Ecological Performance Through Design and Digital Fabrication of Bird Habitats

Niloufar Emami

University of Illinois Urbana Champaign

Abstract

The world is becoming increasingly urbanized, leading to significant land-use changes that have major implications for biodiversity. One critical consequence is habitat loss, which has severely affected numerous species of aerially insectivorous birds, making them one of the fastest declining bird groups in North America. There is an urgent need for activating architecture towards building an ecological performative environment that meets the needs of non-human species alongside those of humans. This is highly relevant since computational design and digital fabrication methods allow design and materialization of complex morphological forms.

This paper presents the process and outcomes of a design studio offered at Illinois School of Architecture. The studio challenged students to design Bird Refuge Installations for migratory birds along Chicago's Montrose Point Bird Sanctuary Lakefront. Students researched and selected their bird species as the clients of the artificial nests, which included Purple Martin (19-20 cm), Eastern Bluebird (16-21 cm), and Piping Plover (17-18 cm). The habits and habitat requirements of each species informed the design of the artificial habitat. Next, 3D printed formwork (3DPF), was employed as the digital fabrication method to produce molds for repeatable casting of artificial habitats. Students designed and prototyped at various scales — staring at 1:4 scale, scaling up to 1:2 and then 1:1. There was a frequent iterative loop between design of the habitat, design of the mold, casting a nest instance and then demolding the cast piece. All mold parts were reusable.

The pedagogy offered opportunities and challenges. Designing complex biomorphic geometries was a challenging task for students, requiring them to shift from using REVIT and its product libraries to alternative platforms such as Rhino. From another perspective, the digital fabrication method of 3DPF posed challenges and constraints to designing forms that were appropriate as bird habitats while creating a topologically interlocking mechanism between nest modules. Students overcame the challenges through hands on learning by doing and iterating between the digital model and the physical artefact. Students were empowered to understand precast and additive manufacturing (AM) technologies and the way that AM can disrupt precast construction through 3DPF. The outcome of the studio was full scale prototypes for bird habitats for multiple species.

This article exemplifies the broader impact of digital fabrication tools on ecological performance in today's architectural education. It highlights a shift from using those tools solely to enhance creativity and efficiency, to employing them in service of ecological design. By bridging the gap between innovative design and fabrication technologies and practical environmental impact, this approach redefines the role of digital fabrication as powerful tools to create scalable and valuable impacts in architectural education.

Keywords: Multispecies design, artificial nests, digital fabrication, additive manufacturing, precast.

Introduction

The world is becoming increasingly urbanized. Today, more than half of the global population lives in urban areas, projected to increase to around two-thirds in 2050.[1] Rapid urbanization and construction cause significant land cover change, degraded environments and novel ecosystems that have major implications for biodiversity and human well-being.[2] In particular, and according to American Bird Conservancy (ABC), habitat loss is the greatest thread to many bird species.[3] Designers and researchers propose creating a new multispecies design paradigm that considers both human and non-human needs.[4]

There is an array of projects that explore making standalone structures placed in the built environment for bird nesting (Fig. 1). Stanislav Roudavski and his collaborators in *Deep Design Lab* at University of Melbourne explore the projects for "nonhuman clients" towards improving biodiversity.[5] As an example, using computational design and digital fabrication techniques — 3D printed wood — they created a habitat structure for a threatened, cavity-dependent bird which was installed on a tree branch.[6] Other examples include Gitta Gschwendtner's design named "Animal Wall" in Cardiff Bay River which is a 50-meter wall including 1000 houses for birds and bats.[7] Another example is a self-standing digitally fabricated clay bird house by SO-IL installed in Brooklyn Botanic Garden.[8] More recently, Formafantasma created a series of hollow cylindrical terracotta pillars to house birds and insects in a vineyard.[9]

Other projects push the idea even further by proposing bird-human co-habitation in building envelopes. Thomas Hauke, Wolfgang Weisser, and their collaborators founded *Studio Animal-Aided Design* startup company in Munich with the goal of promoting the concept of urban animal-human relations and co-habitation, by integrating animals as part of the design of open spaces.[10] In a project, they used Schwegler company's nesting aid which are in the forms of typical brick and concrete blocks.[11] Another example is the novel concept of "ecolope" defined as a shared multispecies architectural space that can replace the currently prevailing building enclosures or building envelopes.[12] Others have utilized clay additive manufacturing (AM) to fabricate façade tiles that can host cavity-dependent animal species.[13]

Fig. 1. (Top-left) 3D printed nest for cavity-dependent birds by Stanislav Roudavski; (top-right) Animal Wall by Gitta Gschwendtner; (bottom-left) clay bird house by SO-IL; (bottom-right) hollow cylindrical terracotta pillars by Formafantasma.

From a different perspective, an array of digital fabrication methods is accessible to designers to create artificial habitats with morphological forms. 3D printed formwork (3DPF) for casting concrete is among these methods, with applications at the building scale. Oak Ridge National Laboratory worked with Gate Precast to demonstrate the viability of using carbon fiber reinforced acrylonitrile butadiene styrene (ABS) plastic and the Big Area Additive Manufacturing (BAAM) in Domino Sugar Tower façade design.[14] They 3D printed the molds and reported that each mold could be cast 200 times without major degradation of the mold surface, which is 10 times more than the traditional method. This could offset the higher costs of the 3DPF which was three times more than the traditional wooden molds. Currently, Additive Engineering Solutions (AES) company is commercializing the technology.[15] Another project, Smart Slab, employed 3D printed formwork to create a concrete slab with rippling patterns for DFAB HOUSE.[16]

Reviewing literature, multispecies design is an emerging field shaped by a growing awareness of the environmental impact of urbanization and supported by the vast possibilities offered by advancements in design and fabrication tools. This article focuses on digital fabrication of stand-alone artificial bird nests. Two gaps that are addressed in this paper include first integrating ecological knowledge in the design process through translation of the species' individual spatial requirements into an artificially fabricated bird nest; and second, employing digital fabrication methods namely 3DPF for casting the artificial bird nests.

Pedagogy

A design studio offered at Illinois School of Architecture challenged students to design Bird Refuge Installations for migratory birds along the Chicago lakefront, Montrose Point Bird Sanctuary Site. The pedagogy of the studio comprises of two projects. The first project with a duration of three weeks focused on analyzing and remaking precast façade case studies. The aim of the project was to build students' skills in computational design, additive manufacturing, and silicon rubber mold making. The students were encouraged to use NURBS modeling platforms, namely Rhino, for CAD modeling. They were provided with OOMOO-25 silicon rubber material by Smooth-On, referred to as rubber mold in the text. They were also provided with PolyLactic Acid (PLA) plastic filaments for 3D printing on Raise 3D machines. Finally, Hydraulic Expansion Cements (HEC), particularly Rockite, was used for casting instead of traditional concrete made up of coarse aggregate. Rockite only requires mixing with water and sets rapidly, allowing demolding within an hour of casting. This project's pedagogy is discussed in a publication by the author. [17]

Once students acquired the fundamental hard skills in precast, the second project, Multispecies Design, was introduced. This project was organized into four milestones, each lasting two to three weeks. During milestone 1, spanning two weeks, students researched various bird species, selected one species to design for, and conceptualized four to six nest designs per group tailored to their chosen client using different media such as clay. Subsequently, they developed CAD models for all their concepts and 3D printed them at 1:4 scale.

Milestone 2 spanned two weeks when students selected one concept for further development. They explored various ways to design a mold for their chosen concept followed by casting it with Rockite. While it was not required to finalize the mold design by the end of this milestone, students were expected to assess the feasibility of casting their concept in a mold and/or identify the necessary modifications to make it castable. The deliverables included producing at least two mold iterations (using either rubber mold material or 3DPF) and creating at least two cast instances (successful or failed) at a 1:4 scale.

In milestone 3 spanning three weeks, students spent the first week integrating feedback from mid-review into the design of the blocks at the 1:4 scale. They then scaled up their block and mold designs to a 1:2 scale. This phase emphasized the development of a mechanical interlocking mechanism between blocks, requiring students to modify their designs so the blocks could interlock along at least one axis. Each iteration involved creating a mold, 3D-printing it and casting it for feasibility.

In milestone 4 spanning three weeks, students scaled up their mold designs to a 1:1 scale. Revisions to the block design were minimal, if any. The primary focus was on refining the mold design, including adjusting its thickness, experimenting with 3D printing settings to optimize printing time, controlling surface textures, and testing the mold's reusability through multiple castings. The final exhibition and studio review was held two weeks after completing Milestone 4, where students displayed prototyping iterations at various scales along with repeatable cast instances of their 3DPF (Fig. 2).

Fig. 2. Prototyping iterations at various scales displayed during final reviews; (left) Beyond Dune; (middle) Cradle; (right) The Aviary.

Student projects

Three teams, each consisting of two to three students, designed and fabricated artificial nests for three bird species: Purple Martins (19-20 cm), Eastern Bluebirds (16-21 cm), and Piping Plovers (17-18 cm). The habits and habitat requirements of each species are summarized in Table 1, while Table 2 outlines the design features of each project in response to the identified habitat requirements of birds.

The Aviary (designed for Purple Martins)

Nupur Agrawal, Aditi Panji, and Himanshi Rathod designed and fabricated the Aviary project for Purple Martins. Students designed a triangular grid to aggregate modules into an assembled wall (Fig. 3 top-row). The final triangular modules measured 8” wide, 6” deep, and 5” tall (~20.32 x 15.25 x 12.7 cm). The size of the modules was doubled at the base to achieve the preferred height of 10’ for placing bird nests. Four module types were designed — nesting, corner, planter, and support modules (Fig. 3 middle-row). The modules were interlocking along the x-axis using asymmetrical half-circular indentations. Additionally, convex and concave double-curved surfaces were incorporated on the sloped sides of the blocks to ensure interlocking when the modules were assembled (Fig. 3 bottom-row). For mold design, the focus was on reusability and interchangeability of mold parts to facilitate casting multiple module types. The general strategy involved creating a base part with a spherical protrusion — which formed the circular negative space of the nest. Four mold walls were clamped to this base (Fig. 4), and the pour hole was positioned at the top.

Fig. 3. (top-row) final assembly from cast modules; (middle-row) drawing of different module types in the Aviary; (bottom-row) interlocking mechanism between the modules.

Table 1. Habits and habitats of selected bird species by the students.

	The Aviary project for **Purple Martins** 	**Cradle project** for **Eastern Bluebirds** 	**Beyond Dunes project** for **Piping Plovers** 
Bird Size (w x h)	19 - 20 cm	16 - 21 cm	17-18 cm
Wingspan	39 - 41 cm	32 cm	35 - 41 cm
Number of eggs	3 - 6 eggs	2 – 7 eggs	3 - 4
Size of the eggs	2 – 2.8 cm by 1.5 – 2 cm	1.8 – 2.4 cm (length) by 1.5-1.9 cm (width)	3.2 x 2.5 cm
Nest volume	~15 x 15 x 7.5 cm = ~1687 cm^3	2800 cm^3	NA
Nest entrance shape and size	Semicircular 3.8 - 6.35 cm	Circular 4.5 cm	Circular depression around 2 cm deep and 10 cm wide.
Nest height	1.8 meters – 3 meters	0.9 m – 15 m	Ground level
Relationship with other bird's nests	Lives in colonies with only purple Martins. Invasive species to it are European Starlings and House Sparrows.	Great with other birds of the same species. Territorial and protective of own nest. Avoid House Sparrows as they kill Eastern Bluebirds and destroy their eggs.	Does not live in colonies.
Relationship with human	Domesticated birds from a very long time, completely rely on man-made nests now.	Lives in backyards and interacts with known humans. Scared at first.	The bird is not friendly and domesticated.
Relationship with nature	They prefer open spaces with sparse trees at least 15 m away from tall trees that allows them to hunt insects and significantly reduces predator attacks.	They prefer an open country with patchy vegetation and large trees. Examples include meadows and golf courses.	This shorebird nests in coastal sand and gravel beaches in North America. It builds its nests higher on the shore near beach grass and other objects.
Other notes:	They have memories of the space they nest during the summer months and migrate back to the same place after spending winter in the South Americas.	NA	NA

Table 2. Design features of each project in response to the identified habitat requirements of birds.

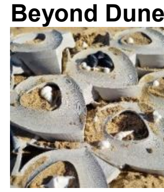
	The Aviary project 	**Cradle project** 	**Beyond Dunes project** 
Design features of the module in response to birds' needs.	The male bird uses the ledge above the nest entrance hole for perching to guard the nest.	The scooped-out curvature on the outside allows the male bird to guard the nest's edges and territory.	There is a hole in the center of the module to allow sand to fill it out so that the bird creates her own protrusion in the sand as her nest.
Entrance shape and size	Semi-circular entrance prevents invasive species such as Starlings from entering.	The circular entrance of the nest is 1 ½" = ~3.8 cm, which is tailored to the bird's size.	The inner opening is designed based on the clutch size and nest size of the bird.
Design features of the assembly in response to birds' needs.	Purple Martins are communal and live in colonies. A bird wall with multiple nest cavities is designed.	The entrance to the nest is located underneath the module, to protect the nest from rainwater.	The modules can move in the z-axis upon pressure from the sand or water. Through the incremental movements of the modules, the assembly is intended to make a dune that protects nesting sites from floods at the beach.
Desired nesting height of the assembly	10' height (300 cm) The support module is designed to elevate the nesting structure to 10 ft.	0.9-150 cm. The tower is designed to reach this height for the top nest cavities. The bottom modules are designed as support.	NA

Fig. 4. PLA mold design for the Aviary project.

Cradle (designed for Eastern Bluebirds)

Khwaeesh Desai, Arpit Amarseda, and Shengjie Li designed Cradle, a nesting tower for Eastern Bluebirds. It featured top and bottom modules with scooped-out shapes forming cradle-like cavities (Fig. 5). Each module measured 6.7" wide, 6.7" deep, and 4.6" tall (~17.2 x 17.2 x 11.7 cm). Each module contained a central nesting cavity, with the entrance located in the lower module. The modules were stacked along the z-axis to form a single nest, with the shaded cradle providing a resting spot for the male bird to guard the entrance.

Inspired by Erwin Hauer's Jerusalem Tower, the stacked modules were arranged in an alternating pattern to create a sculptural tower, while mimicking natural tree hollows. Interlocking mechanism occurred in the z-direction, with gravity in the z-direction ensuring stability. To withstand lateral wind loads, each module included a cavity across the module for inserting a rebar, which ultimately reinforced the tower as it was stacked. Steel dowels were used to create cavities and then a sized-down dowel was inserted as rebar. The even module requires a five-part mold, consisting of a base, two walls, an entrance plug, and a cap to form the interlocking depth. The odd module used a three-part mold consisting of a base and two walls (Fig. 6 top-row and bottom-row).

Fig. 5. Cradle tower for Eastern Bluebirds cast at two different scales.

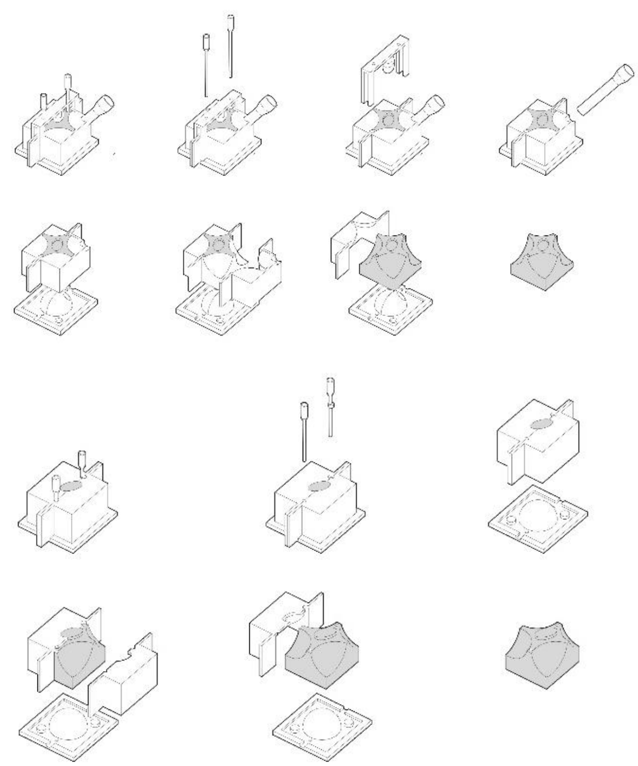


Fig. 6. (top-row) the five-part mold for Cradle's module type-A, with bird entrance; (bottom-row) the three-part mold for Cradle's module type-B.

Beyond Dunes (designed for Piping Plover)

Marcos Rodriguez and Josep Calvet addressed the issue of flooding on sandy beaches, which negatively impacts the nests and eggs of Piping Plovers. Since the bird prefers to dig its own nest in the sand, the design needed to allow sand to pass through the module (Fig. 7-left). Additionally, the pieces were specifically designed to enable movement along the z-axis, allowing the formation of a sloped dune over time due to the pressures of sand and water exerted from beneath the modules (Fig. 7-right). The 3D printed mold consisted of 22 components and was highly complex.

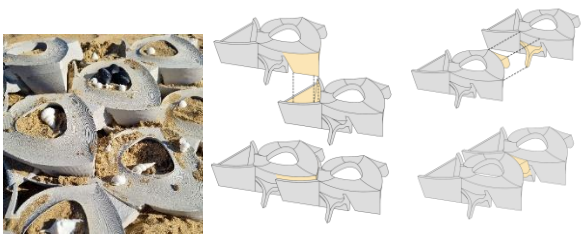


Fig. 7. Beyond Dune (left) cast modules; (right) interlocking mechanism.

Criteria for Evaluating Students' Projects

Students' projects were evaluated according to four criteria related to design and digital fabrication.

Design in support of wildlife

An important aspect of studio pedagogy is encouraging students to consider how designers can act as agents of change through design, particularly in mitigating the negative effects of urbanization. At the core of this project was the students' research into the habits and habitats of birds, which informed the evaluation of their design concepts. The designed nests and their openings adhered to specific geometric parameters, such as size, shape, and placement height, all tailored to meet the identified habitat needs of particular bird species. For instance, male Eastern Bluebirds perch outside their nests to protect the eggs within. In response, the *Cradle* project featured scooped curvatures in the tower, providing a resting surface for the birds. Another example is the *Aviary* project, designed for Purple Martins. To deter House Sparrows from entering while still accommodating the Purple Martins, the nest entry was shaped as an eye-like opening instead of the more common circular or semi-circular forms. This design choice significantly influenced the mold-making process, requiring students to spend weeks designing a removable plug to enable successful demolding of the cast block.

Limiting design variability of the modules while using digital design methods

Today, computational and parametric design tools enable a multitude of designers to create complex and non-identical elements for assembly. In fact, these digital tools are often associated with generating non-identical parts. However, in practice, only a limited number of these complex and variable units are typically built due to their higher costs. The studio pedagogy emphasized the use of computational design tools as a powerful means of creating curved and morphological geometries while also placing constraints on the number of block types that could be designed. For instance, the *Aviary* project utilized two core block types, along with two additional variations: one was a scaled version of a core block, designed to achieve specific heights more efficiently, and the other was a half-block used to define the wall's edge condition. The *Cradle* project relied on only two block types, which were alternately stacked, while the *Beyond Dune* project employed only a single block type.

This design approach has significant implications for the digital fabrication of 3DPF and their cast instances, as it minimizes the costs associated with custom repetitive manufactured components. More broadly, this strategy allows architects to retain creative control over component design while leveraging the efficiencies of repeated fabrication tooling in custom repetitive manufacturing.

Mechanical Interlocking of modules

Another key evaluation criterion was the assessment of the mechanical interlocking mechanism between the blocks, which constrained the movements of assembled blocks in at least one direction (x, y, or z-axis). By focusing on the design of unit blocks while limiting the number of block types, the pedagogy encouraged students to concentrate on the detailed design of the modules and to embed the logic of assembly at the part level. This strategy enabled the emergence of open-ended and customizable aggregations, fostering creativity within the constraints of modular design. All students' projects successfully incorporated topological transformations in the perimeter geometries of the blocks to build a topological interlocking assembly.

Digital fabrication and mold reusability

Over the past two decades, architectural schools have been experimenting with digital fabrication to explore how it can push the boundaries of creativity, efficiency, design variability, and the creation of complex geometries and assemblies. However, only a small percentage of these efforts have resulted in creating scalable workflows and performative projects that address our pressing problems. 3DPF is regarded as a method with significant potential for scaling up in future construction. In the precast industry, the number of casts that can be produced from a single mold is a key economic indicator. As a result, the reusability of mold components was a critical criterion in evaluating students' projects. All the projects incorporated molds designed with reusable parts, ensuring they could withstand multiple casting and demolding cycles while maintaining precision and functionality.

Discussion

The lessons learned from this 3DPF experience can be extended to architectural-scale applications. Insights from this small-scale project have direct implications for building-scale designs:

Lesson 1: Pushing the boundaries of designing complex geometries for precast construction. 3DPF leverages the strengths of additive manufacturing to create freeform and intricate geometries with smooth or textured surface patterns. By casting concrete or other materials within the 3DPF molds, these freeform geometries are solidified into strong and durable forms. Additionally, this approach offers the potential to incorporate insulation or fibers into the cast material, enhancing both its structural and thermal performance.

Lesson 2: Integrating design and fabrication early in the design process. Students who established a clear mold design strategy early in the project were able to dedicate more time to refining the mechanical interlocking mechanism and the digital fabrication of molds in the later stages. In contrast, teams still grappling with mold design challenges during these later phases struggled to focus on interlocking mechanisms or the 3D printing of molds. This highlights the importance of integrating design and fabrication considerations from the outset. Architects can contribute innovative ideas to precast design by engaging directly in the fabrication process, while precast engineers can bring valuable expertise in material properties and manufacturing methods during the early stages of design. Incorporating fabrication considerations through small-scale prototyping ensures successful and integrative solutions by the project's completion.

Lesson 3: Simplicity is key. Students who developed a simple and straightforward strategy for designing the mold at a 1:4 scale were able to progress more efficiently, focusing on integrating the mechanical interlocking mechanism at 1:2 and 1:1 scale. In contrast, students who did not establish a clear mold design strategy at the smaller scale faced challenges in modifying the block design and its corresponding mold at larger scales. This demonstrates the importance of simplicity in mold design, even when digital fabrication tools are available. A well-defined and uncomplicated mold design strategy is a valuable lesson that can be applied to large-scale architectural projects, promoting smoother workflows and more effective outcomes.

There are also lessons from this experience that may not translate directly to large-scale applications.

- Since the designed molds consisted of multiple parts, controlling leakage proved to be a significant challenge. This was managed by applying clay to the overlapping seams — a time-consuming process that required considerable manual effort. In precast industry practices, caulking is typically used to control leakage. However, this labor-intensive approach could pose a barrier to scaling these lessons for large-scale manufacturing processes.

- Rockite was used for casting, allowing demolding within 15 minutes of pouring. This quick demolding process was crucial in preventing deformation of the mold parts and ensuring they did not stick to the cast pieces. However, in large-scale applications where standard concrete mixes — rather than fast-setting mixes — are typically used, it remains uncertain how complex cast pieces could be demolded without encountering these challenges.
- In repeatable casting, the plastic mold pieces experienced slight deformation due to the heat generated during concrete curing. As the mold size increases, the amount of heat from the curing process will also increase, potentially leading to greater deformation. This could negatively affect both the number of times the plastic molds can be reused and the tolerances of the cast pieces. Using heat-resistant plastic materials other than PLA for 3D printing may offer a viable solution for building-scale applications.

Future steps

The fabricated bird nests in the studio were not tested on university grounds or at the Montrose bird sanctuary park due to several obstacles. Installing any structure on university property requires a licensed structural engineer's approval, which was not attainable within the timeframe of the semester-long studio project. As for the Montrose site, attempts to engage with the administrative group to discuss a potential installation were unsuccessful. Currently, the author is collaborating with experts in the Natural Resources & Environmental Sciences at the College of Agriculture, Consumer and Environmental Sciences at University of Illinois to design and fabricate alternative bird nests using the same methods. These nests are designed for installation on designated natural grounds managed by that department. The monitoring methodology involves using iButtons to log temperature within the nest cavities. The success of an artificial nest cavity will be evaluated based on two key metrics: whether birds choose it as a habitat and the number of nestlings hatched and raised in the concrete artificial nests compared to traditional wooden nest boxes installed at the same site.

Conclusion

The pedagogy emphasized the importance of ecosystem preservation and the role of design in supporting wildlife. Architecture must be activated to embrace a multispecies design paradigm. This is because natural animal habitats are often characterized by complex morphologies that have historically been challenging to design and fabricate. However, the integration of computational design and digital fabrication tools into architectural practice has enabled the creation of complex building elements that were once unattainable. The methodology of 3D printed formwork (3DPF) for casting concrete offers significant opportunities for designing freeform, strong, and durable artificial habitats. Building technologies and digital fabrication offer powerful tools to create scalable and meaningful contributions towards building a sustainable future. Future studies will explore incorporating insulation materials into the concrete mix and conducting experiments to determine whether birds select the artificial nests for habitation. Additionally, temperature measurements within the nests will be recorded to assess their suitability for housing birds and their eggs. Another evaluation criterion will be comparing the nestlings raised in these artificial nests to those in traditional wooden nest boxes installed on the same site.

From a broader perspective, designing for nonhuman clients — such as birds — has significant implications. It challenges students to consider the fundamental needs of a client that does not share their characteristics or experiences. This exercise fosters empathy and positively influences the students' future professional practice by encouraging inclusive and thoughtful design approaches.

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Notes:

[1] United Nations, “Wprld Urbanization Prospects” (New York, 2014), ST/ESA/SER.A/352.

[2] Wolfgang W. Weisser et al., “Creating Ecologically Sound Buildings by Integrating Ecology, Architecture and Computational Design,” *People and Nature* 5, no. 1 (2022): 4–20, https://doi.org/10.1002/pan3.10411.

[3] “American Bird Conservatory,” accessed June 11, 2024, https://abcbirds.org/.

[4] Weisser et al., “Creating Ecologically Sound Buildings by Integrating Ecology, Architecture and Computational Design.”

[5] “Deep Design Lab,” accessed August 5, 2024, https://wiki.deepdesignlab.online/.

[6] Dan Parker et al., “A Framework for Computer-Aided Design and Manufacturing of Habitat Structures for Cavity-Dependent Animals,” *Methods in Ecology and Evolution* 13, no. 4 (2022): 826–41, https://doi.org/10.1111/2041-210X.13806.

[7] Rose Etherington, “Animal Wall by Gitta Gschwendtner,” accessed August 8, 2024, https://www.dezeen.com/2009/08/28/animal-wall-by-gitta-gschwendtner/.

[8] Jing Liu and Florian Idenburg, “SO-IL,” 2022, accessed August 8, 2024, http://so-il.org/projects/palace-for-the-eastern-bluebird.

[9] Amy Peacock, “Formafantasma Nestles Biodiverse Installation in Champagne Vineyard for Perrier-Jouët,” 2024, https://www.dezeen.com/2024/09/25/biodiversity-island-formafantasma-champagne-perrier-jouet/?li_source=LI&li_medium=bottom_block_1.

[10] Studio Animal Aided Design, “Studio Animal Aided Design,” 2015, https://animal-aided-design.de/en/.

[11] Schwegler, “No Title,” accessed August 1, 2024, https://www.schwegler-natur.de/?lang=en.

[12] Weisser et al., “Creating Ecologically Sound Buildings by Integrating Ecology, Architecture and Computational Design.”

[13] Iuliia Larikova et al., “Additively Manufactured Urban Multispecies Façades for Building Renovation,” *Journal of Facade Design and Engineering* 10, no. 2 (2022): 105–25, https://doi.org/10.47982/jfde.2022.powerskin.7.

[14] Lonnie Love et al., “Feasibility of Using BAAM for Mold Inserts for the Precast Concrete Industry (CRADA NFE-17-06874 Final Report),” *ORNL Report* ORNL/TM-20, no. September (2019): 1–11, https://www.osti.gov/servlets/purl/1606893/.

[15] “Additive Engineering Solutions (AES),” accessed January 7, 2025, https://www.additiveeng.com/.

[16] Mania Aghaei-Meibodi et al., “Smart Slab: Computational Design and Digital Fabrication of a Lightweight Concrete Slab,” in *ACADIA 2018: Re/Calibration: On Imprecision and Infidelity*, ed. Phillip Anzalone, Marcella del Signore, and Andrew John Wit (Mexico City, Mexico: Acadia Publishing Company, 2018), 434–43, https://doi.org/https://doi.org/10.52842/conf.acadia.2018.434.

[17] Niloufar Emami, “Educating Architecture Students on Precast: Employing Additive Manufacturing to Recreate Historic Precast Facades,” *International Journal of Architectural Computation* 23, no. 1 (2024): 1–19, https://doi.org/10.1177/14780771241254638.