PLANimal:

A Computational Approach To Animal-Aided-Design in Architecture

Andrew Smith

Tutor: Tom Svilans

Det Kongelige Akademi

CITA Studio

Abstract

Urban development has crucial direct and indirect impacts on biodiversity (McDonald et al., 2020). Providing suitable living conditions for some species groups at the expense of others, studies indicate that species density in cities is lower than in the natural habitats they replace (McKinny, 2002). Unfortunately, the architects, planners, and developers who shape our urban environments don’t quantifiably consider the impact architectural-scale design decisions have on a given site's ecology. Understanding and predicting the ecological consequences of architectural-scale design decisions will be increasingly important to sustainable urban development, and to reduce its impacts on global biodiversity. Current architectural modeling platforms enable architects to design and coordinate high-fidelity geometric building information models. However, design-for-construction workflows and their associated software environments are slow to incorporate the capacity for considering non-anthropocentric, ecological information in this process. Broadly, the goal of this project is to develop a software interface and design-to-fabrication process that incorporates gathering and digitally modeling select ecological information, simulating how design decisions influence this model, and measuring the potential ecological impact of those design decisions. Due to a short timeframe, the specific case study of this project is limited to surveying and modeling ecological conditions of a greenfield site within central Copenhagen as they relate to a target species of insect. Then using this model to inform the design of three self-similar architectural expressions in robotically extruded cellulose, whose impact on habitat creation will be measured on-site and used as feedback for their respective ecological models. Three distinct research methods are required in this project. First, developing a multi-platform software interface that extends the capabilities of Rhino and Grasshopper to retrieve, model, visualize, and coordinate ecological data. Second, a methodological process for gathering and modeling relevant ecological information for a geographically specific site using GIS and in-situ analysis. And finally, the fabrication of a series of three concurrent architectural habitat expressions informed by the ecological models that provoke a measurable response in the chosen target species at the site.

Keywords: Ecological Design, Biodiversity, Animal-Aided-Design, Computational Modelling, Robotic Cellulose Printing

Contents

1. **Introduction**
2. **Background**
    - 2.1. Biodiversity Collapse
    - 2.2. The Importance of Biodiversity in Cities
    - 2.3. Ecological Impacts of Urban Development
    - 2.4. Architecture's Role in Urban Ecologies
    - 2.5. Ecological Modeling
3. **State-of-the-Art**
    - 3.1. Ecological Design
        - 3.1.1. Animal-Aided-Design
    - 3.2. Modeling Ecologies
        - 3.2.1. Ecological Modeling in Architecture
    - 3.3 Architectural Habitat
4. **Project Objectives**
5. **Methods**
    - 5.1. Data Gathering
        - 5.1.1. Regional Analysis
        - 5.1.2. Site Survey
        - 5.1.3. Species Targeting
    - 5.2. Ecological Modeling
        - 5.2.1. Species Portrait
        - 5.2.2. Material
        - 5.2.3. Geometry
        - 5.2.4. Simulation
    - 5.3. Fabrication
    - 5.4. Observation

6. **Experiments**
    - 6.1. Ecological Modeling
        - 6.1.1. Site Survey
        - 6.1.2. Regional Analysis
7. **Discussion**

1. Introduction

Architects globally are becoming increasingly aware of the negative environmental impacts that result from their contributions to the planet's rapidly expanding urban centers. One byproduct of urban growth is the rapid conversion of natural landscapes into anthropocentric habitats, which puts increasing pressure on local and global biodiversity (Beatley & Newman, 2013). Unfortunately, the impact of building-specific design decisions on their site's ecosystem is un-investigated and entirely absent from the building delivery process. Understanding and predicting the ecological consequences of architectural design decisions will be increasingly important to sustainable urban development, and to slow global habitat loss. Present-day architectural modeling platforms enable the design and manipulation of high-fidelity and complex geometric and information models. However, design-for-construction workflows and their associated software environments are yet to incorporate any capacity for considering non-anthropocentric ecological information in this process. The development of an integrated, analytical, ecological model as part of the traditional project delivery has growing relevance to the territory of ecological design in architecture. Greater accessibility to methods of implementing 'animal-aided-design' and 'design-for-species' within existing design paradigms is increasingly important to global biodiversity as urban development continues to replace existing habitats for plants and animals.

2. Background

2.1. Biodiversity Collapse

A biodiversity collapse occurs when the diversity of species (i.e., the number of distinct animal or plant species occurrences) in a given ecosystem declines significantly in a short period of time (Lovejoy, 1997). Even if only one cornerstone species disappears from an ecosystem, it can lead to imbalances and disruptions within the entire ecosystem. For example, the disappearance of a predatory animal species can lead to increases in the populations of its prey, which can in turn lead to the degradation of entire landscapes. In severe cases, biodiversity loss can lead to the collapse of an entire ecosystem as a whole (Hirsch, T., 2020). Studies have found that such cases of severe biodiversity collapse also cause the loss of important ecosystem services (i.e., pollination of crops, regulation of pests and diseases, soil erosion, etc.). Additionally, studies suggest that biodiversity collapse also has negative impacts on human health when the loss of certain species reduces the availability of resources needed to produce supplies of food and medicine. Biodiversity collapse can also have social and cultural consequences. Many cultures, especially in developing regions of the world depend on the resources provided by ecosystems for their livelihoods, cultural practices, and even spiritual values (Clark N. et al., 2014). The loss of biodiversity can lead to the loss of these resources and the erosion of cultural practices and traditions. Many factors can contribute to biodiversity collapse, including habitat destruction, habitat fragmentation, climate change, and even the introduction of invasive species (Hirsch, T., 2020). More than

90% of man-made pressure on biodiversity is attributable to the food, energy, infrastructure, and fashion industries (Kurth et al., 2021).

2.2. The Importance of Biodiversity in Cities

A city, with its human, plant, and animal inhabitants, and its manufactured environment is still itself a complex ecosystem. Biodiversity is just as crucial to the health and functioning of these urban ecosystems as it is to natural ones (Lim, A., 2021)(Beatley & Newman, 2013). Studies show that the human residents of cities benefit from the presence of nature in their daily lives, either through the provision of nature-based recreational opportunities or simply through the aesthetic value green spaces offer, such as its proven potential for stress reduction, and wellness benefit (Jo et al., 2019). Additionally, urban biodiversity provides economic benefits in the form of ecosystem services. These are anthropocentric services resulting from natural resources and processes that benefit humans (Daily G., 2003). Air purification, flood control, carbon sequestration, and nutrient fixing are all ecosystem services that can increase the economic performance of a city (Oberndorfer et al., 2007). Biodiversity also helps cities to adapt and mitigate the impacts of climate change. Urban areas have been shown to be especially vulnerable to several impacts of climate change, such as heat waves and flooding. (Beatly & Newman, 2013) Biodiversity can indirectly help to mitigate these impacts by facilitating healthier, and more resilient urban vegetation on an architectural and urban scale. Green roofs, wild easements, parks, vacant lots, and bioswales all help to regulate city temperatures and absorb excess stormwater (Oberndorfer et al., 2007). Biodiversity can contribute to cultural and social cohesion as well. Finally, urban green spaces can provide a sense of place and belonging for communities and can facilitate social interactions and cultural practices (Peters et al. 2007). Having a diverse range of plant and animal species in cities can even provide a range of cultural and recreational opportunities to the city's residents. Having a diverse range of species in cities can also provide opportunities for cultural enrichment and appreciation. For example, certain plants and animals may have cultural significance for different groups of people, and having these species present in cities can provide opportunities for people to connect with their cultural heritage (Clark N. et al., 2014).

2.3. Ecological Impacts of Urban Development

Urban development has a significant impact on local and global biodiversity, both directly through processes of land conversion, and indirectly through its reliance on resource transportation and consumption. Focusing on the direct impacts, urban development (especially of greenfield sites) relies on the conversion of natural habitats like wetlands (in coastal cities), grasslands, and forests, into more typically homogeneous built environments. This practice often leads to the destruction of the habitats of a multitude of species, which in turn has serious consequences for their local populations and for the ecosystems in which they live (Simkin D. et al., 2022). In addition to habitat loss, urban development also fragments habitats, breaking larger ecosystems up into smaller, isolated patch networks. Habitat fragmentation makes it difficult for some species to move between habitats, leading to a reduction in the number of individuals in the population. Even after the development of an area is completed, urban areas tend to have higher levels of pollution due to the presence of industrial activities, poor waste management, and the increased use of vehicles. This pollution has negative impacts on the health of many species and can make already diminished ecosystems less suitable for native species. Finally, all of the disruptions above can facilitate the spread of invasive species (those species not native to the area) which can cause further harm to native species and their ecosystems. Invasive species, especially those better adapted to urban environments, will outcompete native species for resources and further alter the structure and function of ecosystems (McKinney M., 2006).

2.4. Architecture's Role in Urban Ecologies

Architecture can play a significant role in shaping urban ecologies, both at the scale of individual buildings and at the scale of an entire city. For instance, the materials used in the construction of a building can have a significant impact on the local ecology. Locally sourced materials, for example, can help to reduce the environmental impact of transportation, while the use of recycled or sustainable materials can help to reduce the overall environmental footprint of a building. The design and construction methods of a building will impact it's operational and embodied energy efficiency, which in turn affects the local and regional ecologies. Passive solar design, bio-based insulation, and energy-efficient windows are all design decisions that help to reduce the energy demands of constructing, operating, and maintaining a building, which can reduce greenhouse gas emissions and other environmental impacts. The design of a building also has an impact on local water resources, and the regional watershed. For example, the use of green roofs and rainwater harvesting systems can help to reduce the amount of stormwater runoff generated by a building, which helps to protect local water resources. Lastly, and most relevant to this project, Architecture can also play a role in creating habitats for local flora and fauna. For example, the inclusion of green roofs, walls, and other types of vegetation can provide a habitat for a variety of species and contribute to the overall health and diversity of the local ecosystem.

2.5. Ecological Modeling

Ecological modeling is a field of study that involves the development of mathematical and computer-based models to understand and predict the dynamics of ecological systems (Soetaert & Herman 2009). The history of ecological modeling can be traced back to the early 20th century when scientists began to develop mathematical models to understand population dynamics and other ecological processes (Breckling et. al., 2011). One of the earliest examples of ecological modeling was the development of the Lotka-Volterra equations in the 1920s, which described the interactions between predator and prey populations. In the 1950s and 1960s, ecologists developed more complex models that incorporated multiple species and trophic levels and used computer simulations to study the dynamics of ecological systems. Over the past several decades, ecological modeling has become increasingly sophisticated, incorporating a wide range of data and complex modeling techniques. Today, ecological modeling is used to study a wide range of ecological systems, including ecosystems, populations, communities, and landscapes (Soetaert & Herman 2009).

3. State Of The Art

3.1. Ecological Design

"Humanity stands at a crossroads with regard to the legacy it leaves to future generations." Global biodiversity is declining at an unprecedented rate, and the many pressures driving this decline are intensifying. (GBO5 et al., 2020). Faced with this difficult future, architects and urban designers are embracing ecological design practices to reduce the negative impact of urban development on their local ecosystems and wildlife. Ecological design is defined as "any form of design that minimizes environmentally destructive impacts by integrating itself with living processes." (Van der Ryn, Cowan 1996). For architecture, this often means designing buildings that closely consider their environmental impact over their entire lifecycle. Life-Cycle-Assessments, Environmental Impact Reports, and Environmental Product Declarations all emerged in the previous decade in response to these concerns about the environmental impact of a building's lifecycle. Recently, however, several approaches have been put forward that also explicitly include biodiversity into urban ecological design, such as 'biodiversity-sensitive urban design' and 'animal-aided design'. These approaches consider not just the importance of land preservation (i.e., protection of natural wildlife habitats), but go further to consider the entire city as a potentially beneficial habitat for species. (Beate et al., 2019). Research shows that bees, for instance, have higher species richness and flower visitation rates in cities versus their rural counterparts (Piana, Max R. 2014). The following chapter summarizes several projects and articles of research that describe state-of-the-art methods for (qualitatively and quantitatively) considering ecological factors in the design of single and multi-species habitats at the architectural scale. Additionally, examples are provided of how ecologists and architects go about modeling ecologies. Still, despite the growing body of work adopting Ecological Design principals, and the urgent calls to integrate biodiversity into urban development strategies (Niemelä 1999), the reality is that considering biodiversity and ecosystem service provisions are not yet mainstream to the landscape, architecture, and urban planning practices. (AAD 2020). A possible reason for this absence, and the focus of this paper, is that our digital design platforms focus too heavily on issues of architectural form and building systems rather than those of landscape, biology, and other 'soft' building components. More specifically, there is a broad range of ecological elements that lack a developed and distributed computational design technique. (Burry 2015) This gap means there is an unfilled potential for computation to drive a better understanding of ecological information at the architectural scale, and how we can design architecture that is quantifiably beneficial to its local biodiversity.

3.1.1. Animal-Aided-Design

Recent research has highlighted the significance of cities for biodiversity, making them, like their rural counterparts, important places for conservation. Urban conservation approaches typically focus on open green areas (i.e., parks and sports fields) and aim to protect species already known to occupy the site (Fig. 3.1). Though a valid approach, this method of conservation overlooks more vulnerable native species displaced by urban development and does not directly contribute to novel habitat creation (Beate. et al. 2019). An alternative conservation strategy that can be more supportive towards biodiversity, is to target creating habitats for species native to the region that are not commonly observed in the urban environment but have the potential for introduction. *Animal-Aided Design* is a recently proposed methodology for urban development which includes these wildlife conservation approaches within landscape architecture (Weisser, W, Hauck, 2019). The basic idea of AAD is to consider the needs of one, or several target animal species early in the project planning process so that they can be an integral part of its design. The first step of the AAD methodology is the selection of target species by taking into consideration the regional species pool, spatially specific species occurrences, and importantly, native species' potential. After target species selection, the needs of the species throughout their life cycle are analyzed. This analysis requires knowledge about food sources, breeding places, and shelter needed at all different stages of the life of the target species. In their paper *Animal-Aided Design,* professors Wolfgang Weisser and Thomas Hauck propose the refurbishment of an apartment block in Munich, Germany as a hypothetical design case for AAD. The goal of the design was to replace an existing building façade, with one that supports several habitat conditions for the building's local wildlife. The target species for the study included several native bird species and a sand lizard; All of which are known to breed on the building site. Detailed "Species Portraits" were developed by species experts during the proposal's design process. The portraits, a concise reduction of the needs and properties of each species, were used as a checklist during the project conception to inform over twenty specific, and illustrated design decisions (Fig. 3.2). The underlying rationale of AAD, and its proposed methodology forms the basis for how and why a target species approach is applied to the methodology described later in this research project. Unlike the methods described in AAD, this research explores computational techniques that can assist architects in the species selection process and 'portrait' creation for the chosen target species using a novel combinatorial process of filtering open-source ecological and GIS datasets (Dynamic Earth, Bioscore 2.0, and NVDI) within a software interface embedded in Rhino + Grasshopper.

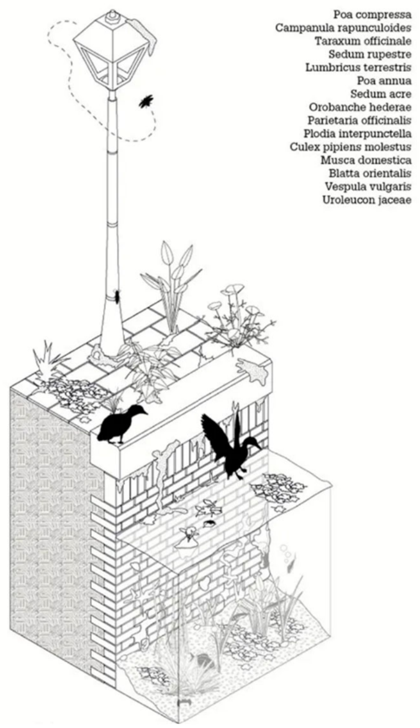


Figure 3.1: illustration of observed animal biodiversity at an Amsterdam canal edge. (Bellotti, G. Revelle, E., 2011)

CRITICAL NEEDS

Places for shelter, resting, and roosting in hedges at the East of the building, with thorns and dense branches, e.g. Hawthorn (*Crataegus*), Privet (*Ligustrum*), hornbeam (*Carpinus*)

Seeds of grasses and herbs in species-rich meadows and dry grasslands in the extensively managed court

Arthropods and their larvae on the ground and on plants, especially in the dry grasslands with bare ground, important in particular for fledglings

Nesting place in Eastern front. Nesting modules for sparrows are integrated in the insulation layer at a height between 3 and 10m, with holes of 35mm and 45mm. Min. distance between nests 50cm

Dust baths for cleaning and removing parasites in sandy vegetation-free areas, near sandboxes and boule lane

Fruits for food from fruit-bearing shrubs/trees in autumn and winter: hawthorn (*Crataegus*), serviceberry (*Amelanchier*), cornel cherry tree (*Cornus mas*), crap apple (*Malus sylvestris*), wild roses (*Rosa*)

Figure 3.2: A partial "checklist" of proposed design considerations that meet the specific, critical needs of a Common House Sparrow. (Weisser, W, Hauck, 2019)

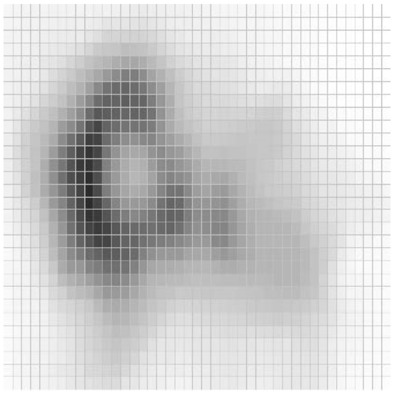


Figure 3.3: Landscape Model (Soetaert & Herman 2009)

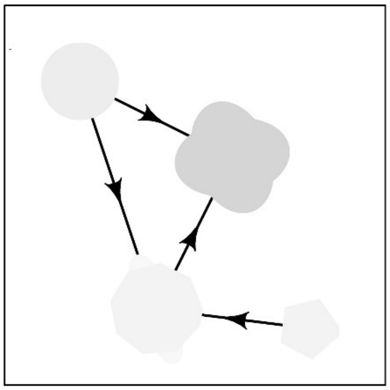


Figure 3.4: Patch Model (Soetaert & Herman 2009)

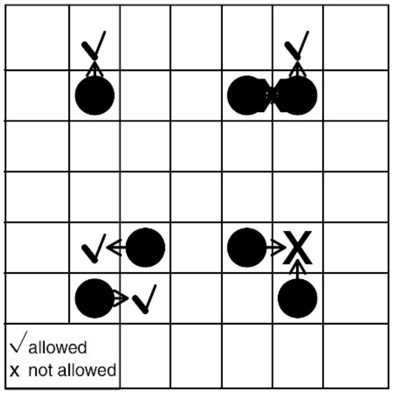


Figure 3.5: Cellular Automaton Model (Soetaert & Herman 2009)

3.2. Modeling Ecologies

The natural environment, with all the physical, chemical, and biological processes going on, is overwhelmingly complex. To make sense of this complexity and provide predictive capability, it is necessary to construct models that abstract this complex reality (Soetaert & Herman 2009). Ecologists often do this mathematically, which has several advantages. For example, mathematical models are precise in form, so any inconsistency in the formulation of processes is easily detected. They are also numerically precise, so by making quantitative predictions that can be tested against observations, the "fit or non-fit" of the model to data is inevitably shown. This can demonstrate whether a concept of natural phenomena is valid or not. There are many ways to construct a mathematical ecological model, however, for architectural applications, we might find spatially explicit models particularly suitable given that they account for spatial dimensionality. Designers must be cautious though, as it is not often practically efficient to calculate objects in 2D or 3D space, despite the profession's precondition to work in this way (i.e., with x, y, and z coordinates). Reducing dimensionality is an important consideration when trying to limit the complexity of a spatial model. Discrete spatial models, for instance, limit complexity by considering each dimension as discontinuous space (i.e., objects can only occupy a limited number of positions in any dimension). Examples of discrete spatial models used by ecologists include *landscape models*, which describe the evolution of populations or individuals in a landscape (Fig. 3.3). They subdivide the landscape into distinct equally sized cells whose properties and behaviors can be prescribed (i.e., cells could represent GIS data). *Patch models* describe dynamics in several discrete regions called patches (Fig. 3.4). Patch models have similar data requirements to landscape models, but the patches can be irregular and discontinuous. A patch model, for example, might be used to understand how geographically separate green spaces work together in servicing one, or several species of birds. *Cellular Automaton models* divide an environment into many equally sized cells that may either be 'alive' or not. In these models, interactions only occur between neighboring cells (Fig. 3.5). In contrast to landscape models, where characterization of each cell was necessary, this type of model only requires a small number of parameters. A key characteristic of Cellular Automatons is that dynamics are specified in a number of generally simple rules. It is sufficient to specify only the behavioral rules of interaction. Cellular Automaton models are often used when modeling vegetation succession, for example, how different species of trees repopulate an area following a forest fire. Finally, *Lattice models* combine qualities of all the previous types as each cell may contain more than one species or individual. In Lattice models, interactions occur 'within' cells, and movement occurs mostly between adjacent cells. A lattice model for example could be used to understand the effects of space and competition on many individual plant growth patterns.

3.2.1. Ecological Modeling in Architecture

As a result of growing interest in ecological design and animal-aided design, it is becoming increasingly necessary to develop suitable design approaches within a computational framework, and workflows that will allow architects, landscape designers, and urban planners to model and simulate ecological systems tangentially to their existing digital design paradigms. A 2014 applied research study by Kieran Timberlake architects, *Green Roofs Over Time* describes a spatially explicit methodology aimed at assessing the long-term performance and dynamics of green roof vegetation. Their method involves the on-site observations of plant species composition and performance based on statistical and graphical analysis of plant cover and diversity (Piana, M. R., & Carlisle, S., 2014). The paper summarizes outcomes from a multi-year case study of a six-year-old green roof in Ithaca, New York. Three metrics: species presence, species diversity, and vegetation coverage, were manually recorded within cells of a 2m x 2m grid constructed atop the green roof (Fig. 3.6). The observations were then repeated three times over the course of seven years (Fig. 3.7 & 3.8). The study, which focuses on horticulture, unfortunately, makes no specific considerations for the wildlife that inhabit and make use of the green roof's landscape. An example of ecological modeling within the framework of AAD: the recent H2020 FET Open Project, *ECOLOPES* emphasizes an ecological approach to design (through computation) that considers a multitude of animal species. Ecolopes is pioneering the application of databases, and the development of information models and algorithmic tools for modeling a range of ecological systems from within platforms like Rhino3D and Grasshopper (Fig. 3.9) (Canepa et al., 2022). Critically, the research describes methods for a data-driven design recommendation system to help designers make informed decisions from their model. To do this, Ecolopes proposes developing an

Figure 3.6: Plot level vegetation performance matrix maps (Piana, M. R., & Carlisle, S., 2014)

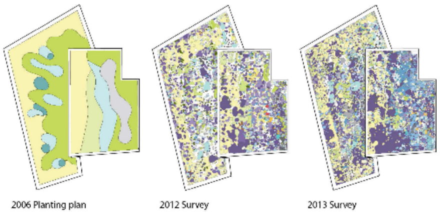


Figure 3.7: Sequential species maps over time (Piana, M. R., & Carlisle, S., 2014)

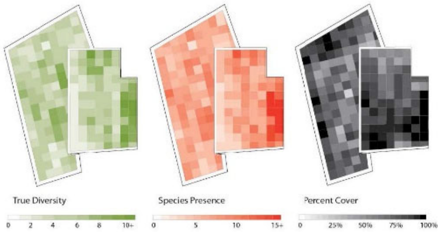


Figure 3.8: Plot level analysis results matrices (Piana, M. R., & Carlisle, S., 2014)

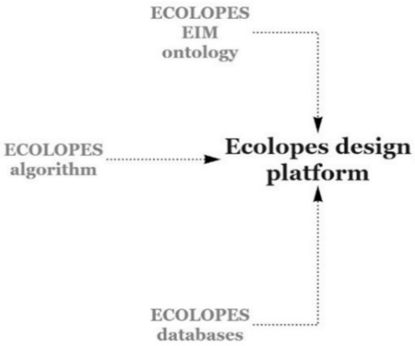


Figure 3.9: Graph of ECOLOPES (Canepa et al., 2022)

information model that defines the relationships between a site's (multi-species) inhabitants, its architecture, and the abiotic environment. Their computational framework aims to make knowledge embedded in the information model available for the design process. The project includes front-end tools for design, modeling, visualization, and simulation of the environment that enables iterative design development integrated with multi-criteria decision-making strategies. However, Ecolopes' design approach, published recently, is yet to be validated through a design case (Canepa et al., 2022). Additionally, Ecolopes does not account for the input of site-gathered data, nor does it consider the feedback of their process outcomes back into the model, for calibration purposes or otherwise. Inspired by the research territories of ecological and animal-aided design, this research project explores the application of ecological information modeling and simulation into the design and fabrication process of robotically extruded cellulose panels in order to measurably impact the habitat creation (and/or pollination services) of Lepidoptera. Building upon the methods described, including AAD and Ecolopes, this research instead emphasizes the importance of site-gathered data and the need for introducing feedback from the design outcomes and simulations back into the ecological models.

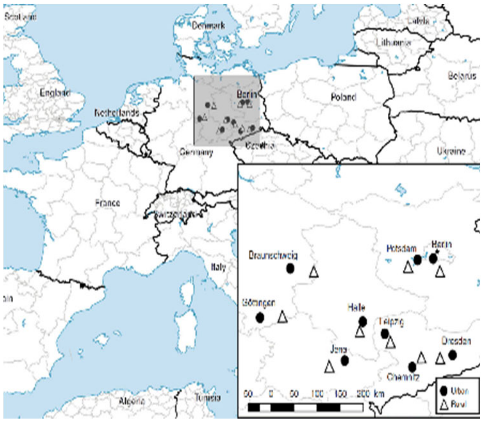


Figure 3.10: Location of 18 insect monitoring sites. (Theodoruo et al., 2020)

3.3. Architectural Pollinator Habitats

Habitat loss reduces the number, abundance, and composition of species in plant–pollinator communities. Insect monitoring in several German cities (Fig. 3.10) revealed that urban sites generally have lower insect species richness of flies (Diptera), butterflies and moths (Lepidoptera), than neighboring rural sites. In contrast, bees, wasps, and ants (Hymenoptera) show higher species richness and flower visitation rates in cities (Theodoruo et al., 2020). processes. It is theorized that the insect pollinator communities responding positively to urbanization, are more easily adaptable to patch habitats that provide nesting and food (floral) resources, despite surrounding land development. Botanical gardens, allotments, residential gardens, and vacant lots appear in themselves to be suitable patch habitats for these select species. It is likely then, that pollinator communities responding negatively to urbanization may require a more homogenous landscape of habitat features in order to thrive in urban environments. In contrast to 'soft' landscape-based interventions (i.e., native flower gardens, or landscape rewilding) several recent projects are exploring how architectural fenestration, and by extension, the built environment can support pollinator habitat creation and activity. Buro Happold and Cookfox Architects have developed a prototypical terracotta

Figure 3.11: Bio-receptive terracotta façade system mock-up (Parkes, J., 2022)

facade system to house insects, birds, and plants (Fig. 3.11). The facade system is designed to support a diverse native ecosystem. The terracotta screen wall is made from stacked modules that create a framework for micro-habitat "pods" designed to suit a variety of native fauna or flora. Chartier Dalix Architects School for Biodiversity, completed in 2014, is a living example of the façade as urban habitat. Its prefabricated concrete façade has indentations that encourage vegetation (bowls for ferns, rough concrete for mousse, etc.)(Fig. 3.12)). Small hollows and folds are aimed at larger animals, overhangs for swallows and other varieties of birds, and small porous nooks for insects (Fig. 3.13). The blocks stagger to increase the variety of potential habitats for the different species expected on the site. Nest boxes are also inserted into the concrete blocks, they are designed for target bird species such as kestrels, bats, robin redbreasts, redstarts, common swifts, starlings, or swallows. At a smaller scale and inspired by the tiling pattern of a bee's compound eye lenses, Harrison Atelier's *Pollinators Pavilion* proposes a new habitat for solitary bee species (Fig. 3.14). The project combines the disciplines of architecture, ecology, art-programing, and agriculture. The pavilion's concrete paneling system houses hundreds of nesting tubes for solitary bees, as well as a solar-powered electronic monitoring platform. (Harrison, Ariane, et al., 2019) The monitoring platform shields several cameras that facilitate the automated identification of specific bee species using AI. The pointed protrusions of the panels act as a rain canopy and a storage space for the solar-powered monitoring equipment. Motion sensors at the base of the canopy are triggered by insect movement and prompt an endoscopic camera to photograph the insect for identification (Harrison, Ariane, et al., 2022). This research seeks to build upon these existing examples by incorporating ecological modeling into the design and fabrication process of architectural elements. Specifically considering the existing site ecology, and a fabrication method that includes the additive manufacturing of a biomaterial at multiple scales.

Figure 3.12: Living façade of the School of Biodiversity, (Guignard, P., 2015)

Figure 3.13: Small folds in concrete to support insect habitats (Weiner, E. Stevens, P. 2015)

Figure 3.14: Harrison Atelier's Pollinators Pavilion (Harrison, Ariane, et al., 2019)

4. Project Objectives

The aim of this research is to explore computational methods that make it more accessible for architects to consider how design decisions impact a project site's existing ecology relative to habitat provisions for target animal species. The first objective of this research is to develop novel computational strategies accessible to architects for gathering and filtering relevant ecological data pertaining to their project site at both regional and site-specific resolutions. This is intended to be an ecologically focused parallel to existing formal processes of site analysis and modeling. The second objective is to examine how physical ecological elements and processes can be defined, modeled, simulated, and represented within the existing architectural software paradigm. The final objective is to explore a design-to-fabrication process that considers the habitat provisions for a target animal species using the previously described ecological-focused methodology. Broadly, and within the context of ecological design, this research aims to make a case for greater data-driven consideration of biodiversity in the design processes of architectural projects from their conception. Given the impact of urban form on local and global biodiversity change, architecture designed with consideration of its local and regional wildlife is increasingly important to fighting global biodiversity decline.

5. Methods

The methods presented in this research are ordered chronologically and are considered complimentary to the needs of traditional architectural project delivery. This methodology also assumes a chosen project site exists and has a defined boundary. The first component, a regional analysis, examines the broader ecological context of a chosen project site. The regional analysis involves gathering, filtering, and analyzing geographic information (GIS) relevant to the ecology of a chosen site (i.e., climate, NVDI, species). The regional analysis should inform expectations and calibrations of more specific findings uncovered in a subsequent site survey. The site survey, though particular to each project, should document and spatially map, among other things, all observed occurrences of plant and animal species within the site. The regional and site-specific analysis should, in partnership with species experts and project stakeholders, form the basis for target species selection, and the development of species portraits. The target species portraits are then used to define the material and geometric qualities of two small-scale architectural habitat expressions that are parametrically designed, and digitally fabricated from extruded cellulose. The final component of the research method involves the close observation of the expressions in-situ, to compare their real-world performance with the earlier simulations. The quantitative outcomes of the observation process calibrate the initial ecological model and will be used to validate the performance of this proposed methodology of data-driven ecological modeling.

5.1. Data Collection

5.1.1. Regional Analysis

To discover which species of flora and fauna potentially occupy a site, and their relationships within the local ecosystem, an analysis of the surrounding region should be performed prior to any on-site survey.

The regional analysis involves gathering all available geospatial data relevant to the ecology of the chosen site and its surrounding region. Data availability will vary based on location. The following list of datasets used in this project includes several sources with global coverage. The specific Grasshopper interface developed for the regional analysis allows a user to combine queries of several global datasets with data gathered from local sources (i.e., municipal maps, local species checklists, etc.). A successful regional analysis needs to give the architect and other stakeholders: 1.) An understanding of what native species could potentially occupy the site, 2.) The statistical probability that they do occupy the site, 3.) An understanding of local ecological needs and challenges current or predicted for the region. 4.) All available geometric data relevant to the site ecology (i.e., topography, building footprints, green-space boundaries, roads, etc.). The regional analysis will help to calibrate later ecological modeling exercises as well as set expectations for what might be uncovered during the site survey. This method is crucial for sites that may not have any existing biological presence on site, as is common with urban re-developments because it establishes a target for 're-wilding' the site plot.

5.1.2. Site Survey

Findings from the regional analysis narrow the scope of the on-site survey by setting expectations of what flora and fauna species could be present on site. Additionally, the regional analysis provides an understanding of what ecological issues may be most pressing to the biodiversity of the project site, and its surrounding region. With this in mind, the survey methodology used in this research is based on the Releve Method, a spatially discrete method of surveying vegetative performance, and the most accepted method for conducting vegetative surveys in the United States and Europe (Fig. 5.1)(Talbot and Talbot 1994). Within the site boundary, the locations and identities of each observed plant and animal species is thoroughly recorded. Sparse vegetation (lone trees and bushes) and monocultures (lawns, hardscapes, hedges) can be easily notated as points or regions on a satellite image or map of the site. Areas of mixed (or dense) species distribution will be discretized into a $2m^2$ grid with marking string and surveyed on a cell-by-cell basis. The plant identification applications Seek and iNaturalist were used in this study to verify the observed species by name. Dead plant material was not included in this survey. After species occurrences on the site are thoroughly documented, the complete names and locations of all observed species are transcribed into a digital Shapefile to be overlaid with the regional analysis data. The combined dataset is needed for successfully targeting species for habitat provision, and for informing ecological models in the following methods. For urban sites that may not have a biotic presence within the site itself, it is recommended that a survey still be performed on one or more nearby green spaces in order to understand the diversity present within the surrounding patch network. The survey methods mentioned above can be repeated across several seasons to understand the annual site ecology more accurately.

5.1.3. Species Targeting

Many methods exist among ecologists for which specific plant or animal species can be the best target of conservation efforts (Beate et. Al. 2019). This research will target two species of insects for each site, with opposing selection criteria for each of the chosen species. Specifically, one of the target species will be known, through the site survey, to already occupy the site in large quantities. This criterion represents a common methodology of conservation that focuses on preserving a species, ideally one in threat of population decline, that is already known to occupy an area, and thus requires protection during the development of a project. The second target species of this study is one, not observed, that is known to be native within the region and has the potential to occupy the site given that sufficient habitat features are provided. This approach acknowledges that many native species occurrences are constrained by a lack of sufficient habitat features that could be added during development. Identifying these features, and how to provide them architecturally, will be the focus of the following methods. The framework used in this research to identify the target species mentioned above involves the use of big data, structured decision-making, documented expert opinion, and in-situ observation.

5.2. Ecological Modeling and Simulation

5.2.1. Species Portrait

An extensive, yet legible snapshot of all target species must be generated so that the properties, behaviors, and needs of the species are understood qualitatively and statistically by all stakeholders in the development process. The basis of this process is adapted, computationally, from Weisser and Hauck's Animal-Aided-Design. Referred to as a "species portrait", this data set describes, in detail, the numeric and descriptive qualities, behaviors, functions, and critical needs of a particular species of plant or animal. The species portrait is a repository for all the relevant information uncovered about the target species throughout this methodology. Computationally, the species portrait exists as a C# object class within the Grasshopper interface. Where available, information for the specie portraits is automatically retrieved from several free, public sources (i.e., TBD). However, missing fields of the species portrait require manual entry in order to have a complete portrait for use in the ecological modeling phase of this process. In addition to being the basis of the modeling phase, the species portrait is a checklist for tracking progress toward meeting all the critical needs of a species.

5.2.2. Material

The material used in this case study will be a bespoke, robotically extruded cellulosic slurry. The specific material profile will be developed to negotiate two competing criteria. The first criteria is the bio-receptivity of the material for the target species based on the species portraits. When possible, the slurry should contain substrates known to commonly compose the habitats of a target species. Substrates in the slurry must also not be harmful to any of the target species. Equally important to bio-receptivity, is the printability of the material. The final slurry must be composed so that it is easily, and consistently extrudable with a robotic additive layer manufacturing process. In this case, a five axis Universal Robot will be outfitted with an extruder end affecter previously developed to extrude cellulosic slurries. The primary limitations of this material include the size of component that can be printed at one time, the geometry of toolpath, the drying time needed after printing, and the deformation that occurs during the drying process as water evaporates from the slurry.

5.2.3. Geometry

The form of the habitat expressions developed in this case study is the result of an Interactive Evolutionary Algorithm (IEA) implemented in Grasshopper using Biomorpher. The algorithm responds to multiple parametric fitness criteria inherited from a weighted sum of the critical needs of the target species, the limitations of the material, the fabrication process requirements, and the functional responsibilities of the expressions themselves. The chosen mesh form is then sliced, using a modified slicing algorithm, into a printable toolpath that minimizes self-intersection, drying deformation, and drying time. The mesh topology of the form is also used in the subsequent simulation component.

5.2.4. Simulation

Two simulation algorithms were developed in this research to evaluate the performance of geometric and material configurations. The first algorithm simulates a possible habitation response of the target species to the habitat expression. This algorithm first initializes a voxelized, three-dimensional landscape model with the ecological metrics inherited from the regional analysis and site survey. Spatially discrete agents representing the behavioral characteristics of the target species are introduced to the landscape based on species occurrence probabilities defined by data from the regional analysis and site surveys. The agent-based cellular automaton model then iterates through a given number of 12-hour steps and provides a statistical basis for decision-making within the IEA interface. The second algorithm simulates expected changes in the regional patch dynamics as a result of development on the project site.

5.3. Fabrication

The fabrication process for this project is based on methods previously developed at CITA for the robotic additive manufacturing of cellulosic slurries. The chosen components of the cellulose slurry are weighed and combined in an industrial mixer and extruded from a motorized end affecter attached to a Universal Robot Cobot 10. The printed components are then moved to a drying room which maintains a constant temperate of approximately 28C and is left to dry for 72 hours.

5.4. Observation

Following the fabrication and assembly phases of this methodology, the observation component involves thorough and repeated updates to the site survey. Specifically, the observation surveys focus on the habitat expressions as they are received by the site's ecosystem. Using the same methods as the site survey performed earlier, the observation surveys should spatially and temporally notate changes to site vegetation and include updated observations of animal occupancy, and species occurrences within the site, and especially within the expressions themselves. Notations of the habitat expressions should be explicit to the geometric topology, so that the observational information can be fed back, in high fidelity, to the existing ecological models. Future development of this research would include exploring the possibility of including image sensing and machine learning to automate portions of the observation surveys where machine vision would outperform manual notation.

6. Experiments

6.1. Ecological Modeling

6.1.1. Site Survey

Prior to establishing the previously described methods of a computational regional analysis, a survey was conducted on a greenfield site in the Dyrehaven nature park, North of Copenhagen. The author, along with three student colleagues spent approximately 90 minutes at the roughly 20,000m² wooded site, surrounded by grassland and a golf course. The focus of this initial investigation was to observe and record the perceived ecological elements of the site, and to draw informed conclusions about the interactions they have with one another through hands-on gathering of samples, field notes, and photographs of flora, fauna, and observed human-nature interactions (Figure 6.1). Mobile apps, Seek and Arter, were used during and after the visit to assist in identifying the photographed species occurrences. The final output of the experiment, and the gathered data, was an illustrated architectural representation of the site's ecosystem as perceived by the group of students.

Figure 6.1: Photographs of termite and fungal activity on a tree in Dyrehavn (authors images)

The final illustration combined graphic elements of plan, section, collage, and diagrammatic representation based on the earlier findings (Figure 6.2). Having no prior research or data gathered on the site's ecological provisions, alongside having no experience in the field of ecology made it difficult to frame and focus the methods of observation used during the site survey. This conclusion was the impetus for introducing a regional analysis to this project's methodology prior to conducting a site survey. In this way, visitors to a site can have informed expectations about what may be observed at the site, and how best to make these observations. Additionally, it was difficult to accurately record the spatial coordinates of the photographs and various species observations on the site during the visit, which is why future site surveys in this project will discretize and physically demarcate the site into manageable cells to help more thoroughly inventory the site's elements.

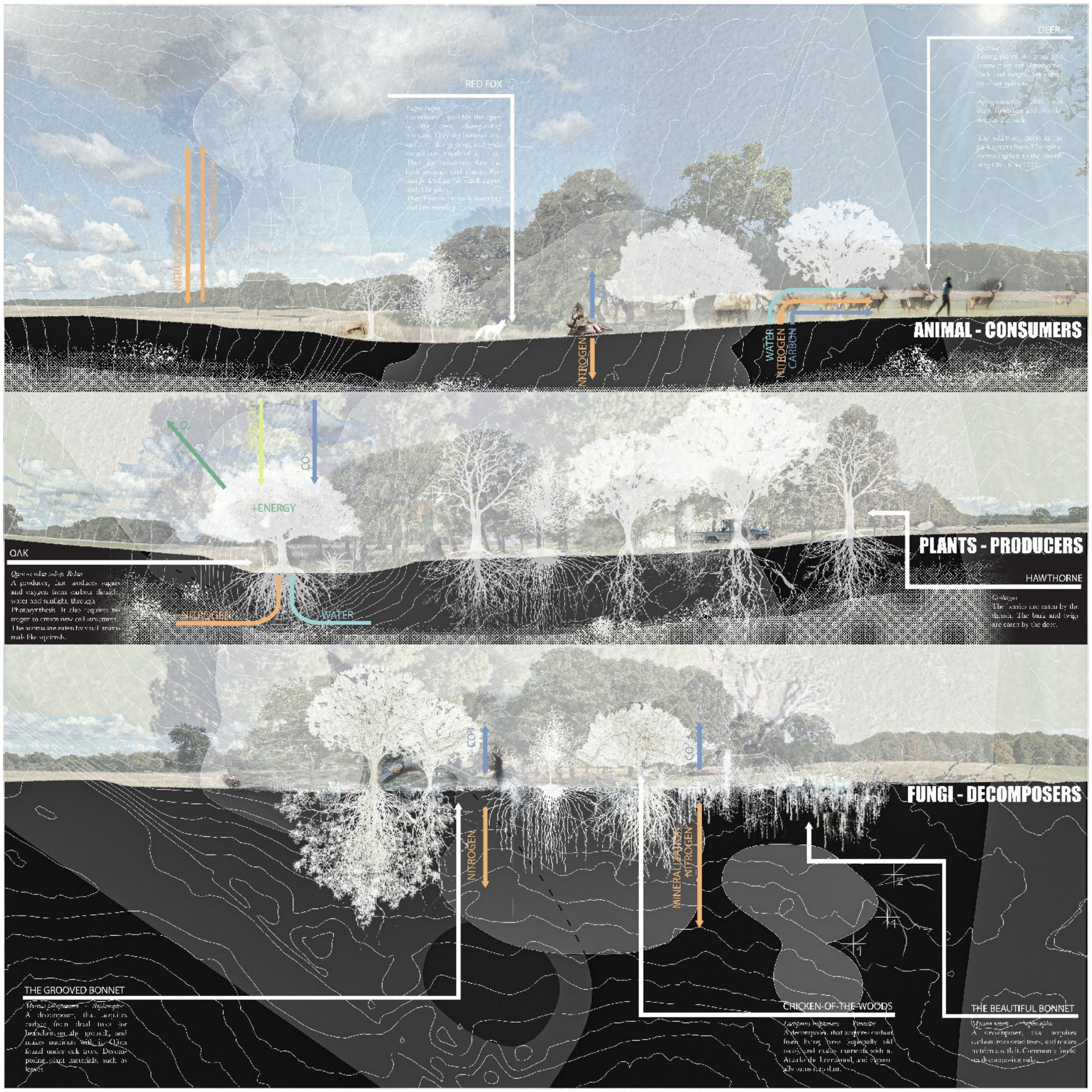
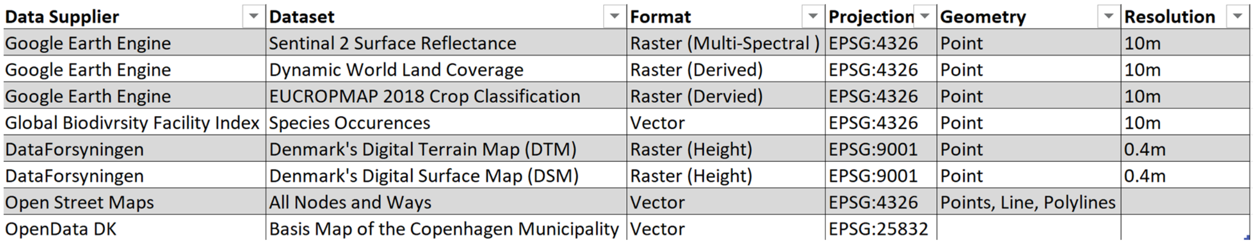


Figure 6.2: Illustration of the various observed ecological elements of the Dyrehavn site, and their possible interactions (Henning et al., 2022)

6.1.2. Regional Analysis

Initial implementation of the regional analysis has focused on 1.) gathering regional, ecologically relevant data of both vector and raster form 2.) storing this information in a locally hosted SQLite database, and 3.) querying this data from within the Rhinoceros3D modeling environment using a custom Grasshopper plugin. The data gathering component of this investigation relies on a collection of programmed, data querying functions written in Python, that utilize (namely) the Google Earth Engine API, GBIF API, Open Street Maps Overpass API, and several Web Coverage Service (WCS) requests. The python functions execute sequentially and require input



Data Supplier	Dataset	Format	Projection	Geometry	Resolution
Google Earth Engine	Sentinal 2 Surface Reflectance	Raster (Multi-Spectral)	EPSG:4326	Point	10m
Google Earth Engine	Dynamic World Land Coverage	Raster (Derived)	EPSG:4326	Point	10m
Google Earth Engine	EUCROPMAP 2018 Crop Classification	Raster (Dervied)	EPSG:4326	Point	10m
Global Biodivrsity Facility Index	Species Occurences	Vector	EPSG:4326	Point	10m
DataForsyningen	Denmark's Digital Terrain Map (DTM)	Raster (Height)	EPSG:9001	Point	0.4m
DataForsyningen	Denmark's Digital Surface Map (DSM)	Raster (Height)	EPSG:9001	Point	0.4m
Open Street Maps	All Nodes and Ways	Vector	EPSG:4326	Points, Line, Polylines	
OpenData DK	Basis Map of the Copenhagen Municipality	Vector	EPSG:25832		

Figure 6.3: Table of datasets (and properties) used for the regional analysis experiment.

in the form of two distinct UTM coordinates to establish the bounds of the analysis. The functions then download data from sources listed in the table (Figure 6.3), and format the data into several structured, two dimensional Datatables stored in local memory. Special consideration is made to reproject the data from various Coordinate Reference Systems (CRS) to one shared projection method. Database records can then be specifically or spatially queried from the Grasshopper environment within Rhino3D (Figure 6.4). Each database record is constructed into a programmed object based on the source record's type. Common to GIS records, these objects contain a numeric ID, a geometry (i.e., a point, line or polyline), and a dictionary of ecological attributes (i.e., species name, reflectance color information, date of record). In addition to informing expectations for a later site survey, the regional analysis is meant to fill in the context of the forthcoming statistical ecological modelling. One particular challenge with the regional analysis is incorporating datasets

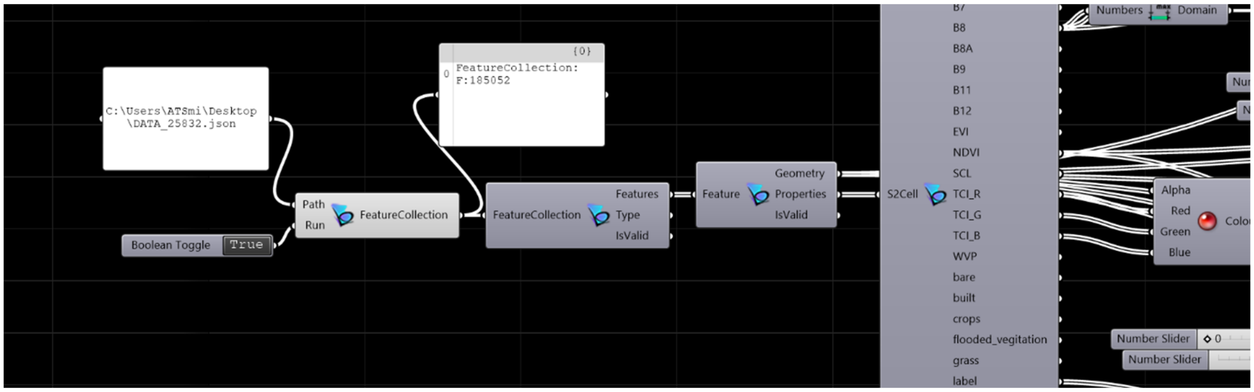


Figure 6.3: Several Lepidoptera Grasshopper Components on a canvas. The components are retrieving data from a (previous) .json storage method.

from outside sources, like local municipal GIS data, alongside the data gathered from the sources previously mentioned due to the variety of GIS data structures and projection methods. Additionally, this experiment does not yet account for how to collect and manage qualitative data and/or data that is not spatially discrete. Finally, this experiment is limited by its reliance on local computing for the retrieval, storage, and visualization of data. Future implementation of the regional analysis should explore web-based methods similar to those used in this experiment.

7. Discussion

Conserving and restoring global biodiversity will require ecology-informed, animal-aided methods of design across all industrial sectors. More than 90% of man-made pressure on biodiversity is attributed to the food, energy, infrastructure, and fashion industries (Kurth et. Al. 2021). The construction industry, responsible for *how* we develop urban and rural infrastructure, is, therefore, no exception to such reform. Motivated by its immense ecological footprint, this paper proposes a methodology shift in the way architects, urban planners, and landscape designers use computational tools to model and decide early-phase design decisions for architectural scale projects on greenfield sites by incorporating principles of animal-aided design into the decision-making process. The computational implementation and case-study components of this project are underway, and still require further development. The current focus of the project remains on the implementation and ontology of the ecological model, which the following case study component entirely relies upon.

Initial regional modeling experiments have proven that a substantial amount of ecologically relevant geospatial data is publicly available at near-global coverage, across a range of resolutions and time scales. The regional modeling experiments also prove that this data can be easily retrieved, stored in project-specific databases, queried, and visualized by a range of common architectural modeling software like Rhino, Grasshopper, Revit, and Dynamo through the development of plugins. The data from the regional analysis also suggests much greater species diversity at a given site than what can be observed during a site visit. Possibly making the regional analysis a useful tool for informing species-specific habitat expectations prior to a site visit or site survey. Further experimentation is needed to test the proposed method of site surveying and its effectiveness for gathering ecological information at a higher resolution than what is possible from geospatial datasets.

The multi-resolution spatially discrete ecological model is needed to provide a quantifiable, statistical understanding of the species occurrences and distribution on and around the given project site. Following the implementation of the ecological model, two target species will be selected for the site, a series of graded architectural interventions will be designed and fabricated, and their impacts on the site's ecology will be measured using the statistical ecological model. Going beyond the caste study component, future research is needed to investigate how ecological models like those implemented in this project can be developed and used collaboratively with stakeholders outside the AEC industry (i.e., by ecologists, anthropologists, local residents, etc.).

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