in insulating properties, and are relatively easy to install (Bernhard Rudolf, 2012). Key parameters that influenced the choice of the façade systems are presented in Table 3: VFS have the advantage of having additional air space between the façade surface and insulation, and thus, a flexible layer thickness, which is crucial for the project, as this additional space has potential to integrate the nesting part of the tile behind the façade surface. VFS also shows good compatibility with ceramic façade tiles. Moreover, the idea of the experimental project is to mix standard industrially fabricated ceramic tiles with customized additively manufactured ones for higher cost and time efficiency. Therefore, the selected VFS sets several parameters for the design of a single façade element: a rear part must fit into the substructure profile, while the dimensions of custom elements should match standard tiles.

TABLE 3 **Duration differences for fabrication, extraordinary maintenance and disassembly activities (the percentages represent the difference of that façade option respect the fastest solution in each phase)**

	Building costs efficiency	Thermal insulation properties	Flexibility of the layers thickness	Revision possibility after installation
ETICS	√	√		
VFS		√	√	√

4.2.4 Fabricatability

The selected AM manufacturing process of robotic clay 3D printing also has specific limitations that need to be considered in the design and parametric studies, i.e., the process requires material to be deposited continuously in layers, the elements must be stable during extrusion 3D printing and drying, and the overall geometry is limited to round edges, specific printing path lengths, specified layer height and thickness, and maximum overhang angles. Parameters from a literature search served as a basis. During a series of digital studies and test prints, the parameters were adjusted according to the experimental results.

4.3 DESIGN STUDIES AND RESULTS

4.3.1 Microscale – Experimental Design of a Single Element

The design of a single element departs from the geometry of an industrially fabricated ceramic tile of a ventilated façade system, which is based on a hollow core and is hung vertically onto a substructure (Fig. 5, left). This ceramic tile can be produced using the typical industrial extrusion method, but due to its geometric features, it can also be produced using the proposed extrusion 3D printing method, either with its standard shape or with geometric variations to integrate the proposed multi-species requirements, that is, to integrate the self-shading effect for contributing to the positive influence on the façade microclimate, and to integrate nesting opportunities, which, additionally to the climate-active function, can host the nests for the selected species. All tiles have the same outer boundary of 35x20cm to fit into the standard size of the ventilated façade system for ceramic tiles. In order to reduce both the solar exposure through self-shading effects and the pressure of the wind on the façade, the front surface of the climate-performative tiles is deformed outwards with a fold of varying depth and angle. According to selected studies addressing the topic of wind pressure, vertical folds are more effective in terms of wind façade pressure reduction (Kwok & Grondzik, 2007; Lignarolo et al., 2011; Simiu, 2011), and also effective for conceiving a self-shading effect. With the help of three parametrically controlled points that create a depth from 2 to 10 cm, corresponding with the amount of radiation or wind pressure needed to be reduced, the folded frontal surface of the tile can be shaped at varying depths (Fig. 5). The climate-performative tiles with nests incorporate openings at the bottom of the front surface which can be parametrically adjusted from species to species (based on data from Table 2: Geometrical requirements of the nests), without changing the overall tile geometry (Fig. 6). These openings are connected directly with the hollow core incorporating the nests as depicted in Fig. 7.

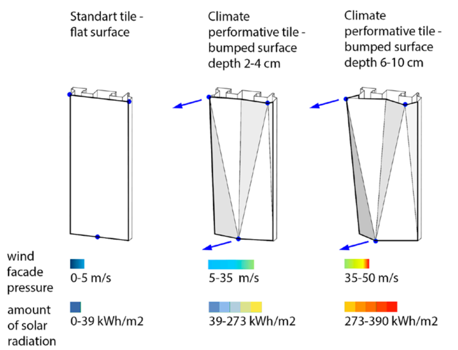


FIG. 5 Climate performative tile, front surface formation principals

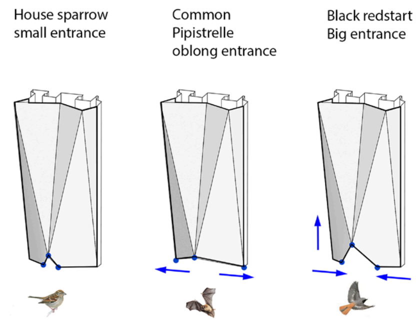


FIG. 6 Climate performative tile with nest, front surface entrances for species principal

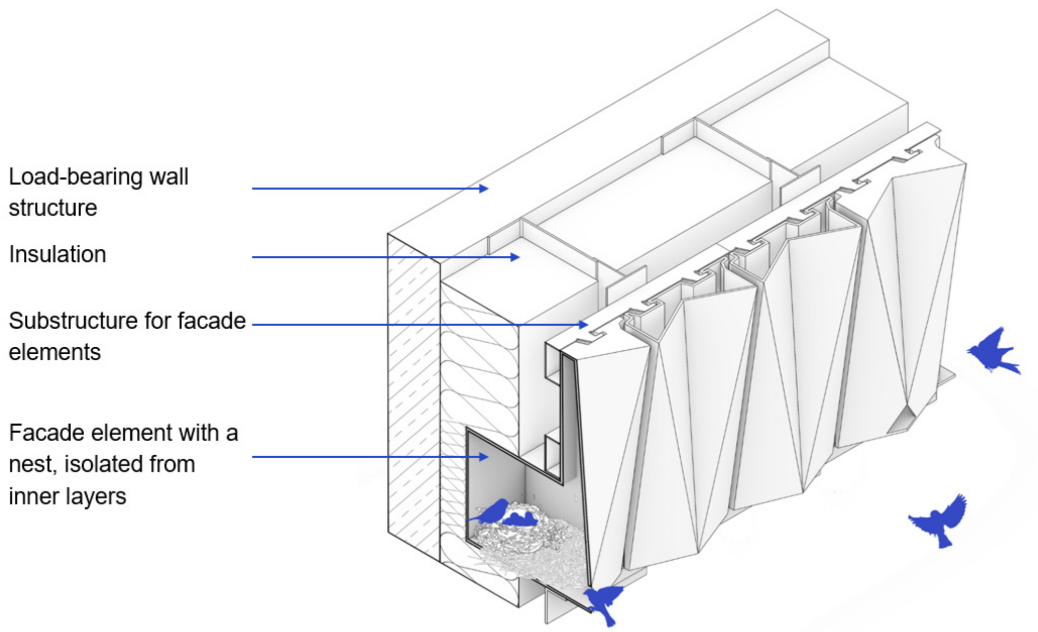


FIG. 7 Axonometry section of the façade fragment (Larikova I., 2021)

Each tile has the same structural profile on the back side as the standard tiles to be installed onto the standard sub-structure. Moreover, the tiles for hosting the animal species integrate the nests into the back side, whose sizes could also vary for different species without the need to change the substructure (Fig. 7).

The air layer and reduced insulation layer allow the incorporation of the nest parts into the ventilated system without interfering with the wall structure, therefore, making the approach relevant for renovation purposes. Unlike the other tile types, the tiles with nests have permanently closed cover tops and temporarily closed bottoms to protect the internal façade systems from birds and litter. The advantage of using the ventilated façade system over built-in components is the ability to provide easier access to the nests after assembly (elements could be taken out individually from any place of the façade after mounting) and thus provide more flexibility in terms of the periodic cleaning required (Table 1: Selected species needs matrix).

4.3.2 Macroscale – Context-Specific Parametric Façade Design

To test the features and potential impact of bespoke tile designs on larger surfaces, the west street façade of the student dormitory building is chosen for more detailed façade design studies. Three façade maps, namely 1) to simulate solar radiation, 2) to simulate wind façade pressure, and 3) to indicate the preferred heights of the species (Fig. 8a), were merged into one map (Fig. 8b) as a basis for the distribution of the custom tiles.

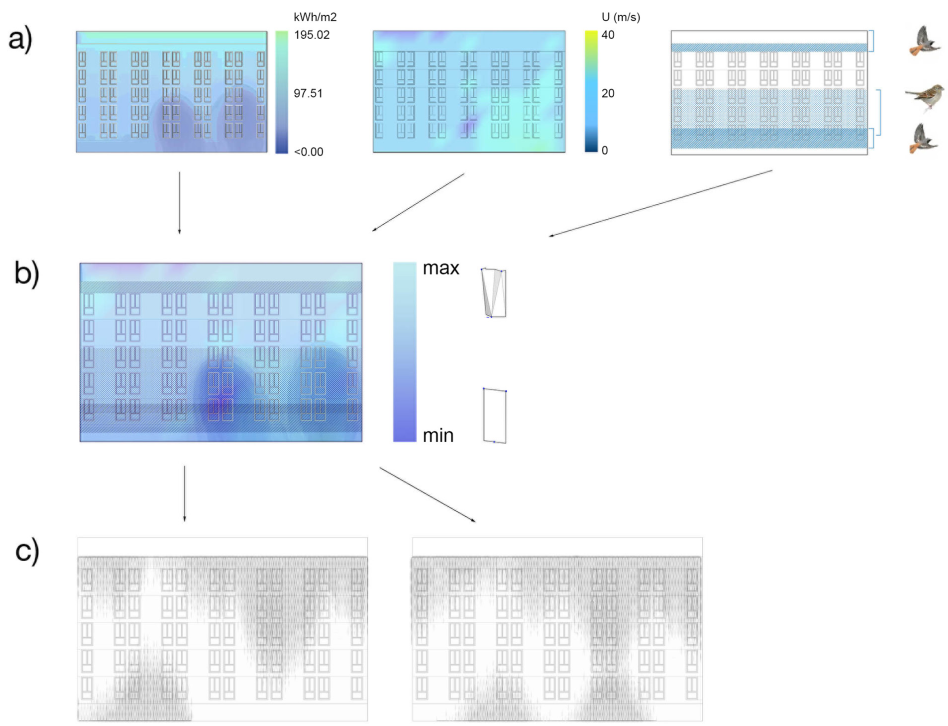


FIG. 8 a) Maps with climate simulations, solar and wind exposure, and the required height for species, b) merged façade maps, and c) generated façade patterns based on the information given in a)/b)

In Fig. 8b, lighter zones correspond with a higher amount of solar radiation and wind pressure, therefore, climate-performative tiles are distributed there; in the darker zones, standard tiles are used, whereas the climate-performative tiles with nests are distributed according to the species' needs. The rule for avoiding undesirable interactions between humans and species and preventing the invasion of litter into apartments was implemented as an additional input parameter: nests were not allowed to be placed directly under windows or balcony doors. Different options of the tiles' distribution resulted in differentiated façade patterns (Fig. 8c), one of which was chosen, manually revised, adjusted for the urban context, and transferred into the final façade design (Fig. 9).

FIG. 9 Visualisation in the urban context (Larikova I., 2021)

To verify the assumption of the microclimatic behaviour of the proposed façade design, namely, solar radiation reductive behaviour, simulations with the façade fragment are conducted. As depicted in Fig. 10, according to the simulations undertaken with the Ladybug plugin within the architectural design environment Rhino (McNeel & Associates, n.d.) and Grasshopper, as a result of the self-shading effects caused by tiles with folds, the solar radiation could be reduced from 200- 150 kWh/m2 to an average of 0-50 kWh/m2 within the analyzed time frame (June to August between 11am and 4pm), the most performative are the tiles with the protrusion/depth ratio more than 7cm.

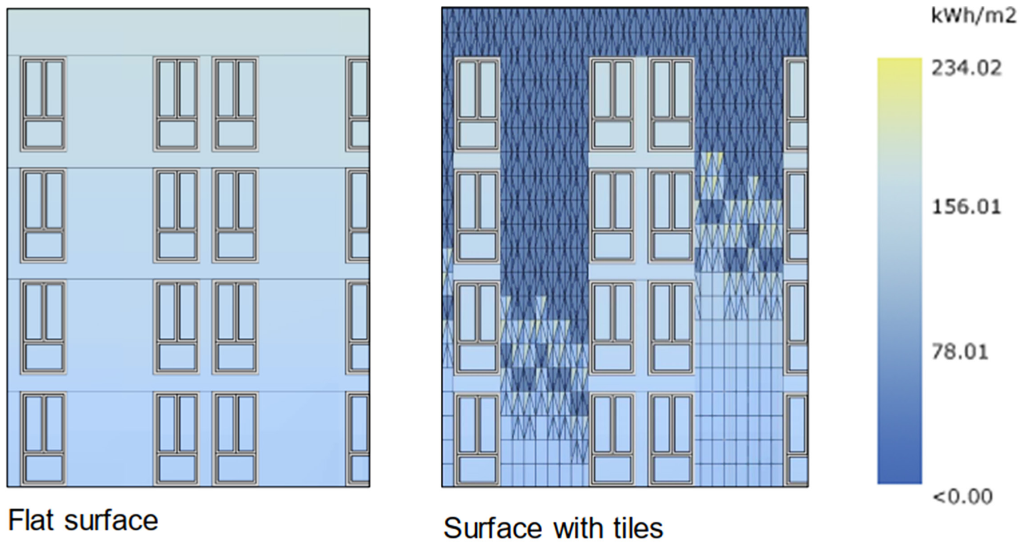


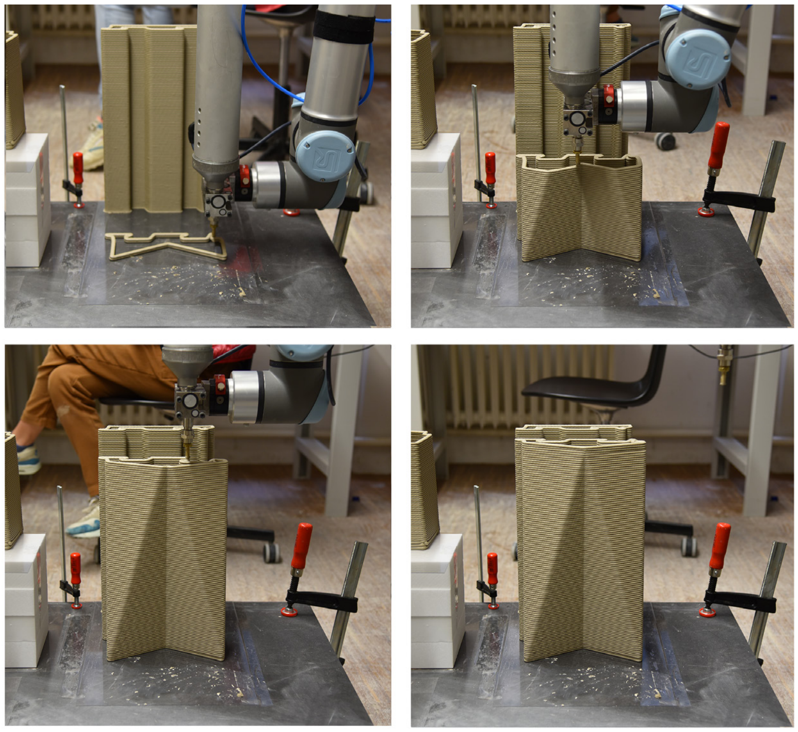
FIG. 10 As intended in the façade design, the simulation demonstrates a reduction in the amount of solar radiation of the façade when fitted with self-shading tiles in areas of higher solar exposure.(Larikova I., 2021)

4.4 PROTOTYPE FABRICATION

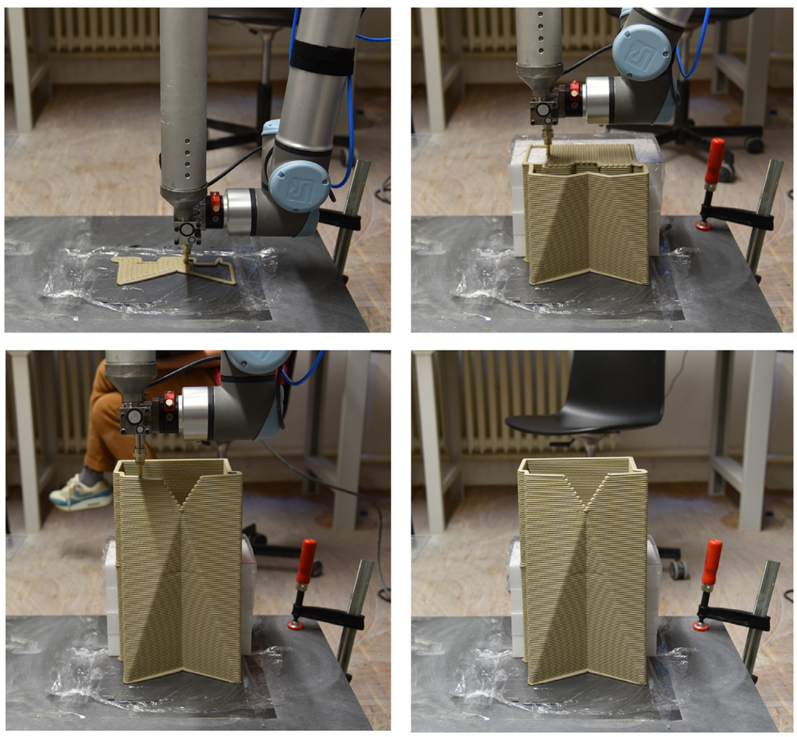
To verify fabricability and evaluate the limitations and prospects of the chosen digital fabrication process, a set of ceramic tiles of a selected area of the designed façade was additively manufactured and assembled into a 1:1 scale prototype. The production of the ceramic tiles includes the following processes: After the 3D extrusion process (4.1.1), the elements have to be dried (4.4.2), which requires defined conditions and preparations. These two processes are followed by the firing of the ceramic tiles (4.4.3), necessary to achieve maximum strength properties and allow the elements to withstand outdoor weather conditions for assembly (4.4.4). During the prototype manufacturing process, 15 tiles were 3D printed; nine of these, found to be of the best quality after firing, were mounted onto the substructure of a standard ventilated façade system of the final 60 x 108 cm prototype. Three of the tiles produced are the tiles with nests for two of the three selected species – the Black Redstart and House Sparrow.

4.4.1 3D Ceramic Extrusion 3D Printing

The original geometry of the tiles is represented by a surface-based geometry that is sliced to generate the paths for 3D Printing. With the nozzle diameter of 5 mm, the required slicing height of the layers is determined as 35 mm; the potential shrinkage from the drying and firing processes is calculated and planned prior to manufacture so that the tiles are produced approximately 11% larger than the final target size. The material used for the tiles is a grossed, ready-made ceramic body from the company Witgert with around 20% chamotte to gain maximum durability after firing. The printing time of one average layer with an average length of 55-70 cm of the bespoke tiles took around 40 seconds, which resulted in a printing time of around 70 minutes for one tile and allowed about three tiles to be produced on average in 8 working hours. Fig. 11.a documents the 3D printing process of a climate-performative tile, and Fig. 11.b documents the fabrication of a climate-performative tile with an integrated nest, which required temporary support for printing the nest cover to be added manually.



a Climate performative tile



b Tile with the nest

FIG. 11 Documentation of 3D printing (Larikova I., 2021)

4.4.2 Drying

The 3D printing process is followed by a drying process with the aim that the elements do not deform unevenly or crack due to shrinkage of the material. The geometry of the elements caused uneven shrinkage of the ceramic material, which became a major problem during the manufacturing process. The lab used for Printing and drying contained about 50% humidity. This low humidity level resulted in a very rapid and heterogeneous drying process, which caused significant deformations, especially twisting, of the vertical elements, with deviations of 5% to 15% from the original shape being observed (Fig. 12). Therefore, some of the elements were printed on a non-absorbent board, as it was believed that allowing this board to absorb water from a printed element would result in further deformation. However, no differences were observed between the elements printed and dried on these two types of boards. The next iteration thence included stiffening bridges within the geometry of the elements to provide better balance and less deformation. The final drying took about two weeks, after which the elements were carefully transported in order to subject them to the first so-called bisque firing in industrial plants. Another issue was the fragility of the elements after drying, which caused some tiles losses during transportation.

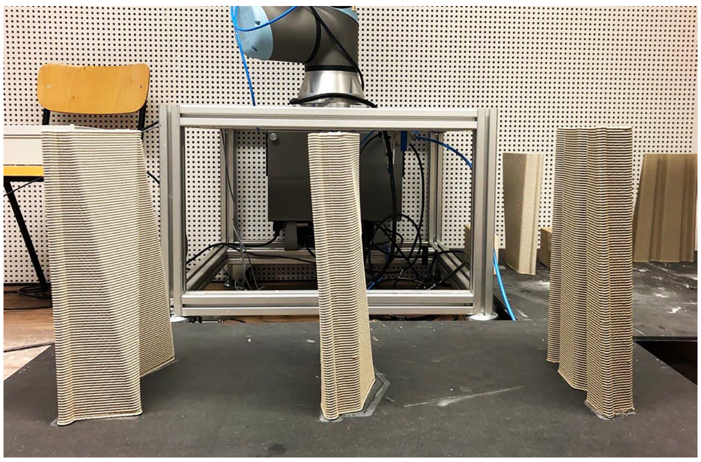


FIG. 12 During the drying process, deformations of the tiles were observed, caused by the low humidity level of the space and the uneven drying process.(Larikova I., 2021)

FIG. 13 Fired ceramic tile with a nest

4.4.3 Firing

To harden the raw ceramic element and to give the material maximum strength, elements were bisque fired at around 900°C. Firing was uneventful – no cracks appeared. The elements were glazed again and fired at 1200°C to achieve maximum durability of the elements enabled by the industrial production facilities. After firing, ceramic elements are typically more durable and stable compared to their dried state. However, they remain fragile, which can lead to further damage during transport and assembly operations. Fig. 13 shows a fired element with an integrated nest before assembly.

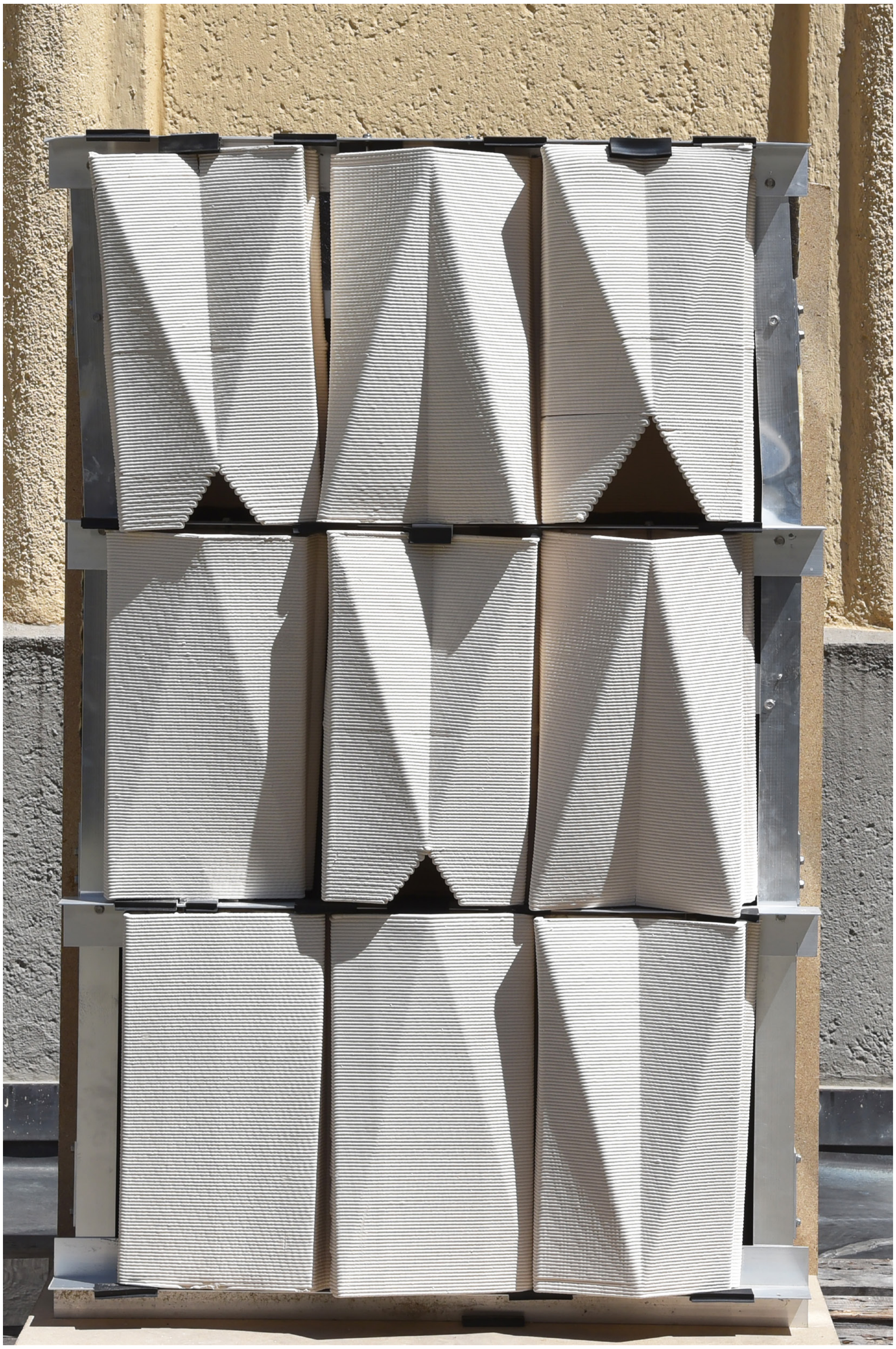


FIG. 14 Final assembled prototype

4.4.5 Assembly

As depicted in Fig. 14 and 15, a final prototype was assembled consisting of: nine tiles, eight of which were climate-performative, and three of the eight include nests; the insulation steel substructure; and the planned insulation layer behind it. Deformations caused mainly by the drying process did not prevent the final assembly, however, they made it significantly more difficult. It demanded additional fastening elements, making it laborious to take one element out for required future cleaning.

FIG. 15 Final assembled prototype

5 RESULTS AND CONCLUSION

5.1 SUMMARY OF RESULTS

This research presented preliminary results of the integrative design method and digital fabrication for wildlife-inclusive façade design. An analytical-based design approach with the integration of digital tools throughout the whole planning process was tested, validated, and analyzed; the AM tools have shown their potential for facilitating wildlife-inclusive façade design in terms of species needs, design quality, and the retrofitting of buildings in the urban contexts.

5.2 INTEGRATIVE DESIGN APPROACH

The integrative design approach for enabling wildlife-inclusive façade renovation has shown that the implementation of digital tools from the early design stages helps to link and collect the information of different disciplines and contributors within one computational design model. In particular, it contributed to the better integration of different functions both within a single façade element and the entire façade retrofitting design through the synthesis of different design criteria. Thus, the thorough analysis and simulation in the preliminary design phases formed a basis for well-founded design investigations, the evaluation of various options, and finding and selecting solutions. Together with experimental studies concerning the fabrication, and feedback loops of design adaptations and optimization cycles with respect to the fabricability of the tile designs, a continuous digital design-to-fabrication process could eventually be achieved. The experimental project has proven that for the successful development of the wild-live inclusive design for façades it is essential that several aspects of façade designs are investigated and improved simultaneously, in comparison with a sequential design approach where different disciplines are integrated on different design stages. Therefore, multifunctionality and visual architectural qualities distinguish the result of the approach. However, the integrative design approach in its current state also has certain limitations. For example, simulation of the actual behaviour of species and evaluation of the design in terms of its wildlife-friendly suitability cannot be performed due to the lack of sufficient background information and data. Due to the experimental nature of the project, the definition of design parameters related to animal behaviour was rather superficial, based on standard design principles and general information about the animal behaviour. The suitability can therefore only be analyzed experimentally on real-world prototypes and then returned to a digital model as part of future research.

5.3 FABRICATABILITY

Digital fabrication, namely extrusion 3D printing AM, has preliminarily proven its feasibility perspective in terms of site-specific animal-inclusive design solutions, which facilitate variability and local differentiation. The experimental project has shown that AM could contribute to the crucial improvement of retrofitting strategies and multifunctionality compared to the current traditional techniques. Manufacturability was demonstrated by producing a 1:1-scale prototype (Fig. 15), in which the tiles could be manufactured, fired, and assembled into the intended façade segment, despite manufacturing-related deformations. Some manufacturing obstacles encountered during the process, such as the shrinkage caused by the drying process and the fragility of the elements, would have to be addressed by more process and optimization iterations in the future. A short summary of the evaluated fabricability criteria could be seen in Table 4: the strongest feature of the AM production is a very high accuracy and resolution of the printed geometry, whereas a major challenge relates to deformation during drying. This obstacle could potentially be addressed by extended process simulation prior to production or by a selection of another cladding system or substructure that is more tolerable to potential deformations.

TABLE 4 **Fabricatability parameters evaluation**

	Accuracy of 3D printed Geometry	Durability after drying	Deformations caused by drying	Durability after firing	Deformations caused by firing	Compatibility with the selected façade system
high	√		√			
medium				√		√
low		√			√	

6 OUTLOOK

Exploring a new experimental topic that integrates several disciplines evokes many questions and discussions about its further scientific development and possible practical application. The chosen methodology has proven its feasibility, however, many aspects of the future work could be optimized. The research was conducted on different scales, and further issues could be addressed regarding scales from urban to macro and include a variety of potential research directions.

On the urban scale, it would be necessary to understand the possibility of species integration not only on the urban block level but on the city planning level; theoretical research, simulations, integration, and interdisciplinary planning on a city scale could facilitate more viable architectural solutions in the future.

On the macroscale, several topics need to be researched further. First, the fabrication process could be improved for future projects in several ways. For example, more suitable drying conditions should be tested, deformations could be precalculated, and the geometry could be adjusted more precisely to prevent deformations (e.g., as tested with stiffness bridges). Another possible direction for further research could be testing other AM or digital fabrication techniques, such as particle bed 3D printing or casting moulds. Second, real-life on-site tests are needed for further development of the design basis. Fig. 16 demonstrates a vision of a façade test bed, that is, to depict that it will be essential to test demonstrators in real-world scenarios, document the behaviour of a species and verify the correlation between assumption and actual practice of the nest usage by the species of interest, as well as analyze on-site climate parameters. Such data would be required to serve as an essential basis for subsequent design iterations.

FIG. 16 Collage of the future vision of multispecies facades for human and non-human urban cohabitation.

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