Flight of the Bumblebee

Improving urban green for ecosystem services in Helsinki

Master Thesis

Aalto University, 2022

Yanxia Qiu
Master of Arts thesis abstract
Abstract

The thesis discusses the impacts of the urban built environment on the movement of bumblebees regarding green connectivity and develops an agent-based modeling framework for the improvement of urban ecosystem services. This data-driven framework serves as an urban planning tool to explore the interaction between ecological research and urban planning. Helsinki is chosen as an example city for the research.

The urban ecosystem is complex since manmade elements are intertwined with natural elements. Modeling, simulation, and systems thinking interpret the complexity of the urban ecosystem in terms of a digital landscape model to introduce a new perspective on complex urban planning methodologies.

The project attempts to address the necessity of the challenge of urban complexity by introducing a data-driven planning tool for ecosystem services. The goal of this planning tool is to use digital technologies to incorporate built environments like buildings, motorways, and green vegetation in urban spatial analysis and methodology. Secondly, this tool aims at building a common ground for decision-makers, ecologists, and general participants through real-time data visualization of agent simulation results when dealing with the complexity of the urban ecosystem. Thirdly, the responsive system envisions the future application as an open platform by integrating various input factors regarding urban impacts caused by changing urban environments, which is universally applicable across multiple scales and different urban contexts.

The thesis aims to design an agent-based model, a simulation based on an abstraction of bumblebees’ foraging behavior. The movement simulation is a simplified model of the foraging process resulting from wandering repulsion and attractive tendencies. The agent simulation process includes two steps: the first is the initial simulation result to imitate foraging behavior in the urban environment; the second optimizes the bumblebees’ flight networks by inputting new attraction and distraction points to inform the simulation. This process is set up in an iterative feedback loop to improve the connectivity of the existing flight tracks. The simulation result points out the problems of exiting green networks fragmented by motorways and the exclusion of courtyard greens blocked by enclosed buildings. Moreover, the simulation process serves as an urban planning tool as the simulation result is applicable both on the urban scale by informing a more connective green network and on the node scale by a proposal of a toolkit regarding various spatial characteristics.

Keywords: urban green connectivity, bumblebee-friendly city, systems thinking, responsive landscape, agent-based modeling, ecosystem services, urban planning tool
# Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>Contents</td>
<td>4</td>
</tr>
<tr>
<td><strong>Chapter I</strong></td>
<td></td>
</tr>
<tr>
<td>Introduction</td>
<td>6</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>7</td>
</tr>
<tr>
<td>1.2 Subject and Research Question</td>
<td>8</td>
</tr>
<tr>
<td>1.3 Objectives</td>
<td>10</td>
</tr>
<tr>
<td>1.4 Problem Statement</td>
<td>10</td>
</tr>
<tr>
<td>1.5 Limitations</td>
<td>12</td>
</tr>
<tr>
<td>1.6 Thesis Structure</td>
<td>13</td>
</tr>
<tr>
<td><strong>Chapter II</strong></td>
<td></td>
</tr>
<tr>
<td>Literature Review</td>
<td>14</td>
</tr>
<tr>
<td>2.1 Urbanization and Urban Biodiversity</td>
<td>15</td>
</tr>
<tr>
<td>2.2 Urban Ecology</td>
<td>16</td>
</tr>
<tr>
<td>2.3 Agent Simulation as a Methodology of Ecology Planning</td>
<td>18</td>
</tr>
<tr>
<td>2.4 Simulation Modeling to Address Complex System</td>
<td>26</td>
</tr>
<tr>
<td><strong>Chapter III</strong></td>
<td></td>
</tr>
<tr>
<td>Site Analysis</td>
<td>32</td>
</tr>
<tr>
<td>3.1 Urban Fabric</td>
<td>33</td>
</tr>
<tr>
<td>3.2 Green Connectivity for Bumblebee</td>
<td>36</td>
</tr>
<tr>
<td>3.2 Example Site</td>
<td>40</td>
</tr>
</tbody>
</table>
Chapter IV
Methodology ........................................................................................................ 41
4.1 Outline of the Methodology ........................................................................ 42
4.2 Indicator Species ......................................................................................... 47
4.3 Coding the Movement of Bumblebees ..................................................... 51

Chapter V
Agent Simulation and Application ................................................................. 57
5.1 Simulation Process ..................................................................................... 58
5.2 Informative Process ................................................................................... 59
5.3 Track Optimization .................................................................................... 64
5.4 Application in Urban Design ..................................................................... 68

Chapter VI
Conclusion ........................................................................................................ 74
6.1 Main Findings ............................................................................................ 75
6.2 Challenges and Further Developments ................................................... 76

Acknowledgments .......................................................................................... 78

List of Figures .................................................................................................. 80

References.......................................................................................................... 84
Chapter I

Introduction

• Background
• Subject and Research Question
  • Objectives
• Problem Statement
  • Limitations
• Thesis Structure
1.1 Background

Rapid urbanization has been seen as a threat to biodiversity, including pollinator biodiversity and ecosystem services. Even though many studies have shown that urbanization leads to the decline of bumblebees (Bates et al., 2011), urban areas are becoming important habitats for bees and pollination since more available pollen sources are in cities. Theodorou and his teams have shown that as cities expand, many insects including pollinators grow accustomed to living in the urban environment. They reveal that urban biodiversity is correlated with pollination as bees promote the pollination services for wildflowers in urban sites (Theodorou et al., 2020), and native animals benefit from the establishment of local native plant communities. However, Knight et al. (2018) argued that the investigation of the impacts of urbanization on ecosystem service is limited by the reflection of studies regarding pollination ecology. In conclusion, regarding the importance of pollination services to urban biodiversity, it is necessary to integrate the concerns of biodiversity and ecosystem services into urban planning for a healthy and sustainable city.

The urban ecosystem is complex since manmade elements are intertwined with natural elements (Lepczyk et al., 2017). Currently, there are only restricted urban planning guidance related to ecosystem services due to the limited understanding of the interaction between complex systems and bumblebee. Agent-based modeling interprets the complexity of the urban ecosystem in terms of a digital landscape model for a better understanding of urban complexity (Cantrell & Holzman, 2015, pp. 34-39). The thesis addresses the research topic of the urban impacts on bumblebee movement by an agent-based model, an abstract simulation of bumblebees’ foraging behavior, which is based on behavioral principles interpreted from the natural movement of bumblebees.

The thesis discusses the impacts of the urban built environment on the movement of bumblebees regarding green connectivity and develops an agent-based modeling framework for the improvement of urban ecosystem services, in which pollination service is specifically taken as an example of one ecosystem service in the city. This data-driven framework serves as an urban planning tool to explore the interaction between ecological research and urban planning. Helsinki is chosen as an example city to demonstrate the practice of the design framework that offers instruction to evaluate the urban pollination service and proposes a design toolkit for users to improve the pollination services, which will be a referenced example for future users of this design framework.
1.2 Subject and Research Question

Rapid urbanization results in increasingly dynamic and complex urban challenges, which raises the ecological awareness of society. To understand the relationships between the human-dominated landscape and the natural landscape in cities, it is important to develop more adaptive urban planning tools to respond to the complexity of cities.

Urban ecology has been widely addressed in landscape architecture (Russo & Cirella, 2021) and at the same time, public awareness of the importance of nature in the urban environment has increased. SCAPE, a landscape architecture studio, develops science-based and research-driven workflows into design practices. In SCAPE’s work, ecological issues are seen as a driver for community participatory and educational tools (Kate, 2016). One of the relevant topics about urban ecology is ecosystem service, which is being increasingly discussed. Many organizations arrange workshops or activities regarding the significance of pollinators and encourage the involvement of the public. For example, a Finnish organization, Pölyttäjäpolut, call for public participation to create pollinator pathways with the guidance of planting flowers in their yards and gardens (Pölyttäjäpolut, 2022). While most of the actions are practically implemented on-site, this is done with a limited understanding of the importance of pollination as an ecosystem service.

In other words, many existing interventions for ecosystem services in urban areas overlook the complex interconnection of urban green infrastructure. For instance, the guidebook provided by ICLEI Europe (Local Governments for Sustainability Europe) lists possible interventions and strategies regarding pollination services without a detailed explanation of the mechanism of how to cooperate with the multiple features in the urban system (Wilk et al., 2019). Currently, limited information on pollinator declines is clarified in the EU Pollinators Initiative published by the European Commission, for which they set several goals to develop a common EU pollinator monitoring system and information center and to increase relevant research on the causes and consequences of pollinator decline (European Commission, 2018). In conclusion, it is important to develop a systematic method to better understand the pollination mechanism for the improvement of ecosystem services and green connectivity.

Landscape architects have involved ecological principles and systems in landscape design and recognized their importance since it guides urban landscapes toward greater sustainability and resilience (Tan et al., 2020). The increasing engagement with ecology has led to the rise of ecological consciousness in landscape design thinking and methods. For example, McHarg (1969) developed a systematic methodology by decomposing the information of a map based on a GIS tool in the Jersey Shore project regarding highway
impacts on the landscape. He separated the layers in terms of land uses and evaluated the values of each layer, after which he combined the layers to understand the interrelation. In this way, he built a holistic assessment of the economy, life experience, and ecological features of the area. However, this method ignored the internal relations and correlation within the system and a deeper understanding of the ecological process is missing, as each layer separately interacts with other layers in the built environment in McHarg’s method.

The new exploration of the interconnection between natural and built environments requires a paradigm shift that has happened in landscape architecture, and this brings new perspectives of responding to the dynamic and challenging landscape to landscape architecture. This shift encourages landscape architecture to develop computer technologies for better integration of ecological system abstraction, filtering, and data-driven techniques for feedback loops (Cantrell & Holzman, 2015). Karen and Keith name the internal system with patterns in Dynamic Patterns, where they define patterns as relational frameworks that reveal structures, processes, and relationships, as well as where they structure physical frameworks reflected by the realistic environment (Karen & Keith, 2017). This shift shows the advantages of digitalizing landscape design with computer technologies. Moreover, the system thinking of complexity is responding to challenges in the physical environment with data-driven models that are more flexible and convincing.

The research question of this thesis is “How can ecology knowledge on the bumblebee movement be integrated with digital tools for the improvement of pollination services in urban planning regarding the barriers caused by the built environment of motorways and buildings?”
1.3 Objectives

This thesis aims at generating a data-driven framework that serves as an urban planning tool to explore the interaction between ecological research and urban planning. Therefore, the design proposals are not the core parts of the research. Currently, the application section only addresses the possible implementations of the tool in urban planning. It is possible to improve the simulation, which can support detailed urban design strategically and geometrically.

The project addresses the challenge of urban complexity by introducing a data-driven planning tool for ecosystem services. The goal of this planning tool is to use digital technologies to incorporate built environments like buildings, motorways, and green vegetation in urban spatial analysis and methodology. Secondly, this tool aims at building a common ground for decision-makers, ecologists, and general participants through real-time data visualization of agent simulation results when dealing with the complexity of the urban ecosystem. Thirdly, the responsive system envisions the future application as an open platform for the evaluation of pollination services, by integrating various input factors regarding urban impacts caused by changing urban environments, which is universally applicable across multiple scales and different urban contexts.

1.4 Problem Statement

Currently, existing urban planning guidelines related to ecosystem service stay at a strategic level or public education level. Many articles on landscape ecology and planning only discuss the possible improvement in planning strategies in a general statement that lacks consideration and involvement in the whole planning process (Hersperger et al., 2021). The National Pollinator Strategy and Action Plan in Finland propose 27 actions and measures, aiming at raising people’s awareness of protecting pollinators and calling for public participation, as well as better understanding the causes of the decline of pollinators, while further discussion regarding systematic complexity is limited (Hyvärinen et al., 2021). Additional understandings of urban mechanisms consisting of manmade elements and natural environments are missing in existing practices regarding urban ecosystem service. The situation results from the lack of common ground for communication between ecologists, urban planners, landscape architects, public participants, and decision-makers (Nassauer & Opdam, 2008). It is significant for everyone to introduce a new paradigm for better elaboration and interpretation of
urban ecological principles to the planning landscape. To understand the dynamic and challenging urban environment, stakeholders need tools and methods to cope with the correlated physical objects within systems and to transcribe the internal relations of the urban ecological system.

Griot (2018) argued that traditional planning under the theory of decomposition of map layers proposed by McHarg (1969) offered widely known answers to design questions while it discouraged a variety of design choices in the last five decades. He believed that the application of code and advanced digital tools as design approaches encouraged more plausible, diversified, creative, and open perspectives and methods. This shift helped diversify designs instead of redundant homogenization of ecological solutions, and it also appealed to a new form of ecology that greatly involved local context through a better understanding of its mechanism (Griot, 2018). Therefore, it is essential to apply computational technologies for convincing and diversified solutions to cope with the increasing complexity of ecological systems.

The urban environment is a complex system that is a combination of the ecology environment and the built environment, which requires a holistic narrative to understand the mechanism of the collaboration of multiple elements in the complexity. This thesis addressed the complexity of urban ecological systems by computational tools, which offers a powerful new approach to ecological solutions for urban ecological planning.

The purpose of this thesis is to interpret the complicated relations by digital tools, which is achieved by designing an agent-based model, a simulation based on an abstraction of bumblebee foraging behavior. The movement simulation is a simplified model of the foraging process resulting from wandering repulsion and attractive tendencies. The approach to spatial transformations plays a role as a structure organization tool based on the understanding of the complexity at the decision-making level rather than a detailed design interpretation.
1.5 Limitations

The primary design method is agent-based modeling and simulation based on the abstraction of the bumblebee movement. The simulation process is an abstract translation of bee movement, which is interpreted to code for computational systems. This simulation process is aiming at understanding the urban space usage for bumblebees instead of the precise modeling of a single bee’s movement from a restricted biological perspective. The study was limited to general ecological planning because the research methods are based on an abstract data model. The restricted ecology demonstration is not the research target of the thesis, but the information collected from ecology research supports the simulation process. However, even though it is an ecological system abstraction, the simulation is still convincing under the biological assumption since the simplification is based on natural agents’ movement principles.

The study is limited to demonstrating the interpretation of bumblebee behavior with existing tools instead of developing custom software. The simulation modeling process is based on the grasshopper plugin, Culebra, developed by Luis Quinones (Quinones, 2021), which has programming limitations. For example, the input values of each component can only be numbers, which means that all the data must be simplified as a data list, which results in the loss of environmental details and agents’ precise reactions to the surroundings. I admit the knowledge gap in programming regarding the possibility of improvement of the simulation inputs. The goal of my thesis is to build a framework as an urban planning tool regarding the improvement of green connectivity for the bumblebee movement. Since this plugin serves as a tool to support biological assumptions, the limitations of the tool will influence the results, but it is still valid as a methodology.

The simulation was restricted to the foraging behavior in summer because of limited vegetation information. The research defined the attraction values regarding different vegetation types based on the assumption of the bumblebee’s foraging activities happening in the summer season because of a lack of flower resource distribution data. My research was conducted on a two-dimensional data model on a large urban scale because of limited vertical green data. The simulation method is adaptable to a three-dimensional model if the data are available. The goal of the thesis is to explore a tool that can improve green connectivity for bumblebees, which can be experimented with in two dimensions. Even though the simulation is based on a two-dimensional data model, the simulation results are presented in a three-dimensional context.
1.6 Thesis Structure

The structure of the urban ecology planning tool and methodology for the improvement of urban green providing the connective network for pollinator movement consists of two parts.

PART I builds up the theoretical framework by existing ecological and biological research related to pollination services and relevant theories of the digital landscape. Chapter 2 discusses the complex urban ecosystem and clarifies the importance of urban pollination services; it also introduces system thinking and the responsive landscape regarding agent simulation.

PART II displays the creative part and the design demonstration of the thesis. It shows the existing green connectivity for bumblebees and explores a new method to improve green connectivity for the bumblebee movement. Chapter 3 evaluates the existing green connectivity and leads to the core research question. Chapter 4 builds up an overall methodological framework and explains the decoding process of bumblebee behavior. Chapter 5 firstly presents the simulation tools and workflow; secondly, it demonstrates the optimization process by integrating new information; thirdly, it presents the main findings and shows the possible applications in urban planning.

PART III discusses the future application possibilities and the possible improvement of the tool. Besides, Chapter 6 discusses future experiments to test the validity of the model and the improvement of the simulation tools.
Chapter II

Literature Review

• Urbanization and Urban Biodiversity
• Current Pollinator Protection Situation
  • Urban Ecology
• Agent Simulation as a Methodology for Ecology Planning
  • Simulation Modeling to Address Complex System
2.1 Urbanization and Urban Biodiversity

Cities and urban green spaces are significant habitats for animals and plants, while construction and urbanization negatively disturb urban green habitats. The United Nations (2018) predicted that by the year 2050, 68% of the global human population will live in urban areas. Constant population growth leads to increasing urban construction. It has been argued that urbanization dramatically changes green land into densely constructed sites and disturbs the local bio-environment (Gaston, 2010). Building blocks, streets, and highways cut the continuous bio-corridors and eco-corridors, fragmenting the green habitats of animals, and decreasing urban biodiversity, which results in the disruption of urban biotopes and endangerment of plants and animals. Compared with agricultural intensification areas, cities with greater proportions of intact vegetation are preferable places for various animals (Aronson et al., 2014). Urban green areas serve as essential patches of wildlife corridors for various migratory species, supporting the movement of animals through the human-dominated landscape (Tam & Bonebrake, 2015). However, the lack of systematic ecological planning and management reduces the ecological values of urban green spaces. Sustainable urban planning strategies, including retaining green connections in cities, can promote species richness and lead to a co-habitat for human beings and animals.

The Impacts of the Built Environment on Pollinators

Urban development negatively impacts biodiversity (Gaston, 2010), and the decreased number of green patches and floral plants further affects other plant-dependent species. Habitat loss, habitat fragmentation, and degradation of habitat quality are among the main threats to biodiversity (Fahrig, 2003). Consequently, the loss of green spaces leads to a decline in urban bee-pollinated plants, which synchronously reduces the number and abundance of pollinators (Biesmeijer et al., 2006). This suggests that the increase in construction land use correlates with a decrease in the abundance and species richness of wild plant species, which results in the subsequent decline of pollinators (Rachael et al., 2009). Furthermore, urban development leads to increasing land use changes, forest degradation, and urban construction, resulting in habitat loss and a fragmented landscape, which disturbs the survival of pollinators by negatively impacting pollinator density, pollinator movement, and plant abundance (Hadley & Betts, 2011). The density and patch size of flowering plants are crucial factors in attracting pollinators, and the ratio of pollinator population density to habitat area size also influences the frequency of pollinator visits (Mustajärvi et al., 2001). These findings emphasize that the decline
Pollinators play a significant role not only in nature but also in urban ecosystems. Research has shown that pollen limitation causes a decrease in species richness by affecting the reproductive mechanisms; for example, plants which rely on pollination might not be able to reproduce without pollinators, which slowly decreases the biodiversity at the ecosystem scale (Ashman et al., 2004). Butterflies and bees are important pollinators in urban ecosystems and securing space for pollinators mean more possibilities for city biodiversity. Galantinho et al. (2020) showed that increased pollination efficiency promotes plants thriving, for which insects can find more habitats. Moreover, the abundance of insects becomes an important food source for birds and small mammals (Galantinho et al., 2020). Panagiotis et al. (2020) revealed that phylogenetic diversity is a valuable predictor of the ecosystem service of pollination; the research also indicates that pollinators can help other local species survive by offering pollination services in cities. In conclusion, a pollinator-friendly urban environment supports other species by offering essential pollination services and promoting the growth of the native plant community. Thus, promoting urban habitats ought to be considered as it is beneficial for pollinators and other animals.

2.2 Urban Ecology

Ecology System Services and Bumblebee

Urbanization is threatening green spaces, resulting in a reduction in capacities to provide ecosystem services and maintain urban biodiversity. Although urbanization results in a fragmented landscape, research shows that bumblebees can colonize urban areas with a relatively small green space (Matteson & Langellotto, 2010), which emphasizes the value of pollination services provided by bumblebees in urban contexts. Meanwhile, various urban gardens and allotments promote the species richness and populations of bumblebees by providing valuable food resources and habitats (Gunnarsson & Federsel,
Bumblebees play an important role in offering pollination services for the maintenance of the natural ecosystem as various wild plants predominantly rely on bumblebees for pollination (Osborne et al., 1991). Fontaine et al. (2005) argue that bumblebees provide functional plant-pollinator interactions by the experimental result of higher fruit production in bumblebee-pollinated communities; the experiment also indicates that bumblebees enhance plant diversity in the natural ecosystem by pollinating tubular flowers while other bee groups mainly visit open flowers. The special preference of bumblebees for tubular flowers results in the important role of bumblebees in the native plant community. In Finland, Valle (1949) estimated that over 75% of Finnish red clover is pollinated by bumblebees, and Hulkkonen (1928) showed that 190 plant species are pollinated by bumblebees; according to the experiment of Terävä in southern Finland, bumblebees offer pollination services to native deep flowers since bumblebees have long tongues (Terävä, 1976). Undoubtedly, bumblebees are irreplaceable in the pollination of native tubular and deep flowers, promoting the flourishing of native plant communities, including other organisms (Fig. 1).
Compared to other European cities, Helsinki is one of the greenest capitals in Europe (Hannikainen, 2016). However, the living conditions of pollinators are still a concern. Helsinki City Plan (2016) released a six radical green fingers plan with greenery covering well over 40% of the city’s land surface. The City of Helsinki published the City Biodiversity Index of Helsinki in 2019, which showed that the state of biodiversity management in Helsinki is good with a total score of 58/96. However, indicators on native biodiversity only received a score of 17/44 (City of Helsinki, 2019), which seems out of sync compared with the high green ratio.

The assessment of urbanization is highly relevant to pollination efficiency evaluation, since urbanization in Helsinki leads to a continued population growth of up to 650,000 inhabitants in 2021 (City of Helsinki, 2021), further disturbing the survival of pollinator habitats in various aspects. For instance, the increased urban traffic flow is leading to higher road mortality rates – the number of road-killed pollinators is predominantly up to 96% of 117,675 killed insects (Baxter-Gilbert et al., 2015). Although Helsinki has large green areas, motorways and buildings divide the green into fragmented greeneries, which results in a complex evaluation of pollination efficiency. Söderman et al. (1997) revealed that busy urban traffic is killing local bumblebees, especially queen bees when they seek breeding sites along motorways in Helsinki. Mitigating the threat of urban impacts on bumblebees, including the loss of habitat and road mortality, is a challenging task, and the design of solutions to reduce the urban impacts on pollinators is unclear without evaluation. Even though new Helsinki city plans have been updated many times, pollination efficiency is still excluded from Helsinki’s City Plan. Therefore, it is valuable to discuss how fragmented habitats and the loss of natural habitats affect the life condition of pollinators in Helsinki.

2.3 Agent Simulation as a Methodology of Ecology Planing

Responsive Landscape

Various explorations have been performed regardless of the interaction and complexity between natural and built environments by using responsive technologies. It is significant to understand the response process since the interconnections of the environment are the basis of landscape architecture. Cantrell and Holzman (2015) demonstrated that the
shift to the digital landscape promoted computational methodologies in the simulation, analysis, and mapping of huge datasets to understand complex ecological relationships. This shift encouraged an expanded perspective of ecological system abstraction, filtering, and embedded intelligence that drives feedback loops of sensing, processing, and visualizing (Cantrell & Holzman, 2015).

One example that shows the mechanism of the responsive landscape is Ecolibrium (Fig. 2), executed by Devein et al (2011). They built a new ecosystem management strategy by coordinating sediment, invasive species, and algae bloom according to fluctuating needs analyzed by a real-time data network, which leaves a dynamic pattern in the landscape that is continuously computed and updated. They define the feedback system in different scales which can support multiscale management, from micro-adjustment to large-scale planning, and at the same time, this system can be updated continuously.

The new relationship between humans and nature is a balanced ecological co-habitat concept rather than separate from nature, which requires new design methodologies and frameworks based on the understanding of ecology and nature. Cantrell and Holzman (2015) mentioned that advanced tools enhance understanding of a complex system through sophisticated simulation of site phenomena, which provides tools for the decision-making process. They argued for the significance of digital tools for landscape architects: “The simulation of dynamic systems within the landscape enables designers to visualize and represent data with an increased knowledge of relationships. These models are effective as an interpretable representation because they establish a metric that translates numerical data from simulations into hybrid or coupled models.” (Cantrell & Holzman, 2015, p. 28)
The Nature Feedback Loop

Landscape architecture greatly involves in ecology, which requires landscape architects to understand the systematic logic behind natural phenomena. The system theory developed in ecology in the 1950s by Odum. He built up a notational language system to study system behaviors, illustrating material and energy flows (Odum, 1953). Cantrell and Holzman defined feedback as “It is the ability of a system to act, process the actions, and then respond with an updated action”, and the feedback loop is “This causal chain of response is the feedback loop and is central to self-regulating or evolving systems.” (Cantrell & Holzman, 2015, p. 35)

It requires systems thinking for landscape architects to understand the self-regulating ecology system. Systems thinking has great influence in contemporary landscape design, which reveals the emergence interpreted from the perspective of ecological concepts; the emergence assumes feedback processes within an ecosystem, which inspires design works to interpret emergence under the assumption of a linear progression of natural systems toward greater complexity (Karen & Keith, 2017, pp. 121-134). Landscape architects need to understand that the natural feedback loop as the form of feedback and resistance are core parts of the design with nature (Fig. 3). The form of nature can be translated into computational intelligence by abstracting and generalizing biological intelligence. The feedback logic is basic in computer programming, which consists of testing a condition and the execution of code in response (Cantrell & Holzman, 2015, pp. 34-39).

![Fig. 3. Iterative feedback, synthetic territories network (Cantrell, 2010)](image-url)
Behavioral Patterns

Karen and Keith define the behavioral pattern in the below description:

“Because patterns are relational, they are conducive to this reformulation; patterns perform systemically rather than categorically. Behavioral patterns, in particular, bridge scales by linking the behavior of physical systems or beings, such as energy or animals, to abstract systems, such as information expressed as digital signs. In other words, behavioral patterns are made visible through information and communication technologies that mediate between material processes and our perception of these processes.” (Karen & Keith, 2017, p. 107)

Laws of Motion

The collective motions of animals tend to be self-organized: a coherent group behavior emerges from simple, purely local interactions between individuals, who have no sense of what the whole group is doing and no ability to perform great feats of anticipation (Ball, 2009, pp. 125-135). Reynolds created a computer model of coordinated animal motion which was based on three-dimensional computational geometry normally used in computer animation or computer-aided design. The generic simulated flocking creatures were named boids (Reynolds, 1987). The basic flocking model consists of three simple steering behaviors (Fig. 4):

1. Separation: steer to avoid crowding local flock mates.
2. Alignment: steer towards the average heading of local flock mates.
3. Stick together: steer to move toward the average position of local flock mates.
Each boid has direct access to the whole scene’s geometric description but flocking requires that it reacts only to flock mates within a small neighborhood. The neighborhood is characterized by a distance between the center of boids and an angle measured from the boid’s flight direction, while flock mates outside this local neighborhood are ignored. The neighborhood could be considered a model of limited perception, but it is probably more correct to think of it as defining the region in which flock mates influence a boids steering. (Reynolds, 2001)

Wander was defined as a type of random steering by Reynolds (2002). The steering force controls the agents to move randomly by changing direction within a sphere. The radius of the sphere (shown as the large circle in Fig. 5) determines wandering strength and the magnitude of the random displacement (shown as the small circle in Fig. 5) determines the wander rate. (Reynolds, 2002)

**Group memory**

Many animal groups, including insects, display clear structural order and tend to follow one another. Individual-based computer simulations are a very useful analytical tool to study these collective behaviors. Couzin et al. (2002) built a more biologically convincing model of aggregation behavior that is based upon an abstraction of aggregation tendencies evident in biological systems (Fig. 6). They simulated the behavior of agents resulting from repulsion, alignment, and attraction based on an individual’s reaction to the position and orientation within the group. Their simulation showed the collective memory occurring, where the previous history of the group structure influences collective behaviors as individual interactions change, even though the individuals do not know the previous history of the system.
Fig. 6.
Four different types of collective behavior (A-D) (Image from Couzin et al, 2002).
(A) swarm; (B) torus; (C) dynamic parallel group; (D) parallel group. (Image from Couzin et al, 2002).

Fig. 7.
Algae as Agents (Woolverton, 2021)
Simulative operations—canal hydrodynamics mitigation (Woolverton, 2021)
Agent-based modeling

Agent-based modeling is a computational simulation tool with the capability of incorporating intelligence by integrating components of learning, adaptation, and evolution based on abstract principles (McLane et al., 2011). Unlike most models that are complex and low efficient with special techniques requirements, ABM tends to address a more general theoretical issue with increasing reference to theoretical ecology and advanced strategy, which is a bottom-up approach starting from individuals of the systems and establishing a systematic understanding from interactions within agents (Grimm, 1999). ABMs have been applied to address a wide range of issues relevant to environmental resource management, including water, forest, and agriculture ecosystem management (Bousquet & Page, 2004). Specifically, there are increasing applications of ABMs in ecology to study species relationships and to understand animals' learning behavior and adaptation to environmental changes (Deangelis & Mooij, 2005).

Landscape architects presume minimum interventions approach when a natural process starts in motion. Many design projects use multiple technologies, including simulation models or sensors, to relate the behavioral patterns of people and dynamic environments and animal patterns, using signals and feedback to mediate between them (Karen & Keith, 2017, pp. 121-134). The concept of organism-centric design proposed by Natalie Jeremijenko highlights the engagement with nonhuman agents to create feedback among humans, animals, and environments in her projects (Jeremijenko, 2015). More landscape architects shift their perspective from human-centric design to organism-centric design with the help of digital tools. For example, Woolverton builds a responsive model (Fig. 7) involving water mitigation as agents to deal with harmful algae which is the indicator of water quality; this agent-based modeling is defined as a research method to understand the urban impacts on the water system, and to test hypotheses while incorporating the expanding agency of computational modeling and live data streams (Woolverton, 2021).

Conclusion: Digital landscape design entwined with ecology

The simulation of ecologies by systematic modeling embraces the possibility of dynamic testing of the complexity on various scales. The response and regeneration of the environmental changes are the basis of landscape architecture, for which it is significant to understand the framework for responsive digital tools that explains interconnection and relates to multiple (Cantrell & Holzman, 2015, pp. 2-16). Cantrell & Holzman (2014) proposed a concept, Synthetic Ecologies, that are manipulated by a control system to elaborate the intertwined relation between multiple objectives; the simulation in this
control system serves as a mode of understanding the world to predict and project multiple futures responding to changing challenges. Here, the application of digital tools in landscape architecture is to incorporate ecological information with spatial changes by implementing computational intelligence, which shows its advances in addressing multiple issues in one coordinated system for a tighter interplay with complex ecologies.

It is important to inform habitat planning and management about the behaviors of wildlife in terms of how they are attracted or distracted by the landscape and the reasons behind their selections of habitats (Morris et al., 2008). Particularly, information on the wildlife’s adaptive behavior, for instance, movement ecology and its responses to a dynamic environment, is integral to successful conservation and future planning (McLane et al., 2011). On the other hand, movement ecology, including internal state, motion capacity, and navigation capacity, investigates how wildlife responds to matrix heterogeneity, which enhances the understanding of spatially structured populations (Revilla & Wiegand, 2008). Under the complex condition that the dynamic natural environment continuously affects animal behavior and motion, a habitat modeling which well defines the animal’s actual environment can be an effective tool in improving conservation planning since the model can point out the complex relationship between animal movement and environmental changes (Nathan et al., 2009). The modeling of animal movement shows great advantages in exploring an animal’s response to the landscape and predicting a changing environment. These models can address the dynamism of the environment, the internal mechanism, and the feedback and adaptions within systems.

Complex information should not be overlooked since a diverse and dynamic nature promotes the thriving of wildlife. Agent-based modeling as a methodology can accommodate spatial-ecological information, connecting the comprehensive knowledge of animal behavior and movement with dynamic environments. There are increasing applications of agent-based modeling in wildlife ecology and management to address the complexity imposed by dynamic challenges; it happens both in biodiversity patterns and the decision-making process for effective conservation planning and to predict future ecological planning by involving more possible features under numerous uncertainties (McLane et al., 2011). For example, Chudzinska et al. (2020) built a pattern-oriented and agent-based model to simulate the influence of distance to the nearest flowering plant, plant height, and flower availability to the bumblebee; they also compared the empirical network statistics of bumblebees with the emergent patterns generated from agent-based modeling (ABM), which showed a precise match between the simulated results and
empirical networks. ABM as a tool for conservation and planning is advantageous with its dynamic interplay that can input various agents and abstract realistic environmental and hypothetical conditions into the simulation.

This thesis explores an ecological solution to improve green connectivity for bumblebees in an urban fragmented green landscape with complex urban fabrications, which requires a multi-disciplinary approach to integrating bumblebee movement ecology and urban spatial patterns. Agent-based modeling is a methodology that easily addresses these two requirements in one system, which meets the research assumption of the thesis. Moreover, ABM as a well-developed tool has been widely applied to animal-movement ecology, including the bumblebee movement (Chudzinska et al., 2020), which is a convincing tool to respond to the research question.

2.4 Simulation Modeling to Address Complex System

Simulation Modeling in Ecology

In ecology, abundant research about pollinators has been done; for example, the Journal of Pollination Ecology especially publishes research relevant to pollinators and pollinations since 2013 (Enviroquest Ltd., 2022). Agent simulation modeling has been advocated as a promising approach for ecological research since agent-based models are capable of simultaneously distinguishing animal densities and can explicitly represent the dynamic environment, as well as accommodate spatial patterns of species (McLane et al., 2011). Many ecologists have built statistical models to simulate the movement behaviors of pollinators based on existing experimental results. Becher et al. (2016) developed a software tool, BEESCOUT (Fig. 8), to theoretically examine the exploration process of bees in a landscape and distribution across space and time. The model can interpret image files into a forage map by colors representing crops or habitat types; moreover, BEESCOUT can detect the location and calculates the size of potential food in the landscape based on parameter values gathered from the flight patterns of bees. They modeled the behavioral response of bumblebees to the environment with patch distribution, which monitors the impacts of environmental change and fragmentation on the foraging process. Behavior in BEESCOUT is defined as the random search phase based on the assumption of the first exploration of the landscape, and the search mode
phase to imitate the possible memory of patches of bees and their information exchange in the bee community (Becher et al., 2016).

Even though BEESCOUT has been addressed in ecology, transformation to spatial design is still limited. In the case of BEESCOUT, the simulation process precisely defines the search patterns of bees, aiming to study the flight behavior of individual bees, while defining spatial barriers in the landscape is less studied. Regarding the connectivity of patches, BEESCOUT only makes a comparison between the patches connected or not connected to the colony via a strip in the simulation process, which lacks the response to the complex system (Becher et al., 2016).
Simulation Modeling in Urban and Landscape design

Agent-based modeling and simulation is an approach to modeling complex systems composed of interacting, autonomous ‘agents’; the behaviors of agents are defined by simple principles and interaction with other agents (Macal & North, 2010). Various computational tools are available for the simulation of the agents’ movements like people walking and birds flocking. The purpose of simulation tools is to establish a platform for users to understand complex systems interacting with various factors and to support knowledge acquisition and decision-making during the research process (de França & Ali, 2020).

A handful of existing architectural theories reviewed agent simulation for interpretations of urban complexity and landscape dynamics, while the application to site-specific problems is limited (Claghorn, 2018). Agent-based modeling like pedestrian simulation is frequently relevant to the application of path finding and movement behavioral rules (Cheliotis, 2020). For example, Claghorn (2018) analyzed site topography to reveal potential paths of movement within a range of allowable slopes, revealing the site’s underlying landscape structure. Digital simulation reveals the dynamics of the urban built environment, which enables the visualization of the interactions between agents and surroundings. Landscape architects advocate for the necessity to engage dynamic environmental phenomena through simulation and cooperation that mimic an indeterminate control framework to develop infrastructures and settlements tightly entwined with complex ecologies (Cantrell & Holzman, 2014). For instance, in the Synthetic Mudscapes project (Fig. 9), Carney et al., (2013) revealed that the links between urban environments and economic drivers restricted dynamic succession of delta mud resulting in the degradation of the regional environment. The simulation in this case is a methodology to integrate historical data, promote the present decision-making process and propose a long-term evolving ecosystem. Moreover, the presenting process of the interactions in Synthetic Mudscapes allows stakeholders to follow the dynamic changes in real-time.
Synthetic Mudscapes- Site Three Recycle (Carney et al., 2013)

A real-time sensing network generated from the simulation of the fluid ecological process which is the framework for strategy proposal.
Simulation Tool

The simulation of this thesis is based on the Culebra grasshopper plugin developed by Luis Quinones. Culebra is a 2D and 3D multi-object behavior library written in C# focused on hybrid system interactions with custom visualization, data, and performance features. It contains a collection of objects and behaviors for creating dynamic multi-agent interactions (Quinones, 2021). Culebra well defines flocking, wandering, attraction, and repelling behavior by the values of different features. The user guide explains all the input values carefully. For example, in the component of flocking behavior, the user only needs to input the values of view angles, search radius, align value, and cohesion based on the research object. It is also possible to merge different behaviors in one simulation by inputting the assumed behaviors into one controller component, which is more biologically convincing by better elaborating the complexity of animal behaviors. Meanwhile, Culebra is well-equipped with a visualization display, which is convenient for users and informative for the simulation result.

Compared to BEESCOUT, Culebra has great advantages to integrate realistic environmental information since it can input geometric vector information, which means that the user can define environmental changes more precisely, while BEESCOUT can only input images or cell-based maps that overlook the complexity of spatial fabrication. In this thesis, the main focus is to systematically integrate complex urban fabrication, which Culebra can do. Secondly, the movement principles defined in Culebra are based on the laws of motion and group memory theories mentioned above, which meet the requirements of the definition of bumblebee behavior. Moreover, Culebra is flexible in changing different input values of the behavioral components, which allows users to adjust the mode with precise parameters regarding different target species.

Rather than focusing on the flight patterns of bumblebees, the focus of the thesis is to understand the physical barriers in the urban built environment on the movement of bumblebees. The simulation achieved by Culebra serves as a tool for a better interpretation of urban green connectivity for the bumblebee movement. In other words, the simulation process in this thesis builds up an adaptive platform for involving bumblebee behaviors and spatial characteristics, and an appliable tool in urban planning by flexible interfaces. Moreover, simulation and modeling methods like Culebra narrow down the knowledge gap between multidisciplinary fields by finding common ground to understand a complex system. Overall, Culebra has great advantages to address ecological concerns and urban impacts with systematic thinking.
Chapter III

Site Analysis

• Urban Fabric
• Green Connectivity for Bumblebee
• Example Site
3.1 Urban Fabric

Bumblebee Biodiversity in the Built-up Environment

Finland’s most common and abundant bumblebee species are B. lucorum, B. cryptarum, B. terrestris, B. lapidarius, B. pascuorum, and B. hypnorum (Heliölä, 2020). B. pascuorum is one of the most important bumblebees because of its significant contribution to native plant species like red clover (Valle, 1949).

The observation record data was published on LAJI.FI (2022) shows that these six types of bumblebees are also observed in the Helsinki city center (Fig. 10). However, as the map shows, B. terrestris is the most common bumblebee in the city center while B. pascuorum is rare in densely built areas.

Building Area Ratio

According to the Helsinki Facts and Figures report released by the City of Helsinki (2020, 2021, 2022), the gross floor area in completed buildings grew at an average area of over 800 000 m² for the three years 2019 to 2021. I evaluate the building density in QGis by calculating the building area ratio, as (Fig. 11) shown, the building density in Helsinki is relatively high.

As the analysis result shows (Fig. 12), in the city center, the built ratio is high; existing construction density is high resulting in limited space for increasing new green area.
Traffic Volume in Helsinki

The road network in Finland is developing rapidly. According to the National Transport System Plan 2021-2031 (2021), traveling by private cars is the most common mode of mobility in people’s residential districts, apart from the Helsinki Metropolitan Area, where traveling by foot is slightly more frequent than by car; the total length of motorway amounts in Finland to about 454,000 km, including about 78,000 km of highways and 31,000 km of street networks (Ministry of Transport and Communications, 2021). In the city center, traffic roads divide the landscape into many fragments (Fig. 13).
Fig. 13.
Traffic volume in the urban of Helsinki, Finland.
3.2 Green Connectivity for Bumblebee

Structural Connectivity

Landscape connectivity is important for bumblebees both in their daily foraging movement within their home range and their annual nesting and mating movement on longer journeys. Andersson and Bodin proposed a graph-theoretical modeling approach to access the urban mobility of target bird species by identifying threshold patch distance and minimum accessible habitat areas based on component-based analysis of exiting forest patches. Instead of calculating the shortest distance to the nearest patch or amount of green area within a buffer zone around a patch, they calculated all the distances from one patch to the rest of the patches and categorized the data by a threshold distance of a species’ movement. Their results showed that a landscape of scattered small patches can provide the same function as a large patch when these small patches are functionally connected by the occupied organisms (Andersson & Bodin, 2009).

Similarly, my thesis starts with a green connectivity analysis based on the edge-to-edge distance of existing green components in Helsinki. For bumblebees, the exploration of new food resources in the city is limited by the distance between patches instead of movement within patches, which is the reason I accessed green connectivity by the edge-to-edge distance. Meanwhile, edge-to-edge distance accessed the connectivity of one patch to the rest of the surrounding patches, which is ecologically more convincing since the adjacent landscape is considered instead of only the one nearest patch. Before discussing functional green connectivity for pollination, I analyzed structural connectivity without considering urban impacts, after which I compared it to functional connectivity in the current urban environment.

Below is the process by that I accessed structural connectivity for green patches:

Setup

Site data source: Helsinki public green areas (forest network, public park, cemetery, biotope), all 931 curves.

Software: Rhino/Grasshopper + Anemone plugin (Zwierzycki, 2020)

The number of selected points: select one point per 100 m on the green patch boundary, all 13 616 points are calculated.

Edge-to-edge distance: from one point in one patch to another closest point in the rest of the patches apart from the points in the starting patch.

This calculation will repeat 13 616 times, generating 13 616 links between green patches.
Fragmented Level Accessment

Green Patches: Edge to edge distance

Ideal environment: Without Barriers

More than 90% of green patches are connected with lines shorter than 600m, which means there are not problems for bumblebees' foraging activities.

Foraging Connection

Only islands are isolated, but the connection distances are still lower than 5km, which means ideally, there are not problems with nesting and mating behaviors.

Fig. 14.

(a) right: green connectivity under ideal environment, all the lines are shorter than 5km; (b) left top: 92.3% of lines are shorter than 600m; (c) left bottom: only islands are isolated
Result analysis:

Foraging: i) select lengths less than the maximum foraging distance of 600 m (Kreyer et al., 2004); ii) calculate the connected patches ratio. The result shows that 927 out of 931 green patches connected with lines result in a connective rate of 98.6% (Fig. 14-b).

Nesting: i) select lengths less than the maximum nesting distance of 5 000 m (Lepais et al., 2010); ii) calculate the ratio of patches connected; the result shows that all 931 patches connected with lines result in a connective rate of 100% (Fig. 14-a).

As the result shows, all the lines are shorter than 5 km, and 92.3% of the lines are shorter than 600 m, which means that the connectivity is high without a built environment. Apart from some islands being isolated and the foraging process can only happen within the island (Fig. 14-c), it seems that there are no problems for bumblebees to forage or search for a nest.

Functional Connectivity

Buildings increase the flying distance of bumblebees since the flight height of bumblebees is usually 1 to 3m for foraging (Osborne et al., 1999). Rooftop greens and vertical greens are rare in Helsinki. Without attractions, bumblebees likely do not spend extra effort to fly higher, which would result in their flying distance being longer than edge-to-edge distance. The analysis shows if their real flying paths are in built environments, the shortest traveling distance between two patches is longer than the edge-to-edge distance without buildings.

In addition, since bumblebees tend to fly around open spaces at ground level, they usually travel along motorways, which leads to high-risk movements. The negative impacts from roads have been observed in various research; evidence shows that collision with vehicles is a significant reason causing pollinator mortality (Baxter-Gilbert et al., 2015). My results show that if bumblebees explore food sources in the city, they need to cross these busy traffic roads. The more roads they cross, the riskier movement becomes.

Compared to flying paths without buildings and motorways, the traveling routes of bumblebees in urban areas are longer and riskier (Fig. 15). Thus, it leads to the core research question of the thesis: how to overcome the barriers of the built environment for the bumblebees' movement?
Fig. 15.
Functional connectivity analysis
(a) left: without barriers, these green patches are highly connected; (b) middle: the dense traffic roads will increase the risks when crossing roads; (c) and the building blocks increase the travel distances.
3.2 Example Site

My research is based on the general impact of the urban built environment on the bumblebee movement. After a comparison of the non-built and built environments, the initial assumption is based on low connectivity and high-risk area.

In this thesis, I selected a city block as a typical sample in Helsinki city center for further analysis and discussion (Fig. 16). There are three main reasons for this selection: 1. High building density; 2. A busy traffic network; 3. Fragmented greenspace.
Chapter IV

Methodology

• Outline of the Methodology
  • Indicator Species
  • Coding the Movement of Bumblebees
4.1 Outline of the Methodology

The overall methodology frames a comprehensive view of the responsive project and bumblebees’ relationship to the urban environment, which is based on the feedback loop of the bumblebee movement and refers to basic logic that the testing of the urban condition and execution of code in response. The process of abstraction translates essential elements to analyze or classify the properties while maintaining connections to higher fidelities; data abstraction selects the critical and core elements of behavior that are allowed to be simplified by coding and programming (Cantrell & Holzman, 2015, pp. 34-49). This thesis project engages the response of bumblebees to the environment as a method of modification to understand the urban impacts on bumblebees’ movement by using agent-based simulation to respond to the challenges in a limited way.

The overall methodology can be concluded into five steps (Fig. 17):

Step 1 is to collect knowledge about the target species, including its movement limitations, living habitat, impact factors, etc.

Step 2 translates the behaviors to code that can be read on a computer. The decoding process of bumblebee behavior is a process to build up a simplified model of movement.

Step 3 is to simulate the bumblebee foraging process in the city.

Step 4 is to input the simulation result from Step 3 and optimize the network by identifying the risky nodes and new green nodes.

Step 5 is to show how the result of risky and attraction points can be applied to urban green system design.

Fig. 17.
Overall methodology outline
Diamond shapes represent the initial input and final output, and round shapes represent the modeling process.
Definition of an Efficient Pollination System

To respond to the research question and objects mentioned above, I try to point out the problem of the current urban green system and propose a solution to improve the connectivity of the urban green network in my thesis. There are two most important factors in the research question which are the built environment and the pollination services. Regarding the built-environment mentioned in the research question, I propose a new green system that is a low-risk and highly connective green system by planning the flight network that bumblebees cross fewer motorways and forage more efficiently in a more connective green network.

Definition of Movement Behaviors

In this thesis, the movement of a bumblebee is defined by four behaviors, including wandering, flocking, attraction, and distraction (Fig. 18). Wandering behavior imitates searching for food; flocking assumes studying from peers; attraction behavior represents the process when they detect flowers; distraction behavior imitates how they avoid barriers. The simulation process performed in Culebra defines the four behaviors with precise parameters collected from ecology research and experiment, and the behavior controller component in Culebra serves as a tool to merge different characteristics of the four behaviors (Fig. 19). In this way, the simulation model is more biologically realistic since the definition of bumblebees’ movement is based on the abstraction of movement in the natural environment. The demonstration of the programming process of each behavior is listed below.
Using behavior controller that merges attraction, distraction, wandering, and flocking behavior.

Movement behavior is defined in Culebra by four components: weaving, wandering, attraction, and repulsion.

**Fig. 18.**
Definition of movement behavior

**Fig. 19.**
Defined movement behavior in Culebra

Movement behavior is defined in Culebra by four components: weaving, wandering, attraction, and repulsion.
Wandering behavior:

The foraging and nesting behaviors of bumblebees are based on exploitation in the first place, and the transition of information to their partners. The BEESCOUT model assumes bees start random searches or fly to a certain point that they have learned from other bees, or a combination of both behaviors (Becher et al., 2016). Similarly, I assume the first round of simulation is the search mode of bumblebees to establish their new colonies or to explore foraging sites in the urban built environment (Fig. 20).

Flocking behavior to model the study behavior of bumblebees:

Flocking can be understood as a mathematical model of the collective motion by a group of self-propelled entities and is a collective animal behavior exhibited by many taxa such as birds, fish, bacteria, and insects (O'Loan & Evans, 1999). Insects, especially bees, show remarkably complex learning abilities. Research has shown that bees can learn information by social transmission (Ellouse & Lars, 2008). Pollinators respond to attractants and rewards through instinct and learning by using sense and mental capacities like vision, taste, touch and distance estimations, and measures of direction; bees navigate themselves by visual landmarks of the landscape and release chemical information to their followers (Kevan & Menzel, 2012). In an experiment using artificial flowers as attractions, Mirwan and Keven (2013) revealed that bumblebees remember the flower from which they get a reward and learn how to manipulate it with information from peers. In this thesis, the simulation assumes that flocking behavior indicates bumblebee learning behavior (Fig. 21). The flocking strength is low since the flocking is to show the tendency of revisiting the same food source and guidance for other bumblebees.

Attraction Behavior:

Both the foraging and nesting behaviors of bumblebees are motivated by flower resources and vegetation conditions, which is the initial definition of attraction behaviors (Fig. 22). In this thesis, I implement attraction points based on the vegetation assessment, and these attraction points are the targets of the bumblebee movement. The detailed interpretation of attraction can be seen in the coding section.

Distraction Behavior:

Technically, bumblebees can fly quite high, but their flying height is primarily influenced by the height of flowers and meadows. Flying at a low height means that there are plenty of barriers in the city, like buildings and busy traffic roads. In this thesis, vertical
vegetation is not taken into consideration. I assume that buildings are distractive objects for bumblebees to cross and that roads are risky areas for them to cross. Here, neither buildings nor roads are defined as restricted areas for bumblebees, but I assume that bumblebees tend to avoid buildings and roads if they cannot detect food sources (Fig. 23). The detailed interpretation of distraction can be seen in the coding section.
4.2 Indicator Species

Common Carder Bumblebee (Bombus pascuorum)

Bumblebees as the native pollinator in Finland promote the community of native species. Researchers have estimated that more than 75% of Finnish red clover is pollinated by bumblebees, and B. pascuorum is one of the most important bumblebees as pollinators of red clover (Valle, 1949). B. pascuorum is one of the most common bumblebee species in Finland, and it is one of the most widely foraging pollinators with 58.4% of flower visits to 47 native plant species during summer (Teräs, 1976).

Even though B. pascuorum is one of the most common bumblebees in Finland, their living conditions are not easy in the city area since their home range is smaller than other bumblebees due to their restricted flying distances (Kreyer et al., 2004). In this thesis, I choose B. pascuorum as the target species since they are one of the most important bumblebees for native plants and one of the bumblebees living in the city with the most challenges, given their limited flight distance.

Life Circle:

In southern Finland, Teräs (1976) recorded the first queen bumblebees emerging from hibernation in early June, and the number of workers greatly increases around 20 June; the first new queens are observed in early August, and the first males emerge on 9 July; afterward their active foraging and mating activity last until mid-September (Fig. 24).
Habitat Type:

Different habitat types support the food and nesting resource for bumblebees, which are affected by their management practices and functions (Ayers & Rehan, 2021). For example, urban green spaces like meadows, barren vegetation, urban parks, and residential neighborhoods have different plant species compositions and are very different in their vegetation cover, revealing variability in resources to pollinators (Sirohi et al., 2015). In Helsinki, variable different public green spaces could be the potential green habitats for bumblebees, including urban parks and meadows, etc. (Fig. 25).

Seasonal Food Sources:

Teräs (1976) showed that in the natural forest of southern Finland, Salix spp. predominated in May, in early June both Geum rivale and Vicia sepium, during almost the whole of July Vicia cracca, and in early August to an increasing extent Trifolium pratense. At the end of the summer, a major source of food was Solidago virgaurea. B. pascuorum visits many different species on its single foraging trip compared with other bumblebees that tend to visit the same plant on their single trip (Fig. 26).
Fig. 25.
Habitat types and distribution in Helsinki city center area
Bumblebee Parameters

**Flying Distance:**

The limitation of a bumblebee’s flying range is relevant to the assessment of a fragmented landscape. Research shows that Bombus pascuorum forage is between 50 m to 150 m from their nesting site, even though the maximum foraging distance can be up to 600 m (Kreyer et al., 2004). Darvill et al. (2004) revealed that B. pascuorum rarely forages more than 300 m from their nest. A key period of dispersal is when bumblebee queens search for a nest location in spring. Lepais (2010) found that B. pascuorum queens tend to travel at least 3 km, and the occasional flight distance can be up to 5 km. Some bumblebee males can even fly up to about 10 km for mating (Kraus et al., 2009). The key parameters of the flight distance of bumblebees are shown below (Fig. 27-b).

**View Angle:**

Bumblebees fly through complex urban environments in search of nectar resources or a nesting site. Bumblebees have big eyes, which determine that they are capable to explore the complex environment. What bumblebees can observe in the surrounding environment is limited by their visual field and angle, or the level of light their eyes can receive. Research has shown that all bumblebees have a similar average inter-facet angle across elevation between -30° to 30° (Fig. 27-a), and between -45° to 15° on average across azimuth (Taylor et al., 2019).

**Search Radius:**

Based on current knowledge, the most frequent flight distance of B. pascuorum is 50 m (Kreyer et al., 2004). Since limited information is available on detection distance (Becher et al., 2016), I assume that the minimum detection distance of bumblebees is 50 m (Fig. 27-c).
4.3 Coding the Movement of Bumblebees

Definition of Starting Points (Bumblebee Agents)

Evidence suggests that the nesting density of B. pascuorum is approximately 193 nests per km² in the natural landscape (Darvill et al., 2004). Colony size of B. pascuorum ranges between 60 and 150 individuals (Vernon, 2013). Based on this information above, the sample density in the natural landscape is defined as:

Patch size * 193 nests/km² * (60 to 150 bumblebees/nest) = 0.01 to 0.03 bees/m²

With this assumption, the total bumblebee agent number of 3313 (Fig. 28), which is calculated from each area of green patch multiplied with the minimum sample density (0.01 bees/m²), is too large for the simulation process. The actual density of bumblebees is far less than the assumption above in the urban environment since the green area is smaller and foraging activities are riskier and less efficient in the city. This simulation simplifies the input agents by selecting a point every 100 m at the boundary of the green patches as one agent, which results in a total bumblebee agent count of 436 (Fig. 29).
Definition of Attractive Values

Attraction Values Assessment:

Bumblebees can fly at various heights and the most important factor relevant to their foraging behavior is the abundance and quality of food sources which determines the attraction strength (Fig. 30-b). The abundance and quantity are correlated with the green patch size. Bumblebees usually fly between 1 and 3 m above the ground, and occasionally, bumblebees will fly up to 6 - 7 m (Osborne et al., 1999). Therefore, the height of different vegetation types determines the attraction level for bumblebees.

Based on the height of different vegetation types and green area size, the habitats are divided into three different layers (Fig. 31),

• Understory plants: vegetation height below 1 m, including grassland, attraction level 40%
• Mid-story plants: vegetation height between 1 - 3 m, including shrubs, meadow, and trees, attraction level 90%.
• Upper story: vegetation height greater than 3 m, including tree canopy, 0%.

Attraction points:

The definition of attraction points is based on the value assessment of vegetation. The size of the circle is calculated by the value of vegetation type and the weight of patch size, which means the larger the circle, the more attractive it is for bumblebees (Fig. 32).
Fig. 31.
Vegetation classification based on the height of plants

Fig. 32.
Attraction circles defined by vegetation attraction level
Definition of Distraction Values

Motorways:

Fitch and Vaidya (2021) demonstrated that roads pose substantial barriers to bee movement, reducing pollen flow between plants located across roadways. These authors also revealed that road width is the most obvious predictor of pollen flow indicated by the pigment flow, while traffic volume has fewer impacts on the movement of pollinators. On larger roads with 3 or more lanes, 71% of the plants receive no pollen; on roads with two or fewer lanes, only 19% of plants receive no pollen (Fitch & Vaidya, 2021).

Phillips et al. (2020) concluded that vehicle-pollinator collisions and roadkill based on previous research, show that busy and high-speed urban roads with traffic volume of 38 650 ± 32 144 SD vehicles/day are considered high risks of roadkill; some pollinators like butterflies are capable to cross a relatively quiet road with traffic volume of ca. 1500 vehicles/day.

Distraction values assessment:

The width of one lane is about 3.5m. Based on the number of lanes and traffic volumes, all motorways are divided into three classes, and each class is assigned with risk impact level with a percentage which is the input of distraction level in simulation modeling (Fig. 33),

1st class, busy road: Road width ≥ 5 lanes (17.5 m); 6000 < traffic volume ≤ 38650 vehicles/day, high-risk impact level 90%.

2nd class, moderately busy road: Three lanes (10.5 m) ≤ road width ≤ 5 lanes (17.5 m); 1500 < traffic volume ≤ 6000 vehicle/day, moderate risk impact level 50%.

3rd class, quiet road: Road width ≤ 2 lanes (7 m); traffic volume ≤ 1500 vehicles/day, low impact level 5%.

Buildings:

As I mentioned before, bumblebees usually fly 1 to 3 m above ground, and occasionally, bumblebees fly up to 6 - 7 m (Osborne et al., 1999). Buildings are crossable for bumblebees while bumblebees mostly avoid crossing vertically, only when there are flowering plants on the balcony or rooftop, they can fly vertically. Since bumblebees navigate by eyesight, buildings appear to be visual barriers that block their views from detecting flowers in inner yards (Fig. 34).

In my simulation, instead of defining the outside boundary of building blocks as
restricted areas, I set the distraction values by distraction strength (Fig. 30-a), which means that bumblebees can still fly through the buildings but there is a repelling force to distract them. I divided buildings into two groups based on the area of the building boundary, which means the larger the circle, the more distractive it is for bumblebees (Fig. 35).

Group 1: building area > 7500 m², distraction value of the circle is 69%

Group 2: building area ≤ 7500 m², distraction value of the circle is 33%
Fig. 33.  
Motorways classification based on the width of roads and traffic volume

Fig. 35.  
Distraction circles are defined by building distractive values into two groups.
Chapter V

Agent Simulation and Application

• Simulation Process
• Informative Process
• Track Optimization
• Application in Urban Design
5.1 Simulation Process

Simulation Flowchart

The flowchart (Fig. 36) shows the interpretation of the bumblebee’s movement to code and the simulation process in Culebra. The most important process is the simulation process and the optimization loop. Behavior simulation is an abstract process of the foraging behavior of bumblebees; optimization is to check if the bumblebee will follow the flight network (Fig. 37). The informative process is to involve points of interest relevant to new conditions, which will redirect the bumblebees’ flight path in the optimization step (Fig. 38).
Behavior Simulation

The simulation result of the foraging behavior is to determine the green connectivity for bumblebees resulting from the inputs of existing green patches and buildings. As the result shows that many courtyard greens are isolated where bumblebees cannot access them; some of the areas are busier and some of the connections are weaker (Fig. 39).

Setting:

Behavior: Wandering + Flocking + Attracting + Distraction

Starting point: 436 bumblebee agents; selected points on curves of green patches, every 100 m

Attractive level: middle layer 90%, under layer 40%

Foraging radius: 50 m

5.2 Informative Process

Simplify the Flying Track Network

Based on the behavior simulation result, I simplified the flying tracks network (Fig. 40), which will be improved in the optimization step. The simplification considers the realistic built environment which is more informative for the next step.
Behavior: Wandering+Flocking+Attracting+Repel
Starting point: all green, including private
Attractive level: middle layer 90%, under layer 40%
Foraging radius: 50

Fig. 39.
Behavior simulation result

Fig. 40.
Simplified flying network
New Attraction Points

Visibility and detection distance:

Visibility is one of the most important methods for bumblebees to navigate and search for food in a complex environment. Esch and Burns (1996) propose an optical flow hypothesis that bees use the speed of retinal image motion perceived from the ground to estimate the distance flown.

There is a significantly restricted assumption in this simulation. Detection of a patch only happens when a bee enters the green patch. In Riley's experiment, a bee can detect food sources within 200 m by flying 1.9 m in height by receiving the dance signal from other bees (Riley et al., 2005). Research has shown that most B. pascuorum individuals forage from 50 m to 150 m away from their nesting site (Kreyer et al., 2004).

Retest the visual connectivity of existing green patches:

As mentioned above, bumblebees mainly fly around 1-3 meters in height, which is a consequence of the height of the meadow, flowers, and shrubs. Buildings technically block their views from food resources since they will not fly through buildings if there are no attractive flowers.

In the second round of the simulation, based on B. pascuorum foraging distance, I select one point every 50, 100, and 150 m respectively on the simplified flying networks (Fig. 41). The points within existing greens must be excluded since the aim of this simulation is to determine the urban area where green steppingstones for bumblebees are missing. I calculate the visibility of each point under different foraging distance assumptions and made a comparison between the three distance assumptions.

Apart from isolated yards, as the visibility analysis result shows, the visible level of a point at 150 m cannot connect all green areas; while the result of points selected every 100 m can connect 80% of green patches; and points selected every 50 m can connect 100% of open green patches. In conclusion, the highest connectivity is based on the selection of every 50 m, while the selection of every 100 m is the most cost-effective option. Finally, I selected one green dispersal assumption which is the most connective attraction point system selected every 50 m. Based on the result from the visibility analysis, I get the result of keynotes to add green patches to improve visual connectivity (Fig. 42).
Fig. 41.
Visibility assessment
62
Fig. 42.
New attraction points as the red dots shown in the map.

Fig. 43.
New distraction points as purple dots shown in the map.
New Distraction Points

I intersected two sets of layers, the simplified flying tracks, and the traffic roads, after which I got the crossing points with motorways of the bumblebee flying tracks. The distraction value of crossing points is decided by the traffic volume.

The distraction value is defined by the classification of traffic volume. Larger circles represent a distractive value of 80% and smaller circles mean that the input distractive value is 40% (Fig. 43).

5.3 Track Optimization

Test the Viability of Behavior Simulation Result by Path Following

Path integration is a computational strategy that allows an animal to maintain an internal estimate of its position relative to a point of origin (Fig. 44). Patel et al. (2022) showed that walking bumblebees also exhibited systematic search patterns when home vectors failed to lead them accurately back to the nest, closely resembling searches performed by other species under natural conditions. These authors conclusively demonstrated that bumblebees use path integration to navigate and are one of the first to show that bees’ paths integrate over short distances while walking. In my thesis, I assume systematic search patterns also happen in the flying process.

The optimization process was performed to test whether the tracks identified work for bumblebees. It is assumed that bumblebees would follow the tracks, and testing what is the new attractions and distractions will change the flying path. Here the two behaviors include path following and wandering to test how the assumed tracks can be improved or modified (Fig. 45).
New Attraction Result

This process inputs the new attraction points into the simulation to test whether it reshapes the flying network. As the simulation result shows (Fig. 46), the new attraction points on the track enhance the flying tracks with more guidance. Meanwhile, it optimizes some of the turning points which shorten the travel distance of bumblebees between green patches.

New Distraction Result

The input of new distraction results shows that bumblebees avoid the distraction points (Fig. 47). However, if they must cross motorways, they cross these roads by the side of the distraction points. This process means that it is important to build connections in some key nodes.
Fig. 46.
Adding new attraction points (red dots) in Culebra

Fig. 47.
Adding new distraction points (purple dots) in Culebra
**Final Simulation Result**

The final simulation result shows the co-impact of new attractions and distractions on the flying network (Fig. 48). This process shows that attraction and distraction points overlapped at some knots. These knots are significant for a connective green network and are at the same time high-risk knots for the bumblebees to cross.

*Fig. 48.*

Adding new attraction (red dots) and distraction points (purple dots) at the same time
5.4 Application in Urban Design

Issue Classification

This thesis aims at optimizing the urban structure for the bumblebee movement. In other words, the application is highly relevant to urban space reorganization. It is significant to categorize these key nodes by their spatial characteristics, which directly inform the solutions of each node. This classification includes two parts, attraction nodes regarding the green system and distraction nodes regarding the traffic system (Fig. 49). Attraction nodes can be categorized into three types: i) linear street, which is limited to adding new green space, ii) poor quality existing green space, and iii) an open transportation crossroad junction where it is possible to increase greenery. Distraction nodes can also be categorized into three types: i) an open area crossed by a motorway; ii) a motorway crossing the building blocks; iii) a busy crossroad. These attraction and distraction nodes were identified by their location in the realistic environment which was indicated by the simulation result.
Application

My thesis aims to generate a highly connective and a low risky urban landscape for bumblebees. The solution to the core research question is a demonstration of a bumblebee-friendly urban landscape. The simulation process can be served as an urban planning tool for designers. Thus, this section is an appliable example to show the implementation of the simulation result in urban planning both on urban and node scales.

Functional Green Structure for Bumblebee:

At the urban block scale, it is essential to reorganize the urban green structure. The second-round simulation informs the effective improvement by adding new attractions and identifies the inevitably risky areas by adding distractions. Therefore, the simulation result of the movement tracks can guide green structure improvement.

By overlapping movement tracks with the existing green system, possible and potential greenways are displayed. The new green structure not only connects the current patches but also shows effective green corridors (Fig. 50).
Toolkit:

Regarding the attraction and distraction nodes classified by spatial characteristics, an applicable toolkit is efficient for solving practical problems (Fig. 52).

Hanging pot streetlight: By increasing the green and flower by hanging flowerpots on a higher level (Fig. 51), I add vertical visual guidance for bumblebees to avoid car crushes. Moreover, this flowerpot can be added to the existing streetlights in linear and narrow streets.

Median strip: To overcome the wide motorways of which the width is more than 10 m, I propose to add the middle green in the motorway. The liner middle green offers space for bumblebees foraging along the road and a stop when they cross the motorway.

Balcony garden: Balcony gardens increase vertical green to attract bumblebees to fly higher to avoid barriers.

Ecological bridge: Add flowers or plants on the ecological bridge to guide bumblebees to follow the connection and fly higher to avoid bees crushing to the cars.

Green underpass: Increasing linear connection by more greenery to attract bumblebees to fly under the motorway avoid bees crushing to the cars.

Rooftop green: Rooftop greenery increases vertical green to attract bumblebees flying through buildings to explore the courtyard green.

Green improvement: According replant or regenerate to increase the quality of existing green areas.

Open community yard: Open the main gate of enclosed building blocks and add visual guidance to attract bumblebees to explore isolated courtyards.

Green crossroads: By increasing the hybrid height of vegetation to guide bumblebees fly higher to avoid bees crushing to the cars on important crossroads.
Fig. 52.
The appliable toolkit to different spaces
Responsive Pollination Landscape

The last urban scenario shows this data-driven model informs spatial planning by implementing the toolkit and improving the green network (Fig. 53). For example, a balcony garden and green roof increase the vertical attractions, which guides them to fly higher to avoid car crashes. The interaction between the response of bumblebees and the environment can be a feedback loop for continuous improvement.
Chapter VI

Conclusion

• Main Findings
• Challenges and Further Developments
6.1 Main Findings

The main investigations of the thesis can be concluded in the following aspects: to explore the potential of using agent-based simulations as a tool to evaluate the urban landscape quality by navigating agents with spatial and vegetation conditions; to bridge the ecology and spatial planning through modeling process which promotes the further understanding of the internal system of urban complexity.

Firstly, the methodology conveyed by agent-based modeling in this project shifts the spatial design from the solution-oriented perspective for one specific problem to a data-driven perspective for dynamic changes. Previous theories and design attempts mentioned in the literature review served as a base for understanding the code behind the system and making programming a functional and operative tool in design and planning. Many animals, including insects, can be defined as agents under a set of behavior principles as I mentioned before. The simplified interpretation allows users to build up a dynamic behavior model, which can help designers dissect the logic behind the behavior. A further understanding of the code promotes comprehensive and systematic solutions to environmental changes.

Thus, a systematic model of bumblebee behavior was developed, which integrates the basic behavioral model of bumblebees and realistic environmental changes. As I clarified before, the task of the model is not to deconstruct a single bee’s behavior, but rather build a framework of basic behaviors of bumblebees in the urban environment that could provide insight into the spatial connectivity of the planning proposal. The model did respond to the research question of the thesis by transforming the spatial environment into parameters and interpreting the green patches into inputs.

In the case of my thesis, the modeling process translated and simplified the complex environmental factors, moreover, the model predicted the impact of the urban environment on the bumblebee movement. The result showed an interesting finding that the model predicted that bumblebees tend to bypass buildings and gather on traffic roads. The contradiction of traffic roads as risk areas and meanwhile as spaces for flight networks was easily predicted by the model. It shows the possibility that this real-time and efficient simulation result could effectively inform the urban planning process, which is limited in the traditional design process.

This approach was to highlight the potential of digital frameworks and simulation tools to bridge ecology narratives with spatial planning. ABM in my thesis not only showed its advantages as an evaluation method to detect problems but played a more significant role in building an adaptive system that can address ecological concerns and spatial planning at
the same time. It provides a new perspective for landscape architects and urban designers to understand that a predictive modeling process can help us to create an eco-friendlier urban landscape more efficiently.

6.2 Challenges and Further Developments

The simulation model as a design tool in my thesis presented many challenges and limitations which could be solved or optimized with further development.

One of the limitations is the model itself since the model conveyed by Culebra vaguely defined the spatial environment by transforming the special characteristics into circles, which might generate a less realistic simulation result. A possible future enhancement is to reprogram the inputs of components in Culebra, which allows for a more flexible and precise definition of spatial features. Besides, the model only simulated the movement of bumblebees on a relatively small urban block scale, while the model might be not capable to simulate the movement of agents on a larger urban scale since the simulation tool might be not able to do the complex and heavy calculation with larger agent accounts and larger data set. For a larger-scale application, it is important to prepare a simplified and clean data set for smooth simulation.

The interpretation and relevant application of the bumblebees’ movement results are open for future development. Agent-based modeling as a design and planning support tool is a relatively new field. Therefore, the attempt to address the bumblebee’s movement in urban planning is limited and specific under hypothetical conditions. The toolkit proposed in my thesis is based on the spatial characteristics of the example site. However, the toolkit could be enhanced regarding the various spatial characteristics and dynamic urban environments.

Finally, the obvious limitation of computational design can be seen as a lack of validity proof. The simulation model in this thesis is a speculative design process since the model is based on assumptions and abstractions that can be read by the computer. However, the assumption of the modeling process was within the realms of reality since the parameter relevant to bumblebees’ behavior were collected from previous experiments and research. Further research could cooperate with ecology experiments to demonstrate the validity
of the model. For example, Chudzinska et al. (2020) made a comparison between the empirical network statistics of bumblebees’ foraging preference with the emergent patterns generated from agent-based modeling (ABM), which showed a high relevance between the simulated results and empirical networks they get from experiments. Similarly, the bumblebees’ flight network result generated from the simulation model could be proved by a control experiment in the future.
I would like to thank first my supervisor Prof. Pia Fricker, for her patience, support, and encouragement during my thesis study. Without your guidance in the digital design field, I would never be aware of my potential of myself.

To my advisor Tina Cerpnjak, I am grateful for her critical comments on helping me frame the thesis structures and her technical support on the grasshopper issues and modeling process.

To my advisor Johan Kotze, I appreciate his strong support of ecology and biology insights toward my research question and his careful and detailed comments on my thesis.

I would also express my appreciation to my friend Sheng Fang for his technical support in programming and coding when I was in the trouble working on the grasshopper. And thanks to my friend Qiongying Cai for helping me with adding details of the building mass.

Warmly thanks to the Yay to Thesis group that creates a critical atmosphere of exchanging opinions and discussions. It is my pleasure to study and make progress with all of you. Also, thanks to Chaowen Yao for the nice talks at the beginning which helped me have an overall understanding of the thesis process and the technical support for GIS issues.

Great thanks to my family for supporting my study abroad. Without their support, I would not have the courage and power to overcome all the difficulties in my study and life.

Finally, I would like to thank my boyfriend Gimy, for his support, encouragement, love, and patience when I was stressed and anxious during the thesis study. Also, warmly thanks to his family for keeping me in mind and caring for me, I am glad that I have all your support.
List of Figures

Fig. 1. .................................................................................................................................................................................17
Urban Ecological System, bumblebees promote the pollination of native plants

Fig. 2. .................................................................................................................................................................................19
Ecotrium, an ecosystem analyzed by a real-time network (Devlin et al., 2011)

Fig. 3. .................................................................................................................................................................................20
Iterative feedback, synthetic territories network (Cantrell, 2010)

Fig. 4. .................................................................................................................................................................................21
Three rules for flocking, separation (modified from Reynolds, 1987)

Fig. 5. .................................................................................................................................................................................22
Wandering behavior (modified from Reynolds, 2002)

Fig. 6. .................................................................................................................................................................................23
Four different types of collective behavior (A-D) (Image from Couzin et al., 2002).

Fig. 7. .................................................................................................................................................................................23
Algae as Agents (Woolverton, 2021)

Fig. 8. .................................................................................................................................................................................27
BEESCOUT simulation interface (Becher et al., 2016).

Fig. 9. .................................................................................................................................................................................29
Synthetic Mudscapes- Site Three Recycle (Carney et al., 2013)

Fig. 11. ..............................................................................................................................................................................33
The built area ratio in the metropolitan area of Helsinki, data from Helsinki Map Service

Fig. 10. .................................................................................................................................................................................34
The observed distribution of six common bumblebee species in the city of Helsinki. Data from LAJI.FI.

Fig. 12. .................................................................................................................................................................................34
Built area ratio in the city center, data from Helsinki Map Service

Fig. 13. .................................................................................................................................................................................35
Traffic volume in the urban of Helsinki, Finland.

Fig. 14. .................................................................................................................................................................................37
Structural connectivity analysis

Fig. 15. .................................................................................................................................................................................39
Functional connectivity analysis

Fig. 16. .................................................................................................................................................................................40
Typical urban block in Helsinki as the sample site

Fig. 17. .................................................................................................................................................................................42
Overall methodology outline

Fig. 18. .................................................................................................................................................................................44
Definition of movement behavior

Fig. 19. .................................................................................................................................................................................44
Defined movement behavior in Culebra

Fig. 20. .................................................................................................................................................................................46
Wandering behavior on-site simulation in Culebra with the input of targets and agents

Fig. 22. .................................................................................................................................................................................46
Attraction force represented by the red circle, and generated pattern in Culebra

Fig. 21. .................................................................................................................................................................................46
Flocking behavior on-site simulation in Culebra with the input of targets and agents

Fig. 23. .................................................................................................................................................................................46
Distraction force represented by the purple circle, and generated pattern in Culebra
Fig. 24. The life circle of bumblebee in southern Finland (based on Teräs, 1976).

Fig. 26. Percentage distribution of different flowering species visited by B. pascuorum in different months (Teräs 1976).

Fig. 25. Habitat types and distribution in Helsinki city center area

Fig. 27. Bumblebees’ key parameters

Fig. 28. Bumblebees sample density in the natural landscape

Fig. 29. Assumed bumblebees sample density in the city

Fig. 30. Distraction and distraction.

Fig. 31. Vegetation classification based on the height of plants

Fig. 32. Attraction circles defined by vegetation attraction level

Fig. 33. Buildings as visual barriers of bumblebees

Fig. 34. Motorways classification based on the width of roads and traffic volume

Fig. 35. Distraction circles are defined by building distractive values into two group

Fig. 36. Overall flowchart

Fig. 37. Detailed steps of behavior simulation, track optimization, and application

Fig. 38. Informative process, multiple inputs

Fig. 39. Behavior simulation result

Fig. 40. Simplified flying network

Fig. 41. Visibility assessment

Fig. 42. New attraction points as the red dots shown in the map

Fig. 43. New distraction points as purple dots shown in the map

Fig. 44. Path following principle

Fig. 45. Path following initial behavior pattern in Culebra

Fig. 46. Adding new attraction points (red dots) in Culebra
Fig. 47. Adding new distraction points (purple dots) in Culebra

Fig. 48. Adding new attraction (red dots) and distraction points (purple dots) at the same time

Fig. 49. Issue classification by spatial characteristic

Fig. 50. Connective urban green structure

Fig. 51. Details of hanging pot streetlight

Fig. 52. The appliable toolkit to different spaces

Fig. 53. Responsive pollination landscape design, the bumblebee-friendly city scenario.
References


Fontaine, C., Dajoz, I., Meriguet, J. & Loreau, M., 2005. Manipulating plant and pollinator communities provides experimental evidence that the persistence of a plant community can be affected by a loss of diversity among its pollinating fauna. PLOS Biology.


