

Doctoral Thesis

Investigating the 5th facades of cities: A parametric computational model of urban agriculture potentials

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Dissertation

Analyse der 5. Fassade von Städten: Ein parametrisches Modell welches die Potenziale der städtischen Landwirtschaft aufzeigt

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"Designing a dream city is easy;

rebuilding a living one takes imagination"

(Jacobs, 1958)

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Maeva

Abstract

The world's population is becoming increasingly urban. By the year 2050, two-thirds of global population will live in cities (UN, 2014). Exploring holistic approaches to city design is crucial to manage tomorrow's urban mutations. In fact, global sustainability depends on how urban systems will be managed in the 21st century (Ferrão & Fernández, 2013). A shift towards innovative planning solutions that are supportive of both social and environmental sustainability is imperative.

Rooftop Agriculture (RA) could play a role in this transformation process. Rooftop gardens are multifunctional; hence provide several advantages such as enhancing biodiversity conservation, reducing flood risks or mitigating the urban heat island effect (Mentens et al., 2005). In many cities, due to urban pressure and land speculation, vacant space is rare. To solve this issue, numerous farm projects are growing on roofs, enabling efficient use of space in increasingly dense centers and converting unused surfaces into a more productive roof landscape. The projects take different forms and scales: from the self-built rooftop gardens such as the *ØsterGro Farm* in Copenhagen or the *Gartenwerkstadt* in Vienna, to the large rooftop soil farms in New York City with the *Brooklyn Grange*.

Based on the Geographic Information Systems (GIS) data of the municipalities of Vienna and Rio de Janeiro City (RJC), the research objective is to conceive a set of parametric models which supports decision-making for implementing urban agriculture on the flat roofs landscape of cities. The targeted improvements are: the potential influence of rooftop gardens to enhance urban biodiversity conservation, the capacity to produce local food and consequently to provide food security, and the contribution to increase the city green cover. Through this investigation, the present thesis will answer the following question: how can parametric modelling methodologies contribute to the spatial analysis and detection of the key locations for rooftop agriculture within an existing urban landscape? In Vienna, the municipality evaluated that 1'068.4 ha, which represents 21% of the overall rooftop surface, would be suitable for intensive greening (Vali, 2011). Based on the inclination and the geometry of the roof landscape of Rio de Janeiro City (Light Detection And Ranging LIDAR data), the present research estimated that 1'383 hectares of roofs would be suitable for RA on 69% of the city surface (without taking into account the structural conditions of the roofs). This productive roof area could produce enough food to meet the yearly demand for vegetables of 39.2% of the inhabitants. The study also demonstrated the great relevance of implementing RA in the poorest communities of RJC in the perspective of tackling food insecurity.

After importing the GIS data of the flat rooftop surfaces into Grasshopper (a graphical algorithm editor that runs with the computer aided-design software Rhinoceros 3D), the developed parametric models allow planners to process a multitude of alternatives during the design process by interconnecting and coordinating design components simultaneously. Based on the results, the models evaluate the key scenarios for RA for the city roof landscapes of Vienna and RJC. By promoting a way of envisioning the urban space across its different layers of complexity, the idea is to look at rooftop agriculture as a possible driver for social and environmental sustainability.

Abbreviations

DSM	Digital Surface Model
DTM	Digital Terrain Model
FAO	Food and Agriculture Organization of the United Nations
FO	Fitness Objective
GCN	Green Corridors Network
GIS	Geographic Information Systems
GPS	Global Positioning System
IDS	Índice de Desenvolvimento Social (portuguese)
	Social Development Index (english)
INS	Inertial Navigation System
IPCC	Intergovernmental Panel on Climate Change
IPP	Instituto Pereira Passos (portuguese)
	Institute Pereira Passos (english)
LD	Location Density
LIDAR	Light Detection And Ranging
MST	Minimum Spanning Tree
NDSM	Normalized Digital Surface Model
РМ	Parametric Model
RA	Rooftop Agriculture
RJC	Rio de Janeiro City
SDGs	Sustainable Development Goals
SMAC	Secretaria Municipal de Meio Ambiente (portuguese)
	Municipal secretary of environment (english)
SIURB	Sistema Municipal de Informações Urbanas (portuguese)

	Municipal Urban Information System (english)
TIN	Triangulated Irregular Network
UA	Urban Agriculture
UN	United Nations
UTM	Universal Transverse Mercator
ZAMG	Zentralanstalt für Meteorologie und Geodynamik (german)
	Central Institute of Meteorology and Geodynamics (english)

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Chapter 1. Introduction

1.1. Problem statement

The chapter gives a brief overview of the five main problems existing in the concerned area of the study. The problems include: conditions that need to be improved, knowledge gaps, areas of concern and difficulties that need to be eliminated. The goal is to summarize the different issues that should be addressed:

Cities face challenges concerning growth and urban concentration

Human activities pushed the planet into the Anthropocene, proposed as a new geological era dominated by human's influence (Steffen et al., 2011). The Anthropocene is marked by three major challenges: the prevention of biodiversity loss, the adaptation to climate change and the sustainable support of a growing population (Kremen & Merenlender, 2018). <u>This growing population is becoming increasingly urban: it is estimated that two-thirds of global population will live in cities by the year 2050 (UN, 2014).</u> The vision of the New Urban Agenda of the United Nations (UN) Habitat highlights that urbanization, if well-planned and well-managed, could be a powerful tool for sustainable development (UN Habitat, 2016). In this perspective, cities should not only grow in size but rather develop in terms of quality (Renner, 2017). This process requires a deep understanding of the city organization, functions and processes (combining various aspects such as social, environmental, economical and governance). Since there are several interdependencies between the different city development goals, it could be counterproductive to consider each objective separately. A view of the whole urban system is imperative to design adequate strategic plans, hence <u>a shift towards a more systemic approach of city planning is crucial to manage actual and tomorrow's urban mutations.</u>

Food is rarely considered as an integrated part of the "Productive City"

The integration of sustainable food systems into urban planning is a crucial and emerging topic. According to a report published by the World Bank, 70 to 100% more food will be needed by 2050 (World Bank, 2008). In Brazil, as a result of insufficient incomes, almost a third of the Brazilian population does not have adequate resources for acquiring appropriate quantity and quality of food (Meade et al., 2018). Although food systems plays a key role to achieve the Sustainable Development Goals (SDGs), Food has been rarely included into urban development plans (Cabannes & Marocchino, 2018; Roggema, 2017). Food security and nutrition are at the core of sustainable urban development and there is a necessity to go beyond the conventional separation between rural and urban spaces (UN Habitat, 2016). Rooftop Agriculture (RA) could play a key role in providing fresh and affordable food close to the consumers in highly urbanized areas.

Urban vegetation and green spaces are lacking in densely populated cities

The UN Sustainable Development Goal n°11 "Make Cities inclusive, safe, resilient and sustainable" underlines the importance of green spaces in urban areas, as inclusive spaces and improving air quality (UN SDG, 2015). Urban vegetation plays a key role in regulating the surface temperatures in the city and mitigating the urban heat island effect (Shishegar, 2014). Urban heat islands can have severe impacts on public health and lead to increased mortality rates of the population (Souch & Grimmond, 2004). For the city of Vienna, the heat-related mortality rate could grow by more than 100% in the forthcoming decades (Muthers et al., 2010). An analysis of the number of hot days between the years 1961 and 2010 demonstrated a noticeable increase from 9,6 to 15,2 days (Czachs et al., 2013). The *Zentralanstalt für Meteorologie und Geodynamik* (ZAMG) estimated an augmentation of summer days (ie. when the land surface temperature is greater than 25 °C) by 30 to 50% between 2017 and 2100, which would result in a significant increase of the urban heat island effect (ZAMG, 2012). Rooftop gardens strategically combined with green facades and urban tree planting could play a

role in minimizing the urban heat load of cities. RA enhances the evapotranspiration in urban areas through soil and plants by redirecting the energy latent heat (Li et al., 2014). <u>A well-designed green infrastructure system is therefore crucial, since it helps cities to mitigate the negative effects of urbanization and to be more resilient to environmental changes</u> (European Commission, 2011).

Scientific knowledge about how urban planning and design can support ecosystem services is surprisingly lacking

Policies often fail in integrating environmental aspects in a way that truly impact design practices. Although findings on ecological processes have increased significantly, applications in sustainable urban development are missing (Hayek et al., 2010). <u>Knowledge about how to</u> <u>maintain essential ecosystem services in urban areas with the use of urban planning and design is also very limited (Marcus et al., 2014).</u> Cities are heterogeneous and dynamic ecosystems and greening them remains a very complex task. It is also important to note that RA is rarely integrated into the city strategic plans, especially in the perspective of reconnecting the fragmented urban green landscape. For example, the Biotope Area Factor (BAF) is an instrument which was developed in Germany to support the ecological situation of the existing sites in the inner cities (Kazmierczak et al. 2010). The planning policy tool offers a basis for green planning, aiming to facilitate the conservation and enhancement of the "green qualities" of city centers. However, this tool does not include the potential of enhancing the green network connectivity.

Bridging visions of the different stakeholders for facilitating efficient decisionmaking in greening urban landscapes is challenging.

The design of nature-based solutions in the existing built environment requires a highly collaborative approach involving various stakeholders. Every greening action needs to be

carefully identified, quantified, priced and prioritized in order to develop efficient greening strategies (Jim, 2013). The alignment of the stakeholders with different interests is challenging and the decisive project inputs may change during the planning process (such as for instance the size of the investments). There is also a missing transfer of the information to decision makers in a coherent and intelligible manner (Deinhammer, 2018). This uncomplete decisional process contributes to slow down the planning phase; based on conflicting needs of the stakeholders. This process highly influences the quality of the final project, whereas design exploration is needed to support decision. <u>Greening plans need to evolve from a static design towards the dynamic generation of alternatives for greening complex urban environments.</u> Parametric design tools deliver a flexible approach to the production of urban plans and would facilitate and improve this planning process (Beirão & Arrobas, 2013).

The following action fields have been identified for the present thesis: Urban Food Planning, Urban Green Infrastructure Planning, Sustainable Urban Development, Green Spaces Connectivity, Interdisciplinary Planning and Urban Parametric Modelling. In order to address all these domains, the research aims to develop a set of parametric models for envisioning the key scenarios and configurations for the implementation of urban agriculture on two existing flat roof landscapes: the cities of Vienna in Austria and of Rio de Janeiro in Brazil.

1.2. Research objectives

The work aims to create a set of parametric models which supports decision-making for planning Rooftop Agriculture (RA) in cities. As stated in the theory of urban acupuncture initiated by the architect and urbanist, Manuel de Sola Morales, cities can be viewed and treated as living organisms. This approach supposes that small surgical and selective interventions into the built environment can have a strong and catalytic influence on the urban ecosystem when these are planned in strategic positions (Kaye, 2011). The present thesis assumes that strategically

planned RA is one key instrument to reduce the negative effects of urbanization, contributes to local food production and the preservation of urban biodiversity.

This assumption involves the idea that rooftop gardens could play a key role in reconnecting fragmented urban green networks. The idea is to present an overview on how the roofs of cities could be greened; by identifying their potential connections with the existing green infrastructure and creating optimal networks to link them. The targeted improvements are the enhancement of the green corridors connectivity, the production of local food and the even distribution of the urban green cover. The basis for the analysis is the GIS data, provided by the municipalities of Vienna and Rio de Janeiro. Within such parametric models, all studied parameters and their impacts are translated into visual programming using the graphical algorithm editor Grasshopper that runs with Rhinoceros 3D (a computer aided-design CAD application software).

The present study objectives are:

Concerning the area "Urban Green Infrastructure Planning" (Chapters 3, 4, and 5):

- 1) <u>Identifying the key characteristics and configurations</u> of green spaces and rooftop gardens for enhancing the dispersal power of urban pollinators.
- 2) Evaluating the growing capacity of the roof landscape of Rio de Janeiro City (RJC).

Concerning the area "Digital Mapping and Modelling" (Chapters 4 and 5):

- Identifying and mapping the flat roofs and terraces for RJC based on a 3D Light Detection And Ranging (LIDAR) point cloud.
- 4) <u>Elaborating and testing a method workflow which combines GIS applications and</u> <u>Parametric Modelling</u> for the analysis of the flat roof landscape potentials. The study provides insights regarding the applicability of combining city geometry (using GIS) and generic algorithms (using Grasshopper) to define the key locations for RA. Rather than

large scale and expensive urban renewal plans, selective and targeted greening interventions within city centers could be the basis of efficient greening strategies.

5) <u>Developing a set of parametric tools</u> that helps decision makers in analyzing the existing green capital of cities and identifying the key locations for RA. The research addresses three influence domains: the capacity of RA to enhance the connectivity of the green corridors network, the growing potential of the existing roof landscape and the potential of RA to increase the urban green cover. The models provide hints on the prioritization of roofs and the methodology is planned to be applicable to similar urban contexts. A set of 6 parametric models were conceived based on the roof landscape of Vienna and 3 were tested on Bangu, a district of RJC. The results aim to be a support for urban planners for decision-making and to influence urban local policies.

The nature of work is multiple:

- 1) A set of digital parametric tools for planners to analyze the green capital of cities and design greening strategies. The research investigates the potential for applying parametric design processes over conventional urban planning processes. Since the definition is based on parametric modeling techniques, the model is conceived to be flexible to different cityscapes. The idea is to provide a design process method for greening urban roof landscapes, which is responsive to the city geometry and the designer's demands.
- 2) The starting point of a statement for both citizens and planners to shape collaboratively the social and environmental green structure of our cities with the use of RA. With informed design, small catalytic initiatives made by each individual could have a great impact on the city ecosystem. The models provide citizens a platform to envision the connexions between human and urban pollinators, revealing the fragile and ephemeral trajectories between these worlds. The work encompasses both a bottom-up approach

(the results aimed to be shared publicly) and a top-down approach (a tool for city officials and planners), which are important for turning visions into action.

1.3. Research questions and scope

The main research question is:

1) How can parametric modelling methodologies contribute to the spatial analysis and detection of the key locations for rooftop agriculture within an existing urban landscape?

By answering the main research question, the study also investigates the following subquestions:

- 2) Where to site new rooftop gardens in order to best optimize the distribution of the urban green cover? Consequently, which areas have a relative or absolute lack of green spaces in the case studies of Vienna and Bangu (RJC)?
- 3) What are the optimal locations and conditions for rooftop agriculture given an existing fragmentation of the green infrastructure of a city?
- 4) What is the flat roof landscape potential in RJC? What would be the associated growing capacity?
- 5) What are the key social parameters to be considered for the implementation of rooftop agriculture in Vienna and in RJC?

The present study focuses on the roof landscapes of two cities: Vienna and RJC. The analysis includes all the roofs and terraces with a pitch angle comprised between 0 and 5 degrees inclination and a minimum area of 5 m^2 . Further details regarding the selection and classification of the roof surfaces are described in Chapter 4.

The process of sustainable urban development could be defined by 8 distinct phases (Yigitcanlar et al., 2015). The present research addresses the early stages, which correspond to phases 1 to 4:

1) "The preparatory and exploration phase": planners identify and define the environmental, social, institutional and economical problems and objectives;

2) "The goals and objectives phase": planners refine and prioritize the objectives;

3) "The alternatives phase" which aims to generate propositions and scenarios based on the selected goals of phase 2;

4) "Evaluation and plan selection phase": the stakeholders evaluate and assess the alternatives.

If the selected alternatives meet the requirements of the levels of sustainability, the plans are transferred to: 5 "Feasibility and development" phase, 6 "Construction" phase, 7 "Completion and delivery" phase and 8 "Occupation" phase. To select the key scenarios for RA, the evaluation is based on:

- the capacity of the scenario to increase the length and the connectivity of the existing green corridors network,
- the feasibility of the scenario based on building use, ownership, monument protection and structural capacity,
- the capacity of the scenario to maximize the potential urban food production.

The focus is made on intensive green roof systems with an agricultural purpose. However, since intensive greening systems have more strict requirements than extensive greening systems, it could be interesting to use the results for the implementation of extensive green roofs. Concerning the modelisation of the growing capacity, two RA designs are tested: 1) production with soil-based vegetable beds (depth of the growing media is min. 30 cm); and 2) production with a rooftop hydroponic greenhouse (exclusively for the flat roofs larger than 1'000 m²).

1.4. Research methodology

Figure 1 describes the different steps of the research methodology.



Figure 1. Diagram depicting the methodology used in the present research.

STEP 1. Preliminary research and context analysis

- Literature review,
- <u>Interviews</u> with city officials, research institutions, associations and selected experts in the fields of urban agriculture, landscape ecology, botany, entomology, zoology, city planning and structural engineering,
- <u>Co-supervision of two design studios</u> of each approx. 15 master student projects.
 The goal of the class was to plan a hydroponic rooftop farm on the roofs of the TU Wien and of the Markhof community building,

<u>Collection of the results</u> informing about the architectural and structural design challenges and opportunities associated with the implementation of a hydroponic rooftop farm on existing buildings in Vienna,

- <u>Co-research and supervision</u> of one Master thesis (Ms. DI. Barbara Laa) and one Bachelor thesis (M. Gwenael Moysan) for the collection of information regarding rooftop hydroponic greenhouses in Vienna,
- <u>Collective mapping workshop</u> at the *Kunsthalle Wien* on the topic of urban acupuncture and community gardening in Vienna,
- <u>Visits</u> of several existing urban agriculture projects in Vienna and in Rio de Janeiro.

STEP 2. Collection and preparation of the GIS data

- <u>Collection of the GIS data</u> of two different city scapes: the municipalities of Vienna (*Magistrat 22* – Environment Department) and RJC (*Instituto Municipal de Urbanismo Pereira Passos* – IPP),
- <u>3D LIDAR data analysis, classification and mapping</u> of the flat roof landscape of the RJC using LAStools, QGIS and ArcGIS (Isenburg, 2018; QGIS, 2019; ArcGIS, 2014),

<u>Feedback Workshop on the mapping results</u> with city officials, researchers and students at the Federal University of the State of Rio de Janeiro (UNIRIO): collection of the participants feedback regarding the challenges and opportunities for implementing greening policies and rooftop agriculture in RJC,

- <u>Preliminary analysis</u> of the two flat roof landscape potentials,
- Filtering and preparation of the data for the parametric modelling phase based on the observations of Step 1.

STEP 3. Transfer of the GIS data into Rhinoceros 3D & Grasshopper

- <u>Definition and test of a workflow method</u> for transferring the GIS data into the Grasshopper Platform using the Meerkat Plug-In (Lowe, 2015),
- <u>Prototyping</u> of parametric models for the analysis and design of the green corridors network in Vienna using the SpiderWeb Plug-In (Schaffranek, 2016).

STEP 4. Parametric Modelling

Appendix 1. Roadmap of the parametric models created in the present study gives detailed information on the parametric modelling process. The modelling phase is composed of 3 different levels:

Level A. Analysis of the existing urban green landscape:

 <u>Definition of a set of 2 Parametric Models (PMs)</u> which analyzes the existing urban green landscape for a case study of Vienna. The PMs which were developed for level A are:

PM "Green desert" - Chapter 5.4.

PM "Location Density" - Chapter 5.5.1.

Level B. Analysis of the key roofs surfaces for RA "From green areas to flat roofs":

<u>Definition of a set of 3 PMs</u> based on the observations of steps 1, 2 and 3, and the zones of opportunities identified in Level A for the case study of Vienna. Level B integrates the flat roofs landscape polygons and points out how and which flat roofs could be used to reconnect (or strengthen) the existing urban green cover. The PMs which were developed for level B are:

PM "Green desert" (extension) – Chapter 5.4.

PM "Minimum Spanning Tree" - Chapter 5.5.2.

PM "Food Production" - Chapter 5.6.

Level C. Proof of concept on the region of Bangu & Analysis of the key scenarios "From flat roofs to combination scenarios":

- <u>Testing and Optimization</u> of the PMs on the case study area of Bangu in RJC and <u>Proof</u> of concept;
- <u>Definition of a set of 3 PMs</u> based on the results of the levels A and B. Level C aims to detect the spatial synergies between the outputs of the PMs (1) "Green desert", (2) "Food Production" and (3) "Minimum Spanning Tree"; and to define the best combination scenarios for RA for the case study area of Vienna. The Plugin Wallacei enables the multi-objective optimization and the ranking of the combination scenarios (Makki, 2019). The PMs which were developed for level C are:

PM "Minimum Spanning Tree" (for the scenario "shortest Minimum Spanning Tree") - Chapter 5.5.2.

PM "Detecting spatial synergies" - Chapter 5.8.1.

PM "Wallacei" - Chapter 5.8.2.

STEP 5. Conclusions and Discussions

- <u>Conclusions and recommendations</u> are drawn based on the preliminary research phase, the limitations, the outputs of the GIS analysis and the results of the parametric modelling phase.

1.5. Thesis outline

Chapter 2 "The benefits and limitations of urban agriculture" presents an overview on the types, advantages and current knowledge on urban agriculture. The chapter focuses on RA and its contribution to support ecosystem services and to provide fresh and local food in urban areas.

Chapter 3 "Suitability for rooftop agriculture" gives an overview of the context of the cities of Vienna and RJC for RA and green infrastructure planning.

Chapter 4 "GIS Analysis of the rooftop agriculture potential in Vienna and Rio de Janeiro **City**" presents the study methodology for the generation of the models (ie. implementation of GIS data into Grasshopper). The chapter also describes the processing of the LIDAR data (collection, analysis and classification) for the mapping of the potential for RA in RJC.

Chapter 5 "Parametric modelling" presents the parametric modelling process: the study shows the results of the PMs on the case study of Vienna and how the PMs definition were improved based on the case study of Bangu (ie. Proof of concept).

Chapter 6 "Conclusions" presents the conclusions and recommendations regarding the study outputs.

Chapter 2. The benefits and limitations of urban agriculture

- 2.1. Food urbanism
- 2.1.1. Urban agriculture concepts in city planning

• Planning Agriculture with the city

In 1826, Johann Heinrich Von Thunen presented the Von Thunen Model, describing his vision of how to organize agricultural use around the city core (Von Thunen, 1826). Planned before the industrialization, the model proposed a unique spatial distribution of farming types based on the distance to the city center, the resource availabilities and a careful prioritization. According to Von Thunen, vegetables and dairy products should be close to the urban areas in order to ensure the quality and freshness of the products for the city markets. Large field crops and ranching were located on the outer layers of the model (Figure 2).



Figure 2. Von Thunen's model of agricultural land use. Composed of 4 concentric rings around the urban center, the location model illustrates the balance between land value and transportation costs. Adapted from the *Isolated state,* by J.H. Von Thunen, 1826: Pergamon Press. Copyright 2017, by Springer International Publishing AG.

Similarly, Howard (1902) designed the Garden City, which located the food production areas on the periphery of the city, but established a close relationship between the urban space requirements and the agricultural needs. The size of the Garden City was relatively small (around 1'000 acres) since the layout was planned according to the movement of pedestrians and bicyclists (Howard, 1902). Howard recognized the importance of green spaces in the city by fully integrating them into several and concentric green layers. The surroundings of the urban center were planned with green areas (with a recreational purpose). The 1'000 acres of the Garden City were enclosed by the "Agricultural Belt" (5'000 acres space dedicated for farming and forestry). These large green areas served as a barrier to contain urban sprawl and aimed to preserve the size and shape of the Garden City. Figure 3 illustrates the spatial representation of the urban model.



Figure 3. Plan of the Garden City imagined by E. Howard. The plan displays the spatial distribution of the green areas and other type of land uses. From *Garden Cities of To-morrow,* by E. Howard, 1902: Swan Sonnenschein & Co. Copyright 1902, by Swan Sonnenschein & Co.

The objective was to offer to the citizens of the Garden City a compact center with large green areas and within a small distance. The model was conceived by considering the inherent interrelations between the city space (which is partially greened) and the agricultural land. Although the agricultural activities were not directly "urban", Howard established here a close relationship between the City and Farming concepts.

Wright (1932) also had a strong interest in better connecting the countryside with the city. He proposed a radical vision of the city organization which would encourage citizens to live from and with Agriculture. In his book *The Disappearing City* published in 1932, Frank Lloyd Wright presented the concept of Broadacre City (Wright, 1932). His vision was driven by the idea that the decentralization of cities, enabled with the technologies of the automobile age, would offer more independence to its citizens. In Broadacre City, there is no rent since every individual should possess its own land. The shape and the scale of this new space do not correspond to any conventional plan: spreading over 100 square miles the city does not possess a center. Wright removed the traditional separations between city and rural areas. Housings, industrial buildings, leisure areas, and offices are surrounded by farmland and forests (Fishman, 1977). On each unit, a family possesses a land where they can farm, cultivate and enjoy nature. The citizen of Broadacre City has the choice to farm or to enjoy urban activities located within a reachable distance. The conventional barriers separating town and country are no longer existing. The goal is here to chase away the inconveniences of the fragmentation of modern life. Figure 4 shows a view of Broadacre City.



Figure 4. Model of "Broadacre City" by Frank Lloyd Wright. The city concept includes a mixed use of the landscape with various housing types in a low-density pattern. From The *Disappearing City*, F.L. Wright, 1932: William Farquhar Payson Publishers. Copyright 1932 by Frank Lloyd Wright Foundation.

This radical transformation of the conventional urban model shows the prime importance for Wright to offer to citizens the advantages of the city with the access to nature and the possibility to farm.

In 1934, during the economic crisis the "Great Depression", Le Corbusier provided new ideas regarding the planning of agricultural spaces (Le Corbusier, 1934). His approach was very unique among architects in that time: instead of rethinking cities and integrating agriculture within the urban space, Le Corbusier focused on improving the living conditions of the farmers in the rural areas. In collaboration with Piace (1932), he imagined *La Ferme Radieuse* and *Le Village Cooperatif*, proposing new architectural and planning solutions for farms at a large range of scales (Figure 5).



Figure 5. Photography of a model of *La Ferme Radieuse* imagined by Le Corbusier. The objective of the project was to reimagine the conventional layout plan of rural areas. Photography taken by L. Herve and retrieved from fondationlecorbusier.fr. Copyright 2019 by FLC/ADAGP.

Le Corbusier shows here the importance of better planning rural areas. Cities and land possess an unbreakable connexion; therefore none of these spaces should be ignored by planners (Jornel, 2013). He wrote *"II n'est pas possible de songer à urbaniser les villes modernes si l'on ne pense pas à aménager les campagnes."* - in english: *"We cannot consider urbanizing modern cities if we don't look at ways to plan the countryside"* (Le Corbusier, 1934). In that perspective, what would be the concept of the "Agricultural" city (or urban agriculture) if planners do not design an "Urban" countryside as well (Donnadieu, 1998)?

These different visions show how planners imagined the connections between society, food and cities. However, it is important to note that food is often considered as a source necessary to supply the city rather than an integrated part of the productive city itself (Roggema, 2017).

Urban voids and the agricultural prosthesis

The Agricultural City was an urban concept proposed in 1960 by the architect and founder of the Metabolist Movement, Kisho Kurokawa (Kurokawa, 1960). The city plan was composed of an elevated grid structure on pilotis which overlapped the rural areas. Kurokawa questioned the

conventional separation between the city and the rural spaces by showing how the city could be configured into several grid units (which were flexible and planned to be extended) and, simultaneously, how this elevated urban space could keep a close relationship with the agricultural areas on the ground level (Figure 6).



Figure 6. Models and drawings of the Agricultural City designed by K. Kurokawa in1960. The construction, in the shape of a mushroom, is raised above the agricultural land to be more resilient to flood risks. From *The Agricultural City* by K. Kurokawa, 1960. Retrieved from archeyes.com/agricultural-city-kurokawa-kisho/. Copyright 2019 by Kisho Kurokawa architect & associates.

Inspired by the challenges of floods faced by the region of Chubu in Japan, Kurokawa believed that the urban functions, as well as the productive areas, should not be divided but instead arranged strategically into a 3-dimensional system which would shape resilient and compact communities.

Following a similar spatial logic, Yona Friedman imagined the *Ville Spatiale* in 1959 as a 3D superstructure which could overlap non-constructible zones and existing cities (Friedman, 1976) (Figure 7).



Figure 7. Study on density and natural light of *La Ville Spatiale* drawn by Yona Friedman. From *Comment habiter la terre* by Y. Friedman, 1976: Ministere de la qualite de la vie. Retrieved from yonafriedman.nl. Copyright 1976 Yona Friedman.

Like Kurokawa, the goal of Friedman was to rethink the spatial arrangement of the city functions into a three-dimensional model. In his drawings, he proposed a unique spatial system where the agricultural surfaces were strategically situated on the different levels of the superstructure. The spatial configuration of agricultural activities depended on the sunlight incidence and the proximity to other "matching" functions such as the housing units *Vivienda*, the corridors and the patios. The ground floor layer, located under the structure, was designed for public use and agriculture. The structure was conceived in a way that the ground is as less as possible touched by the pilotis construction. Yona Friedman proposed an open and flexible grid where the inhabitants can choose to design their own space according to their needs. His vision consisted in bridging the concepts of the industrial city, the residential city and the agricultural city. By modifying the common city model, the idea was to question new urban processes.

• Indoor Farming

Multiple solutions are now available to cultivate edible plants. This includes extending crop production into the vertical dimension, in the underground spaces, and inside or on the top of buildings to produce a higher yield using less floor area. One of the most provocative and recent urban agriculture concepts is the contribution of Prof. Dickson Despommier with its book *The Vertical Farm: Feeding the World in the 21st Century* published in 2010 (Despommier, 2010). The architectural concept consists in locating agricultural production directly inside towers in the center of cities (also named "Farmscrapers"). The idea is to redesign agricultural systems by cultivating crops not horizontally but vertically. Indoor farming and the use of hydroponic systems (soil-less systems) would enable a more sustainable way of producing and consuming food by cultivating crops within the urban and peri-urban areas. This process would reduce costs of transportation, CO2 emissions and waste (with the reuse of the irrigation water).

However, large vertical farming constructions generally require a close and controlled environment which involves a high demand for energy (such as heating and cooling and hydroponic lightning). The building typologies of the Farmscrapers can be very different and some concepts have already been built in large cities such as Aerofarms in New York City, Skygreens in Singapore and Vertical Harvest in Jackson (Figure 8).



Figure 8. 3 built examples of Indoor farming projects: *Aerofarms* in New York City, *Skygreens* in Singapore and *Vertical Harvest* in Jackson Hole. The projects show the possibility of producing food and medicine in vertically stacked layers in peri-urban areas. Photographs retrieved from aerofarms.com; zainalandzainal.com; rendering retrieved from verticalharvestjackson.com. Copyright 2019 by Aerofarms, ZainalandZainal and VerticalharvestJackson.

The projects combine hydroponic growing systems with innovative architectural configurations and may serve commercial, social or research purposes.

2.1.2. Towards circular cities

Cities and regions are complex ecosystems. Key resources such as water, energy, material goods, and food are in constant flows within the built environment. This process is based on the assumption that it is possible to produce, and produce endlessly. Our current modes of production and consumption are increasingly threatening the planet, our health, and the economy. Accordingly, appropriate measures should be taken to tackle the problem. Changing this mindset includes modifying our current consumption pattern and disposal spree in order to to leave behind this linear model. It is important to rethink this system and find solutions for using and handling these resources in a more efficient way. In that perspective, natural ecosystems show the possibility to sustain models within cycles: "nothing is lost but only transformed". Shifting from a "standard" linear urban model ("take, make and waste") to a circular metabolism requires the detection of the key opportunities in these flows and the finding of suitable solutions in order to close some of these resources within the city space (Figure 9).



Figure 9. Towards a circular metabolism in cities. The diagram depicts the differences of flows between an urban linear metabolism and urban circular metabolism. The concept of urban Metabolism is a metaphor used to compare

cities with nature's organisms. The objective is to define the relationships between the urban production and consumption. In the case of a circular urban metabolism, the ciy outputs are partially reused or reintegrated into the urban system. From *Creating sustainable cities* H. Girardet, 1999: Green Books for the Schumacher Society. Copyright 1999 by Schumacher Society.

The circular metabolism model generates fewer outputs and thus, requires fewer resources as inputs. Unfortunately, for municipalities, there is still a lack of awareness of what and where are the opportunities to close their resources for their specific urban context. The first step to support this transition would be to make a detailed assessment of the opportunities. This analysis may be conducted on different scales, from the region to the city and has to be context-sensitive. Based on these results, cities should create an action plan describing the measures to catch up with these opportunities. Instruments such as policies can be created by cities to implement circular criteria into their urban development strategies. This transition process would also reflect on design, where a new planning culture needs to emerge, involving simultaneously all the stakeholders. The key element for the conception of circular cities (especially in the field of construction) is to support an intensive, collaborative and interdisciplinary design in the early stage.

Another important point is the use of regenerative design which would support the development of systems for the co-evolution of human and other species. Regenerative solutions aim to restore, renew and revitalize by integrating both the needs of society with the integrity of species (Attia, 2017). In the food sector, a strong example of regenerative design is the use of regenerative agriculture, based on permaculture techniques.

2.1.3. Creating sustainable and circular food systems in cities

According to a report published by the World Bank, 70 to 100% more food will be needed by 2050 (World Bank, 2008). Rethinking the urban food system requires the adoption of hyperlocal and decentralized food production processes. The report *Cities and Circular Economy for Food,* produced by the Ellen MacArthur Foundation, acknowledges cities as one of the key drivers for supporting the development of a healthier and regenerative food system (Ellen MacArthur

Foundation, 2019). In this report, three major solutions towards this urban transition were highlighted:

- developing local food production in urban and peri-urban areas
- strengthening the connexions between farmers in the peri-urban areas and city dwellers;
- using regenerative agricultural techniques such as permaculture, agroecology, agroforestry,etc.;
- reusing and transforming food waste.

Most cities don't have sufficient space for growing food in order to meet the demand for quantity and diversity of vegetables and fruits. 40% of the world's cropland is located in peri-urban areas (within 20 kilometers of cities) (Thebo, 2017). Therefore, peri-urban areas are key zones and could be transformed into innovative and sustainable agricultural hubs. Figure 10 illustrates how the creation of a farm belt in the peri-urban areas could become an integral part of this new system and could contribute to this circular process through recycling and composting.



Figure 10. Diagram illustrating the concept of "Closing the loop" using the peri-urban areas. The output flows could be partially reused as nutrients to grow food in the peri-urban areas. One objective of the model is to achieve a short-distance based food-chain. From *Cities and Circular Economy for Food* by The EllenMacarthur Foundation, 2019: Ellen MacArthur Foundation. Retrieved from: ellenmacarthurfoundation.org. Copyright 2019 Ellen MacArthur Foundation.

The goal of regenerative agriculture is to build healthy soil, which would ensure long-term food production. These transition or "buffer" areas connect urban and rural environment and hold a great potential for developing local and regenerative food production systems. Also well-connected to the transportation system of the cities nearby, with a lower cost of the land but close to the customers, peri-urban areas are key centers for the development of a more sustainable agriculture model and the experimentation of regenerative agriculture methods (EllenMacArthur Foundation, 2019).

2.1.4. The future of food and cities

The representation of the world and space has been shown traditionally in visible forms. Mapping cities gives a picture of the shape of urban space with its physical characteristics and boundaries such as buildings, infrastructures, green areas, etc. The digitalization of the world provides insights in the way cities work and react to human activities. A new perception is now available based on data visualization, detecting the intangible properties of space and making the invisible discernible. Data has a great influence on our daily lives and its visualization helps planners to better understand and interpret these attitudes and flows. The shift in data is a chance to understand the city in a more holistic way. Moving towards the digitalization of cities is an opportunity to engage citizens for designing collaboratively the built environment. Using data should be seen as a vector for detecting social and environmental vulnerabilities and converting these challenges into opportunities for more sustainable urban design. With digital technology, the city becomes a flexible environment that is both owned and shaped by its inhabitants. Future cities should become more sustainable, resilient and inclusive. Innovative food production systems are growing across cities and shows the development of a global trend of rethinking the way we shape our cities with food. Unfortunately, the concept of "Smart cities" rarely includes the topic of Food. What is a smart city without fresh food and water? How could we better integrate urban agriculture into the agenda of smart cities?

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In addition, cities will face multiple challenges associated with climate change, population growth and a high urbanization rate (United Nations, 2014). The agricultural sector will be strongly impacted by these changes (rise of the sea level, pests and diseases) and by frequent extreme climatic conditions such as heat waves, heavy rainfall, floods, and drought (Vermeulen et al., 2012). The sector has to learn to be more resilient in order to tackle these future changes and not aggravate the current situation (Tendall et al., 2015). By creating a more decentralized and diverse food production system (i.e. different from monoculture), our food system could be more resilient to climate changes (Altieri, 2015).

As a complementary supply solution, cities should investigate key locations for growing food directly by or near the consumers. By decentralizing food production and locating food closer to cities, pollution and CO2 emissions associated with excessive packaging and the long distribution supply chain could be significantly reduced (Ellen MacArthur Foundation, 2019). Cities may be highly urbanized and compact but space can be found on several locations such as roofs, facades, indoor-environments and in basements. Urban food production systems (such as indoor rooftop agriculture, technological urban greenhouses) are suitable for only a small and specific range of crops such as leafy greens, and selected fruits and vegetables. The choice of the plants must be strategic in order to be competitive and profitable for urban farmers. In addition, indoor growing environments still face challenges in terms of efficiency and energy supply with high heating and lighting demands (Ellen MacArthur Foundation, 2019).

Nonetheless, if carefully designed and implemented, outdoor urban agriculture presents a large range of socio-environmental benefits such as the extension of green areas in the city, the mitigation of urban heat islands, social inclusion, food education, carbon sequestration and the reduction of food risks. In the present study, the focus is on finding the spatial synergies between the built environment and the potential benefits associated with the implementation of RA.

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2.2. Designing green corridors network with rooftop agriculture

2.2.1. Uncovering the hidden urban landscapes

"The map is not the territory", wrote Korzybski to express the infeasibility of an accurate representation of the space (Korzybski, 1933). The difficulty of modelization stands in the transcription of reality through this unavoidable prism of perception. Creating a city model is a complicated task: it is impossible to include all relevant parameters that are making a city what it really is; a highly complex and dynamic system. Despite these facts, modelization is a medium for planners and scientists to analyze and investigate urban morphologies. Valery poetically observed "Everything simple is false. Everything which is complex is unusable" (Valery, 1942). In other words, the model needs to give a representation that is accurate enough to be useful. "Remember that all models are wrong; the practical question is how wrong do they have to be to not be useful" (Box et al., 1987).

Keeping in mind these constraints and limits, the present study tries to give a representation of what cities could offer with the use of urban agriculture on roofs. One of the study goals is to design a parametric model providing the best locations and configuration of the new rooftop gardens with respect to enhancing the green corridors network connectivity. The strategy consists in taking into account the roofs surfaces and trying to integrate them into a single model matrix. By considering all horizontal surfaces of the city landscape (from the ground floor to rooftops), the model gives an overview of what potential benefits those "extra" urban areas could provide. The objective is to give a possible mapping tool of pollinators' interactions towards an urban space with the case studies of Vienna and Rio de Janeiro.

2.2.2. Making space for pollinators in urban areas

While roads, bridges and tunnels allow us to move throughout the urban space, not every infrastructure is made of asphalt and concrete. Some networks are discontinuous and composed of a variety of green patches and islands. These tracks do no exclusively occupy the

street-level but instead conquer the 3-dimensional territory of our cities. Several names may be used to designate these hidden networks: "Pollinator Paths", "Wildlife Corridors", "Bee highways". Habitat loss and the increase of habitat fragmentation are the results of ecosystems being split into small fragments in urbanized areas (Liu, 2016). Not known by most citizens, the connectivity of green corridors network is nonetheless an important element for protecting urban biodiversity (Najihah, 2017). Cities hold a great potential in sustaining pollinators population if properly designed and managed (Ahrné, 2009; Jansson & Polasky, 2011). The city space is attractive for insect pollinators for several reasons: the plant diversity and the absence of insecticides, fungicides or fertilizers (Damon et al., 2016). Biodiversity is richer inside the city than on the borders of the urban space. It is difficult for insect pollinators to get substantial food in cultivated areas such as corn and wheat fields, where no proper type of pollen and nectar is available in large quantities ("green deserts" as called by experts and beekeepers). So, what if we start envisioning cities as green refuges, which would simultaneously rebuild the threatened pollinators population and create valuable green areas for citizens? What about making visible these flying paths drifting above our heads? The way that species other than human perceive and respond to urban landscapes may be very different from the way people perceive the same landscape. How could we shift our vision on how we use our city topography to the way pollinator species discern it? In 1960, ecologists MacArthur and Wilson developed the theory of insular biogeography.

"Islands" are considered as any area of habitat suitable for a particular ecosystem which is surrounded by unlike ecosystems, such as (in this research) human land development (MacArthur & Wilson, 1967). In 1984, Merriam presented the concept of landscape connectivity as "the degree to which absolute isolation is prevented by landscape elements which allow organisms to move among patches" (Merriam, 1984). Forman proposed the patch-corridormatrix model in 1995, that gives a representation of the landscape as a mosaic of 3 entities: patches, corridors, and matrix. Green corridors are identified as a series of connected green

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areas within an urban region, usually consisting of patches linked by corridors (Figure 11) (Forman 1995, Forman et al., 1986).



Figure 11. Schematic representation of the 3 entities: Habitat patch, Habitat corridor, and Matrix. The urban landscape structure is shaped by a heterogeneous combination of green patches and corridors in the man-made urban matrix. The patch-corridor-matrix model is generally used to categorize the spatial structure and function of an area. Diagram from *Move_Live_Thrive* by J.M. Drohan, 2019. Retrieved July 14, 2019, from: canadianurbanism.ca. Copyright 2019 by Council for Canadian Urbanism.

The city landscape is considered as a model where space is transformed into a network of habitat patches connected by green links. In graph theory, the patches are depicted by nodes and represent the natural habitats located in the city (for instance parks, cemeteries, etc.). The corridors are the linkages that enable the dispersion of urban biodiversity between the green nodes. In reality, those linkages are not continuous but a series of "stepping stones" or other patches that connect larger green areas.

In dense and compact urban areas the amount and access to green spaces is usually significantly reduced (Pauleit et al., 2005). The location of green spaces within the urban matrix is an important factor for city biodiversity because it defines the degree of habitat fragmentation for each species (Wilcove et al., 1998). Biodiversity movements are highly influenced by the connectivity of the landscape (Schippers et al., 1996). The same urban landscape may have different degrees of connectivity for different species (Kindlmann & Burel, 2008). The important

questions are "which species is the corridor for?" and "how would it be possible to optimize green planning according to the city shape?" This suggests that strategic green locations may ensure good connectivity of the "islands" and create an effective network for organisms.

Several researches have been conducted in the past decades in order to analyze (with the use of graph theory) the connectivity of green spaces in different cities. In 2014, the power of dispersal of pollinators has been analyzed based on graph theory for the city of Stockholm in Sweden (Marcus et al., 2014). The study showed that the connectivity of urban green patches is the most important parameter for the resilience of the ecosystem. The vertical dimension of habitats, such as green roofs, has been investigated in the project Enhance in Zurich (Braaker et al., 2014). The results demonstrated that, despite their height, green roofs and RA are valuable stepping stones for green networks and enable a higher permeability of the urban landscape for arthropod biodiversity. The roof size parameter does not have an effect on the community: even small green surfaces can provide a relevant space for urban biodiversity (Braaker et al., 2014). A recent study carried by the Institute for Ecosystem in Italy assesses that green rooftops, if planned with diverse plants, are valuable for any biodiversity and prevent from habitat fragmentation caused by urban expansion (Bretzel et al., 2017). In addition, a study showed the importance of the plant diversity of green patches to increase their pollinators attraction potential in Toronto (Tommasi et al., 2004). In 2014, a study aimed to identify the potential hotspots for RA for the city of Bologna in Italy (Orsini et al., 2014). The network was designed to connect the three existing biodiversity reservoirs through a network of rooftop gardens within the flight foraging distance of 500m; suitable distance for most common pollinators (Gathmann & Tscharnkte, 2002). A famous "on-site" project is "The pollinator Pathway" initiated for the city of Seattle, which aimed to create paths for pollinators by encouraging people to green their private spaces on a preselected track (Bergmann, 2012). This illustrates the great potential of collaborative initiatives between private and public entities in order to apply green corridors planning strategies. By promoting a way of designing across

"unusual" networks, the idea is to look at our city landscapes as a driver for environmental sustainability.

2.3. Cooling cities with urban vegetation

The Urban heat island effect (UHI) is described as the phenomenon when the temperature in cities is higher compared to the rural environment (Kwok Wai Wong & Siu-Kit Lau, 2013). This effect is usually created by the accumulation of several factors such as urban density, high traffic rate, extensive impervious surfaces as well as the lack of vegetation and water in urban spaces. The loss of vegetation in the city reduces the amount of cooling and intensifies the UHI effect. The phenomenon induces greater health risks related to high temperatures, especially in dense city areas (Basu & Samet, 2002; Martiello et al., 2007). The extensive use of materials such as asphalt and concrete results to the reduction of evapotranspiration and increases the heat storage capacity of the city surfaces (Grimmond, 2007; Oke, 1982). The implementation of impervious surfaces also increases floods risks. In southern and central Europe, heat waves are expected to be longer and more frequent according to the Intergovernmental Panel on Climate Change (IPCC) climate projections (Christensen et al., 2017). Defining UHI mitigation strategies is one of the major challenges for cities in the next decades.

To analyze the potential benefits of greening interventions across the city, several studies investigated the influence of the built environment and the distribution of green spaces on maximizing their potential cooling effect. In Greece, a case study assessed with ENVI-met 3.1 (a three-dimensional non-hydrostatic software for simulating surface-plant-air interactions), the impact of green space distribution on the microclimate of idealized urban grids in Thessaloniki. The results demonstrated that centrally located parks should be prefered over large green surfaces often found on the limits of the urban core; hence promoting micro-targeting as a greening strategy (Vartholomaios, 2015). Between 2012 and 2015, the EU-funded Project *Green4cities* also developed an evaluation method and planning tool called GreenPass. This

tool visualizes the potentials of urban areas for the implementation of green infrastructure with a special focus on local climate (Schnepf, 2017). In 2016, a study of the ZAMG showed the potential of heat load mitigation with the use of green and blue (ie. water surfaces) areas in Vienna. The results proved that the cooling efficiency of green surfaces depends on the surroundings (terrain, neighbouring areas...), the wind conditions and the type and the size of the patches. Accordingly, green spaces located in the city center should be favoured since their potential cooling effect is greater in densely built urban areas (Zuvela-Aloise et al., 2016). Within a certain threshold, the cooling distance of urban green space is greater with larger surfaces. Irregular green shapes influenced the cooling effect in some cases. For urban planning, within a limited urban space, relatively scattered and evenly distributed green areas are recommended (Zuvela-Aloise et al., 2016).

Covering roofs with vegetation contributes to mitigate the Urban Heat Islands (UHI) effect by providing benefits in cooling and energy-conservation at the building scale (Alexandri & Phil, 2008). To implement the most accurate and suitable greenery into the city, it is important to integrate all the potential benefits induced with the use of intensive greening such as reduction of urban heat, improved stormwater management, lower building energy demand and urban biodiversity conservation and enhancement. Figure 12 compares the different advantages between a conventional roof system and green roof.



Figure 12. The diagram shows a schematic comparison of the heat exchange and water runoff of a green roof versus a traditional roof. Green roofs can significantly reduce stormwater runoff and improve building energy efficiency by limitating the heat transfer through the roof layer. From *Estimating the environmental effects of green roofs: A case study in Kansas City, Missouri* by U.S. Environmental Protection Agency, 2018. Retrieved May 26, 2019 from: epa.gov/heat-islands/using-greenroofs-reduce-heat-islands. Copyright 2019 by U.S. EPA.

In Vienna, a recent study showed that roof vegetation can have a significant impact on the urban heat load if the measures are taken extensively over the city (Zuvela-Aloise et al., 2016). By modelling a green roof type of with an approximate depth of 0.25 m, the average cooling effect was estimated to 0.5 degrees, which is close to the values of 0.4 to 1.3 degrees obtained in similar modelling studies (Rosenzweig et al., 2006; Savio et al., 2006). The intensity of the cooling effect covers a larger surface when the amount of green roof units increases. However, a large amount of flat roofs are located in industrial areas, on the periphery of Vienna, where UHI adaptation measures are not the priority. Maximizing the cooling effect could be achieved by combining green roofs with high reflectivity materials on the neighbouring pitched roofs, especially in the city center where the amount of flat roofs is low (Zuvela-Aloise et al., 2016). In addition, other measures should be considered: trees and green facades lower surface and air

temperature through evapotranspiration and by providing shade (peak summer temperatures can be reduced by 1 to 5 °C) (Huang et al., 1990; Kurn et al., 1994).

2.4. Urban agriculture and its social benefits

Urban food production provides several social benefits on the individual and the community scale. It enhances food security by giving a better access to healthy and local food. In addition, it improves the health of the participants by providing a physical activity for seniors, enhancing mental health (with decrease of stress and improved self-confidence). Last but not least, urban gardens facilitate social cohesion and community empowerment (Specht et al., 2017). On a city scale, the presence of urban gardens can also raise awareness on the necessity to consume better and more locally. However, urban agriculture is not always well-accepted by the inhabitants since the gardens are often constructed with recycled materials and self-built raised beds.

Often considered as a "Third Space", community gardens may also support the creation of a neighbourhood identity. This identity is different according to the urban and social context and questions the conventional separation between public and private spaces, rural and urban, productive and recreational use, conservative and progressive concepts. Social justice benefits may also be generated through urban agriculture: in this case, occupying public space for agriculture becomes a political engagement. In Vienna the *Salatpiraten*, illustrated in Figure 13(a), is an example of this political approach towards urban agriculture. In RJC, implementing a community garden in a slum, where drug trafficking and poverty are omnipresent, becomes an act of resistance where population takes control over public space (Figure 13(b)).



Figure 13. Community gardens as political engagement for a more inclusive public space. (a) The example of the SalatPiraten in the city Vienna. The garden is used to increase public participation; (b) Urban gardening in the slum of Rocinha supported by the Favela Verde NGO in RJC. Participants actively shape and occupy public space. From Stadtspaziergang des Österreichischer Städtebund zu Wiener Projekten der Grätzlbelebung by Stadt Wien, 2015; Lições de sustentabilidade na Rocinha by Projetocolabora, 2019. Retrieved from: staedtebund.gv.at.; projetocolabora.com.br/mapa-das-ongs/ong-favela-verde-ensina-criancas-a-cultivarem-horta-na-rocinha. Copyrights 2015 by Stadt Wien; 2019 by F. Tribino.

Planning city agriculture is a long process and should involve the community in order to clearly understand the needs and requirements of a specific urban territory (Specht et al., 2017). The physical organization of the city connections such as roads, streets and underground subways enables people to circulate within the urban space. Planning and activating those linkages must be coordinated with social behaviors. In fact, the architect and design theorist Alexander wrote "for the human mind, the tree is the easiest vehicle for complex thoughts. But the city is not, cannot and must not be a tree. The city is a receptacle for life" (Alexander, 1965). The idea is to promote the physical connections of the city in accordance with what "life" would need and not what the built environment organization would dictate. In 1976, Yona Friedman presented autoparticipation as a form of planning (Friedman, 1976). For this purpose, he proposed a series of manuals for participative planning. The buildings are designed from the hand of the future users and should be flexible to their wishes as hybrid spaces. The manual also teaches with simple and intuitive drawings on how to grow plants. These manuals have been widely shared around the world. In this case, the text does not matter, since images are considered as a universal language. Through his work, he showed that no one knows better how to plan a space than its own users and inhabitants. Based on these observations, Chapter 3.4.4. "Mapping the for community gardening in Vienna" describes the results of a workshop, conceived for collecting qualitative data about the key requirements for implementing community gardening initiatives in the context of Vienna.

Chapter 3. Suitability for rooftop agriculture

3.1. Policies for rooftop greenery and agriculture

The Food and Agriculture Organisation (FAO) of the United Nations, defines Urban Agriculture as "the growing of plants and the raising of animals for food or other uses within an urban setting" (FAO, 2019). Urban Agriculture have different size, shape, typology and purpose. The projects present a large range of typologies such as small-scale private gardens, allotment gardens, collective neighborhood gardens, rooftop gardens, urban farms, indoor farms or hydroponic greenhouses. Rooftop gardens provide new green spaces and a large range of benefits: enhancing biodiversity in the city, food education and security, mitigation of the urban heat islands and improvement of the quality of life, especially for the most vulnerable groups such as children and seniors.

In dense urban centers, land speculation and urban pressure leave limited room for further green infrastructure development. Several cities consider flat roof surfaces as an attractive alternative, therefore enabling efficient use of space in increasingly urbanized areas. Exploiting structures such as roofs and building facades is an opportunity for consolidating the green infrastructure in dense city centers.

Adequate financial and incentive policies are essential for convincing building owners to install intensive greening or agricultural systems on their roof. The growing trend of "Greening cities" and "Urban gardening" helped the recent development of policies and planning regulations by municipalities, promoting the creation of green roofs and rooftop gardens. Besides these legal frameworks, important actors are the financiers of the building projects. The implementation of rooftop greening or agriculture highly depends on their motivation to create and manage more sustainable constructions.

Rooftop agriculture and planning legislations

Rooftop greening with an agricultural purpose is not commonly explicitly demanded by planning legislations. On the contrary, restrictions for building heights and accessibility make the process for implementing greenhouses or rooftop gardens challenging. However, it is possible to promote RA through other municipal planning objectives relating to green structure planning, climate planning, planning for ecosystem services, leisure or social cohesion (Delshammar et al., 2017). Quality assessment schemes such as BREEAM, LEED, CASBEE and Green Star are also some references and tools which may support rooftop farming initiatives.

• International examples for the promotion of rooftop greenery

The city of Toronto is a pioneer in the governance of green roofs construction. The Green Roof Bylaw, voted in 2009, sets out a green roof requirement for new development that are larger than 2'000 m² gross floor area (Green Roof Bylaw, 2009). France adopted in 2015 the amendment, which plans the installation of green roofs on every new building in commercial areas (Assemblee Nationale, 2015). Germany is the european country with the highest rate of conversion from traditional roofs to intensive greening systems and in Munich every roof with a surface area larger than 100m² has to be landscaped (Ansel & Appl, 2015). In Germany, there is also a stormwater fee charging building owners for pollution in stormwater drainage from impervious surface runoff (Keeley, 2007). The tax is reduced if the owners choose to implement greenery systems on their property. Mostly focused on large roofs units with an industrial or commercial use, these international examples show the growing interest in developing roof greening policies.

Incentive policies for the cities of Vienna and Rio de Janeiro

In Vienna, the *Magistrat 42 - Stadtgärten* supports the implementation of green roofs between 8 and 25 euros per square meters, if the characteristics of the intervention comply with the

ÖNORM L-1131 (Wien Stadt Administration 2, 2019). However, there is still a large room for the development of further policies.

In RJC, heavy rain with floods and mudslides is a recurrent challenge for the municipality. Therefore, rainwater harvesting is an important leverage point for promoting green roofs policies (Prefeitura Rio, 2018). Interviews with experts from the municipality showed that incentive policies and programs should be preferred in the context of RJC. Most citizens are not yet fully sensitive to environmental concerns and the use of green roofs. The strategy of the municipality is to encourage rather than obligate greening interventions. Two examples illustrate this approach:

- 1) In RJC, citizens need to verify the right to use the last floor of the building according to a fixed maximum height. This information can be found on the legal document defining the zoning of the city, which is described in Decree 322/1976 (Leis Municipais, 2019). If the last floor of the building is situated above the maximum height authorized by the local regulation, people must pay a tax to use this space. However, the municipality of RJC offers to discount this tax if the use of the roof involves intensive greening or photovoltaic panels (Prefeitura Rio, 2018).
- The Qualiverde is an incentive program, which promotes sustainability actions including the implementation of green roofs for new and existing constructions (Qualiverde, 2012). The certification is optional and grants tax benefits to the qualified projects.

3.2. Types of rooftop agriculture considered in the present research

There are different options for implementing agriculture on roofs. Several names are given to rooftop agriculture systems such as rooftop farming, rooftop agriculture, rooftop gardening, productive rooftops, etc. There is a clear difference between a rooftop farm and a rooftop garden:

- **Rooftop farming** usually refers to practicing agriculture for profit and as a source of income. Farms are usually bigger than gardens.
- Rooftop gardening commonly refers to small-scale gardens, which can be productive or non-productive.

In the present study, the terms "rooftop agriculture" and "rooftop gardens" refer to both techniques "farming", and "gardening". To evaluate the potential for RA in Vienna and RJC, the study includes all roofs and terraces with a pitch angle comprised between 0 and 5 degrees and a minimum surface area of 5 m^2 .

The study considers two types of urban food production:

1) Open air and soil-based system (for all flat roofs larger than 5 m²): this design indicates that the rooftop gardens possess a soil structure with a minimum thickness of 30 centimeters and produce vegetables or fruits. It can also combine soil-based vegetable beds with intensive green roof systems with an agricultural purpose. This system presents a potential for enhancing the green corridors network connectivity, growing food and extending the urban green cover. The potential of implementing open air and soil-based systems in Vienna will be investigated and modeled in Chapter 5 for the definition of the three PMs "Green Desert", "Minimum Spanning Tree" and "Food production". This typology corresponds to the design of the Brooklyn Grange in New York City (the world largest rooftop soil farm), the *Sargfabrik* in Vienna or the *Operation Grüner Daumen* in Vienna (Figures 14 and 15).



Figure 14. Photograph of the *Brooklyn Grange* rooftop farm. Retrieved from brooklyngrangefarm.com. Copyright 2019 by Brooklyn Grange.



Figure 15. Photographs of the roof garden of the *Sargfabrik* and the self-built containers of the *Gartenwerkstadt* in Vienna. Retrieved from: sargfabrik.at; *Exploring the possibilities for urban rooftop farming in Vienna* by B. Laa, 2017. Copyrights 2019 by Z. Weiner; 2019 by B. Laa.

2) Rooftop hydroponic greenhouse: in the present study, this typology is considered relevant exclusively for flat roofs larger than 1'000 m². This design corresponds to commercial farms located on roofs and using hydroponic growing systems. The production units are placed inside a greenhouse which protects the plants from extreme weather conditions. Hydroponic systems have higher yield than soil-based systems, are light and may be stacked, thus optimizing the use of space (Mandel, 2013). Gotham Greens, situated on the roof of a shopping center in Brooklyn is an example of this design typology (Figure 16).



Figure 16. Outer and inner view of the *Gotham Greens* farms, which are located on the top of Whole Foods Store in Brooklyn, New York City. The hydroponic farms produce leafy green vegetables without the use of pesticides and year-round. Retrieved from gothamgreens.com. Copyright 2019 by Wholes Foods Market IP. L.P.

Regarding the calculation of the growing capacity for the case study of Vienna, the crop yields of existing rooftop gardens projects have been collected and compared. The yields of the two different categories have been evaluated to 5 kg/m² per year for systems 1 "Open air and soilbased" and 29 kg/m² per year for system 2 "Rooftop hydroponic greenhouse" (Laa, 2017). These values were reused in Chapter 5. Parametric Modelling for the evaluation of the growing capacity of the parametric model "Food production".

3.3. Additional weight caused by rooftop agriculture

Based on the typology of the rooftop garden or farm, different payload values can be considered. For soil-based rooftop farms with a minimum soil depth of 20 cm, the distributed load caused by the soil is at least 1.9 kN/m² (Krapfenbauer, 2011). Increasing the depth to 40 cm may lead to a distributed load of 5.6 kN/m² (Laa, 2017). Concerning hydroponic systems, Urban farmers 2 has constructed a hydroponic system with a distributed load of 2.0 kN/m² (Urban Farmer 2, 2017). However, the load of aquaculture systems may raise up to 9.0 kN/m² or to 15.0 kN/m². Additional loads should be considered such as the construction materials of the raised beds, the storage room or the corridors. Rooftop gardens should be strategically planned

according to the existing structure of the roof, in order to place the raised beds over the underlying supporting structure. Accordingly, it is considered that the additional load (or dead load / payload) of a rooftop garden (or farm) lays approximately between 3.0kN/m² and 15kN/m². Other loads should be included such as the wind actions, the snow loads and the crop actions.

In the context of Vienna, it is necessary to obtain a building permit for the implementation of RA (in the shape of a garden or a hydroponic greenhouse). For each project, a certified structural engineer must conduct an analysis of the load bearing capacity of the roof based on the local building regulation. The goal is to evaluate the existing and additional bearing loads which will be caused by the rooftop farm.

3.4. The context of the city Vienna

3.4.1. The green capital of Vienna

The population of the city of Vienna was 1'888'776 inhabitants in 2018 (Statistik Austria, 2018). Vienna possesses numerous green areas, urban and non-urban. With 41'487 hectares the city has 45.5% of its whole surface dedicated to green areas (STEP 2025, 2014). The city is surrounded by a green belt formed by the Viennese Woods, the *Lainz Game Preserve*, the *Donau-Auen National Park* and other green surfaces. Across the city flows the Danube that occupies 1'913 hectares, thus 4.6% of the total surface area of Vienna. The "Green Lung" of the city is shaped by the Green Belt, the *Prater*, and the Danube island. The metropolis also has a National Park called *Lobau* and the *Wienerwald* Biosphere Park. Green areas play a key role in providing some ecosystem services. The municipality wishes to preserve this high capital of green spaces since it contributes substantially to the ecological fabric of the city.

A third of the vegetables consumed in Vienna is produced by the city. Around 6'000 ha of the city area is dedicated to agriculture (16% of the city area), including 870 hectares exclusively for vegetable production. This represents 60'000 tons of fresh vegetables produced each year

(Vienna City Administration 10, 2019). As illustrated in Figure 17, the category *Land* (which corresponds to the agricultural surfaces) is mainly located in the 22nd district (with 1'120 ha), in the 10th district (with 892 ha) and in the 11th district (with 301 ha, predominantly used for vegetable production).



Figure 17. Spatial distribution of the green blue areas in the city of Vienna. The map was created by the author of the present thesis based on the GIS data of the Stadt Wien.

The farming area in the 19th district is primarily used for the production of wine (Landwirtschaftsbericht, 2015).

Existing roof greenery has been evaluated by the municipality in a study published in 2010 (Magistrat 22, 2010). The report estimated that around 5'242 hectares of roof areas are already greened. This represents 5% of the roofscape of the city of Vienna in 2010. However, these results are only indicative since some of the roofs were identified as "greened" by the model because they were covered by tree canopies.

3.4.2. The vision of the STEP 2025

For the ninth consecutive year, the city of Vienna is ranked as the most liveable city in the world by the consulting firm Mercer (Mercer, 2018). In 2018, the city has also been ranked for the first time at the top of the Economist Intelligence Unit's Global liveability Index followed by Melbourne and Osaka (EIU, 2018). The Mercer report highlights the high public security, well-designed transportation system and the diversity of cultural and recreation facilities existing in Vienna (Mercer, 2018). According to the EIU, Vienna's top position is justified by its very low crime rate, great healthcare system, education and infrastructures (EIU, 2018). Vienna is also the most rapidly growing metropolis of the German-speaking region.

To cope with future urban challenges and remain attractive, the city needs to focus on long-term plans and prepare strategic planning decisions. The Urban Development Plan 2025, *Stadtentwicklungsplan* (STEP), identifies and analyzes the major challenges and opportunities for the city of Vienna by the year 2025. The instrument is a support for planners and gives a vision of the key missions. Published in January 2014, the plan pinpoints three elements for the sustainable development of Vienna (STEP 2025, 2014):

- 1) Housing
- 2) Free and green spaces
- 3) Mobility

According to the forecasts of Statistics Austria, more than 2 million citizens will live in the Austrian capital by 2030 (Statistik Austria, 2018). It is important to identify the age groups impacted by this growth: in 2050, the amount of 75 years old residents will increase by 50'000 and the proportion of children and teenagers will increase by approximately 30'000 as compared to 2014 (STEP, 2014). This type of population growth would constitute a great opportunity for the development of green spaces with an agricultural purpose since productive gardens are often attractive to children and seniors. Urban gardens could be implemented in schools and contribute to food education for the young generations. These areas are also important for seniors since gardening activities provide them substantial health benefits.

Chapter 4.2 "Open spaces: Green & Urban" of the STEP Plan focuses on urban greening. More than 50% of the city surface area is occupied by green and leisure areas (Magistrat 22, 2010).

The two main strategies consist in 1) "strengthening and further developing networks of green and open spaces"; 2) "High open space quality in all parts of the city" (STEP 25, 2014). The report stresses the importance of enhancing the quality of public spaces, preserving and expanding the existing green areas, and considering open spaces as a key element to withstand the effects of climate change. Multiple measures are associated with the mitigation of climate change in Vienna; including small scale designs such as green roofscapes and facades. Special attention is given to green roofs; but these are only considered for their cooling effect against excessive heat in the summer, not for the extension of green corridors network nor their food production capacity and recreational function. In highly urbanized districts (such as *Neubau, Innere Stadt* or *Alsergrund*), the use of roofs and facades could substantially extend the existing green areas. Unfortunately, the report does not clearly specify actions or plans for the promotion of these greening techniques.

The map "Mission statement for green spaces" provides a visualization of the overall greening strategy of the STEP 2025. Figure 18 depicts the planned measures for strengthening the existing green corridors network.



Figure 18. Mission Statement for green spaces published in the STEP25 by the Municipal department of urban planning of the city of Vienna. From *Stadtentwicklungsplan 2025* by Vienna City Administration, 2014: AV + Astoria Druckzentrum GmbH. Retrieved from: wien.gv.at/stadtentwicklung/studien/pdf/b008379b.pdf. Copyrights 2014 by Magistratsabteilung 18 – Stadtentwicklung und Stadtplanung Wien.

The categories of measures called "Open space networking (characteristics of landscape)",

"Open space networking (urban)" and "Networking with the environs" give an overview of the

greening strategy of the city of Vienna in the perspective of enhancing the connectivity of the network. The map shows that the municipality considers exclusively ground-level surfaces for the extension of the urban green corridors and does not clearly integrate the potential of the flat roof landscape. In addition, the planned extensions are only located next to the main road and street axes. Although the STEP 2025 did mention in several chapters the importance of using intensive green roof systems as a measure for greening the city, roofs are not considered in the Mission Statement.

1'078.7 hectares are suitable for intensive rooftop greening in Vienna (Vali, 2011). RA could be one answer for several objectives set by the STEP 2025 including: Social cohesion, Rainwater harvesting and the Reinforcement of the green infrastructure. The STEP 2025 map will be used as a basis to design the green corridors network in Chapter 5. Parametric Modelling. The results of the modelling phase should be considered as an additional planning support for greening the city of Vienna.

3.4.3. Building and roof structure

Regarding the structural analysis of the roofs, there is no detailed database describing the structure of each roof in Vienna. Two methods were considered for deducing the capability of roofs to support a garden and based on GIS-data:

- Option 1 "Building standards comparison": Comparing the date of construction of the building with the building standards valid at the time of construction. The values of the minimum pay loads can be used as a reference for evaluating the load bearing capacity;
- Option 2 "Roof surface materials": Identifying the materials covering the roofs using high resolution imagery. For instance, a typical thickness of 8 cm gravel layer results usually in a load of 1.44kN/m². This type of cover suggests that the roof is flat and

structurally more suitable for the implementation of a rooftop garden than other types such as clay-tiled roofs or rubber membrane roofs.

Option 1 was investigated for the present study. A master thesis was conducted for this purpose by the master student in civil engineering Barbara Laa to analyze the evolution of the Building standards in Austria (Laa, 2017). The results should be considered as a rough estimation of the structural capabilities of the existing building stock.

In Vienna, the ONR 24009 regulates the evaluation of the load bearing capacity of existing building constructions. Both existing and additional loads caused by the rooftop garden should be considered during the structural analysis. The ONORM EN 1991-1-1 (Eurocode 1) and the ONORM B 1991-1-1 are the two reference documents for the evaluation of the pay loads. The objective of the investigation was to compare the current building standard of imposed loads (ONORM EN 1991-1-1 (Eurocode 1) and the ONORM B 1991-1-1 (Eurocode 1) and the ONORM B 1991-1-1) with old standards that were valid at the time of the construction of the buildings. The study focused on pay loads since they affect both the supporting structure of the building and the foundations (Laa, 2017). The buildings with the lowest structural capacities at a specific construction date and with a specific building category were identified and classified in Table 1:

Categories of buildings	Time frame of the building construction
	with the lowest structural conditions
A: Residential	No significant differences between the
	construction standards over the years
B: Offices	1955-1981
C: Restaurants, Cafes, Schools	From 2003
C: Churches, Theaters, Cinema	Before 1955 and from 1997
C: Museums	Before 1955 and from 2003
C: Public buildings, Schools, Hotels, Hospitals	Before 1955
C: Dance hall gym	Before 1955
C: Concert halls, Sport hall	Before 1955
D: Shopping areas	From 1997
E: Industrial building	Before 1955
F: Parkings	From 1988

Table 1. Crossed conditions for detecting the lowest load bearing conditions of buildings in Vienna (adapted from the results of Laa, 2017)

The results of this comparison highlighted that the highest potential lays for industrial buildings: these constructions are imposed with lower pay loads than the ones they were initially designed for. Buildings where people might congregate like schools, restaurants, cafes, theaters, museums or exhibition halls should also be favoured (Laa, 2017).

The filtering process is achieved with QGIS based on the GIS-data "*Bauperioden_detail (WFS)*", which was provided by the municipality. The dates of construction of the data are very precise for the years before 1976. Unfortunately, the buildings built after 1976 are categorized into large time frames such as "*After 1976*" without giving further details. The dates of the data were not compatible with the results of Table 1. Therefore, it was not possible to build precise queries which would support the classification of the buildings built after 1976 and to deduce the different categories of buildings according to their structural conditions. However, this part of the research study could be used in the future if the municipality provides more detailed information on the building construction date after 1976. If provided, it would be easy to integrate this condition into the grasshopper model by using a boolean condition (True/False) which would include or exclude the buildings with a low structural potential.

3.4.4. Mapping the opportunities for community gardening in Vienna: "How to grow together" workshop at the *Kunsthalle Wien*

As defined in Chapter 2.4, urban agriculture, if well-managed and integrated into the city, could be an important driver for community building and social engagement. However, defining the best locations for urban gardening highly depends on the community and the urban context. It is highly important to bring citizens in the center of the investigation in order to map appropriately the space opportunities for urban agriculture. With the intention of getting a better understanding of these key locations, a collaborative mapping workshop was organized in the frame of the research study and parallel to the exhibition "How to live together" at the *Kunsthalle Vienna* in *Museumsquartier*.

• Description of the collective mapping session

The collective mapping, called "How to grow together" was launched with a one day workshop and conducted over 3 months. The workshop was followed by an excursion through two different community gardens in Vienna: the *Salat Piraten* and *Paul's Garten* gardens, both located in the 7th District *Neubau* (Figure 19).



Figure 19. Collective Mapping "How to grow together" at the *Kunsthalle Wien*. From the exhibition *How to live together* by the Kunsthalle Wien, Museumsquartier 2017. Retrieved from: http://kunsthallewien.at/#/en/events/how-grow-together. Copyright 2017 by Kunsthalle Wien GmbH.

The research goal was to collect qualitative data about the key spaces for community gardening

in Vienna and the important conditions for the successful implementation of these interventions.

The mapping aimed to answer the following question: where would community gardens have

the most significant & positive influence on our existing urban environment?

Using public space perception as a metric, the project intended to follow the emotions of the participants with the purpose to look at urban situations with a new perspective. During the session, the visitors collectively created a mapping of Vienna which displays the spatial opportunities for urban gardening based on their knowledge of the city.

The zones investigated were the public spaces, on the ground level, thus not including the rooftop areas. Nonetheless, it was considered that mapping the key locations in the open public areas would be a valuable indicator of rooftop gardening opportunities and could orientate the study to some specific areas with a high potential.

Inspired by the theory of urban acupuncture, the pinning process referred to the metaphor of practicing acupuncture on the body of the city. By finding the "nodes" or "blockage points" where a stimulation would be necessary, the idea was to create a network of community gardens within the existing urban space. The workshop gave the opportunity for the participants to perform themselves urban acupuncture.

The first part of the mapping focused on investigating public space and highlighting the vulnerable sectors of Vienna that could be regenerated through urban agriculture interventions. The process of defining these vulnerable sectors relates to personal memory as well as emotions. To help the participants to find the vulnerable parts of the city, they could associate their choice of these urban spaces with the following adjectives "Unappealing", "Hectic", "Unstimulating", "Unsafe" and "Others" by selecting the corresponding colored pin.

Two possibilities could have been asked in that perspective:

Option (1): How does the person feel in this space?;

Option (2): How does the person feel about this space?.

Option (2) was chosen since feelings in a space may be caused or not by the space. While being asked about the relation of the person towards a space, the answer is usually clearer. By connecting personal memory with the public space attributes, the objective was to map the intangible characteristics of the built environment (Figure 20).



Figure 20. The urban acupuncture mapping process during the collective mapping workshop. The participants could insert their preferred locations for community gardening on the map of the city of Vienna. Photographs were taken by the author of the present thesis.

After defining the vulnerable sectors of the city, the participants were asked to pin with a yellow flag where they believed the location would be suitable for community gardening. Qualitative feedback and observations were collected at the end of the workshop session.

Results of the collective mapping

The number of participants for the introductory workshop was approximately 20 persons, 60% women, 40% men with an age average of 28 years old. The workshop took place in the museum of the *Kunsthalle Wien* and the background of the audience was not very diverse since most of the participants were working or studying in the field of art, architecture or city planning. At the end of the workshop, the map was hanged for 3 more months in the museum so that more visitors could participate to the collective mapping. Therefore, it was not possible to have precise statistics of the amount and profile of all the participants of the experience. The results of the mapping of the vulnerable areas in the city of Vienna are displayed in **Appendix 2.** "**Results of the collective mapping "How to grow together": the vulnerable areas of the workshop results**" shows the workshop results as a heatmap of the vulnerable areas of the city of Vienna.

Few clusters of pins were identified and prioritized:

- 1) the surroundings of the subway station *Praterstern*,
- 2) the public square Schwedenplatz,
- 3) the surroundings of the subway station Stephansplatz,
- 4) the surroundings of the station *Matzleindorferplatz*,
- 5) the public square in front of the church Votivkirche,
- 6) the public square Schubertpark,
- 7) several parts of the street *Mariahilferstrasse*, especially in proximity to the train station *Westbahnhof*.

These 7 zones should be highly considered for the transformation of the public space since these were identified as either hectic, unappealing, unstimulating or unsafe. The implementation of a community garden could be one of the solutions to improve and stimulate these zones. The suitability of such an intervention should be further analyzed and investigated.

At the end of this selection phase, the participants were asked to pin a few locations where they would imagine a community garden to be the most suitable. While pinning the map, participants had to keep in mind that community gardens have the potential for strengthening neighbourhood community, promoting healthier food and nutrition habits, etc. The results are mapped in **Appendix 4. "Preferred locations for community gardening according to the workshop results".** The selection of the locations for the mapping of the vulnerabilities in the built environment did not correspond to the results of the preferred location for the implementation of community gardens. The preferred sites were mainly located in the western zone of the city. Among all the pins inserted into the map, the selection of the location was often oriented to green areas such as *Rathauspark, Resselpark, Richardwaldemarpark, Stadtwildnis Gaudenzdorfer Guertel* or *Prater*. Imagining the "upgrading" of a park with a community garden appeared for a lot of participants the easiest and most logical transformation process. Preferred locations were also situated directly inside the **courtyard of the University**

of Vienna and in some areas close to the *Guertel* or in proximity to the U4 train line (5th district).

• Further results and observations

Qualitative information was also collected during the workshop, giving further insights into the mapping results. Participants could write remarks on a separate sheet of paper (reasons why a specific location would be suitable for urban agriculture). Among the collected answers, the participants highlighted **the lack of active engagement in most public places** in Vienna. **Public spaces were often qualified as underused, "dead spots", "too grey" or with too little opportunities of engagements of citizens**. The park of *Prater* and *Turkenschanzpark* were considered as a high potential for urban agriculture. The idea of community gardens seemed seducing for most participants: urban agriculture is a transformation which stimulates and upgrades a space without fully changing its original nature. Therefore an important goal for the participants was to **keep the original essence of public spaces while improving the qualities and functions of the environment with the use of community gardening.**

The results of the workshop supported the definition of the focus area for the case study conducted in Chapter 5. Parametric Modelling. The final focus area was drawn in a way that it included approximately 30 locations pinned as "Preferred locations for community gardening gardening" out of the 50 pins. This study area is further described in Chapter 5.3. Case Study area in Vienna.

- 3.5. The context of the city of Rio de Janeiro
- 3.5.1. The green spaces of Rio de Janeiro City

With 1'200 km² and 6.4 million inhabitants, RJC is a complex and dynamic urban system in constant expansion (IBGE, 2013). The climate of RJC is classified as rainy tropical climate with a higher rainfall period between November and March (Da Silva Neiva et al., 2017). The

metropolis has a chronic problem with floods as a result of the lack of sustainable planning in urban areas of low permeability.

The north-east of the metropolis is the densest urban area with very few green spaces and public squares (Lucena et al., 2013). Throughout the city, several environments can be spotted: large tropical forests contrasting with heavily impervious and gray streets where most of the population lives. After centuries of urbanization and industrialization the green urban landscape of RJC need to be regenerated. In 2016, the RJC presented 28.85% of the surface area with vegetation, which is a significant decrease compared to the year 1986 when the city possessed a proportion of 32.57% of green areas. This significant loss of vegetation can be explained by the high urban population growth occurring between 1991 to 2000 (+11% in less than a decade) combined with increased urbanization (Brito, 2006).

The forests and other green areas, providers of ecosystem services, are fragmented and surrounded by dense urban occupation (Herzog, 2017). The loss of vegetation in the city reduces the amount of cooling and increases the UHI effect. In 2015, a study conducted for the Metropolitan area of Rio de Janeiro estimated the UHI zones (Lucena et al., 2015). By considering the average land-surface temperature as an indicator of the UHI of the region, several areas were highlighted (Figure 21):



Figure 21. Metropolitan area of Rio de Janeiro. (a) Land use in 2007; (b) Average land-surface temperature in the 2000s. The two captions illustrate the relationship between urban areas and the average land-surface temperature measured in the 2000s. From *Estimation of the urban heat island in the Metropolitan Area of Rio de Janeiro – Brazil, by* A.J. Lucena L. Peres, O. Rotunno Filho & J.R. Franca, 2015: Joint Urban Remote Sensing Event, JURSE 2015. Copyrights 2015 by JURSE 2015.

Heat islands were observed in the highly urbanized areas (often located away from the seaside) such as the West and the North Zones of the city, where the poorest population lives. More specifically, the critical zones are on the western side of the *Guanabara Bay* and surrounded by the *Tijuca Mountain*, the *Pedra Branca Mountain* and the *Mendanha Mountain*. These zones overlap greatly with the zones of urban use depicted in Figure 21(a).

The municipality did not integrate landscape ecological processes and flows into its development, and hence threatening city biodiversity conservation and protection (Herzog, 2017). Corredores Verde published in 2012, describes the planning strategies for reinforcing the existing green corridors network (Prefeitura, 2012). One important finding of the report is that the vegetation cover is highly fragmented and not evenly distributed throughout the city. Considering the 80 districts that possess less than 1% of vegetation cover, 63% are located in Zona Norte. Only 9 districts have more than 50% vegetation cover and are exclusively located in Zona Sul and Zona Oest. The urbanization process of RJC severely fragmented the existing forests, which were transformed into green "islands" surrounded by dense urban occupation. In 2012, the Mosaica Carioca, which was created by the Secretaria Municipal de Meio Ambiente (SMAC) of the Prefeitura Rio, produced a green corridors plan named "GT Corredores Verde Resolução SMAC nº183", which proposes to connect the Tijuca, Pedra Branca and Gerocino massifs (SMAC, 2012). The objective of the mapping was to reconnected fragmented forested patches and to protect the existing urban nature capital (Herzog, 2017). Based on the GIS data of the Atlantic Rainforest ecosystems fragments "SIG-floresta", the map displays the eleven priority zones for the extension of the green corridors (SIG-floresta, 2019) (Figure 22).



Figure 22. The map displays the eleven crucial areas for the implementation of green corridors. The objective of the project is to enhance the connectivity of the Tijuca, Pedra Branca and Gerocino massifs with the existing urban green infrastructure. From *GT Corredores Verde - Relatório do Grupo de Trabalho (Resolução SMAC P nº183 de 07.11.2011)*. by SMAC, 2011. Retrieved from: rio.rj.gov.br/dlstatic/10112/4595787/4116261/corredores_verdes. Copyrights 2011 by Secretaria Municipal de Meio Ambiente RJC.

The proposal does not mention the use of roofs for reinforcing the existing green corridors network. It focuses exclusively on punctual or large greening interventions on the ground-level which could reconnect the isolated green patches.

In Chapter 5.7."Optimization of the model on the roofscape of the region of Bangu and Proof of Concept", the modelling test focuses on the district of Bangu (RJC), which is located within the densely built-up area circled in red on Figure 21(b). This approach gives the basics of a reflection on how green roofs can be linked to the green corridors network and can enlarge the existing urban biological system of the district of Bangu.

3.5.2. The challenge of food security in Rio de Janeiro City

Food security is defined as: "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO, 1996). In the context of Brazil, food security is an ongoing challenge. The current economic crisis and the unevenly distributed income increased the gap between the richest and poorest classes in the last years. As a result, of insufficient incomes, almost a third of the Brazilian population does not have adequate resources for acquiring appropriate quantity and quality of food (Meade et al., 2004). By 2050, it is estimated that 68% of the world population will live in urban areas. In Brazil, up to 92% of the population is expected to settle in cities by the same year (UN, 2014).

In RJC, purchasing food is difficult and expensive for most residents of the poorest communities, also called *comunidades* or *favelas*. Almost a quarter of the population lives in slums in RJC, where large supermarkets are rare. Buying fresh food can be challenging: few small shops exist but sell mainly pre-packed food, cakes, candy and alcohol (Roggema, 2017). Other challenges include a poor water system, crime, violence and a limited amount of space for the residents.

It is also very difficult to use the ground-level to grow vegetables since the slums were built on steep slopes and often rocky or unfertile soil. However, the block typology of the constructions allow the use and access of the last floor of the building. The present study intends to look at the potential for implementing RA in these areas where the food insecurity challenge is the biggest.

Chapter 4. GIS Analysis of the rooftop agriculture potential in Vienna and Rio de Janeiro City

4.1. Preliminary observations

4.1.1. Lidar scanning

Geographic Information System (GIS) data and application tools have been widely used to study the green roof potential of cities (Luo, 2011). Several countries such as Spain, Denmark, Finland or the United Kingdom allow open access to their airborne laser scanning data, but the potential of this high quality data is still not yet fully exploited by architects. Provided as point clouds, this high resolution data is a great opportunity for researchers and public institutions to evaluate and propose efficient and pinpoints greening strategies.

For both RJC and Vienna, the collection of spatial data for the RA potential map was performed through Light Detection and Ranging (LIDAR) technology. LIDAR is a laser-based remote sensing technology which calculates the distance to a target by illuminating it using laser light (Lohani & Suddhasheel, 2017). The surveying method is generally used to create high-resolution maps with applications in geography, geodesy, archeology, forestry or seismology (Cracknell & Hayes, 2007). LIDAR technique is a suitable method to analyze the geometry of roofs since it can recognize very narrow and poorly visible objects. Since roof sizes can be very small (less than 5 m²), LIDAR is considered as an accurate method for identifying the roof boundaries. The output of the LIDAR laser scanning is a 3D point cloud with a point density depending on the sensor characteristics and the flight parameters. The technology may also be utilized and integrated into autonomous cars. The collection of the LIDAR data is performed through an aircraft, a vehicle or a helicopter, a laser scanning system, a Global Positioning System (GPS) and an INS Inertial Navigation System (INS) (Figure 23).

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Figure 23. Illustration of Airborne LiDAR Scanning. From *Integration of LiDAR and IFSAR for mapping* by I.J. Dowman, 2004: OAI. Copyright 2004 by I.J. Dowman.

The collection of the LIDAR 3D point cloud is rather expensive, therefore not every city has the budget to acquire this high-resolution data. Another technology called Photogrammetry is used to create 3D models of urban spaces based on photographs. This method offers the possibility to generate visually attractive models of buildings. Nonetheless, this technique is more suitable for visual assessment of constructions than accurate slope calculations.

The evaluation of the potential for RA would be ideally conducted through the combination of the two techniques: (1) Identification of the roof boundaries and slope based on LIDAR data and (2) Roof material recognition with Photogrammetry (ie. it would give assumptions on the capacities of the roof structure). In the present study, the research is conducted exclusively based on LIDAR scanning techniques. The objective is to evaluate the size, the geometry and the slope of the roofs in order to quantify the RA potential.

As described in Chapter 3.4.3. "Building and roof structure" the structural conditions of the roofs could be deduced if more accurate data regarding the construction date is provided by the municipality. In any case, this parameter would require an on-site investigation.

4.1.2. Limitations
Overlapping of trees and other objects

Due to the total or partial overlapping of trees over some buildings, some roof objects present a smaller flat roof area than in reality. The flat roof portions covered by the trees are not considered as flat (Figure 24). This imprecision could be manually identified and corrected.



Figure 24. Flat roof surfaces covered by vegetation or other objects are not considered as flat by the present study. Graphic adapted from *Gruenraumanalyse Dachbegruenung* by Magistrat Wien 22 Umwelt, 2010. Retrieved from: www.wien.gv.at/umweltschutz/raum/pdf/gruenraumanalyse-dachbegruenung.pdf. Copyrights 2010 by Magistrat Wien 22.

Structural conditions

The mapping of the RA potential does not include the structural conditions of the roofs. It exclusively considers the geometrical characteristics of the surface : size, boundaries, and if the roof pitch angle is inferior or superior to 5 degrees. Nonetheless, in Chapter 3 "Suitability for rooftop agriculture", the study gave indications on the structural conditions of the rooftops in Vienna based on their construction date and the austrian construction standards.

Year of the data

The GIS datasets used in the frame of the study present different years of production.

For the city of Vienna: the Roof greening potential cadastre is dated from 2008 and the Land Use map correspond to a dataset from 2009. Minor changes were observed in some parts of the city during this time frame (ie. new constructions, renovations, building use).

For the RJC: the two selected datasets are dated from 2013 and 2014. The study assumes that the urban and green structures did not significantly changed between these two years.

Shading on the roofs and solar radiation

Shading and solar radiation are two elements which were not included in the study. However, for both Vienna and RJC, a Solar potential map is available. These aspects should be taken into consideration for further research in order to get more accurate results regarding the suitability for growing edible plants on the roof surfaces.

A preliminary GIS Analysis was conducted to test the polygons overlaps between the dataset "Roof greening potential cadastre" and "Solar potential" for every roof larger than 1'000 m² in Vienna. The combination showed that the total area of the filter combination (Roof greening and Solar potential combined) presented a difference of only 0.59% in comparison to the total Roof greening potential areas (Laa, 2017). Since this difference is very small, this aspect was not considered.

Roof peaks and other non-suitable elements for greenery

Although the dataset was filtered and "cleaned" using QGIS and ArcGIS (as described in Chapter 4.3.4. "Slope calculation and mapping with GIS applications" for the dataset of RJC), a few roof peaks, chimneys and other non-suitable constructive elements may remain. These errors should be manually corrected.

4.2. The potential for rooftop agriculture in Vienna

4.2.1. Collection of the data

The *Magistrat Wien 22 Umwelt* provided the two following GIS datasets, basis of the research study:

1. The roof greening potential cadastre - "Dachbegrünungspotentialskataster" dated from 2008. The GIS data includes information about the roofs and the building footprints. This map identifies every flat roof area that is less than 5 degrees inclined, larger than 5 square meters, and with a quotient of Area / Perimeter > 0.3 (Vali, 2011). The building footprints map "Gebauede_f" was combined with the cadastre and gave further indications regarding the shape, the address and the height of the building. Note: since 06.04.18, a 3D-model of the roof landscape of Vienna is available on the

digital platform "*digitales.wien.gv.at*".

 The Land Use map - "Realnutzungskartierung" dated from 2009. The map shows the spatial distribution of 3 different uses in Vienna: Building land use, Transportation use and Green areas. Each category is subdivided into classes such as for instance Forests, Parkings, Train stations, Parks, etc.

4.2.2. Analysis of the roof greening potential cadastre

The roofs were classified into two types:

- Category 1: **the roofs suitable for intensive greening** and extensive greening (the roofs have an inclinaison comprised between 0 and 5 degrees);

- Category 2: **the roofs suitable for extensive greening** (the roofs have an inclinaison comprised between 5 and 20 degrees).

The Magistrate 22 *Umwelt Wien* estimated a total surface of 1'078,7 ha of roofs which could be suitable for intensive greening. This total surface represents 20% of the overall roof landscape of the city of Vienna (Figure 25).



Figure 25. Flat roofs identification and mapping using ARCGIS. The map was created by the author of the present thesis based on the GIS data of the Stadt Wien.

This surface potential is equivalent to 3.5 times the surface of the historical city center *Innere Stadt*. This result does not include important aspects such as the roof structural conditions, the monument protection zones, the solar potential and the land-use restrictions.

The report *Analyse des Dachbegrünungspotentials Wien* gives an overview of the zones with a high potential for intensive greening in Vienna (Vali, 2011). The largest flat roofs elements are located on the periphery of the city such as the industrial area of *Inzersdorf*, the area of *Kagran* or the industrial zone of *Floridsdorf*. Figure 26 shows the distribution of building use for every building with a flat roof larger than 1'000 m² in Vienna:



Figure 26. Number of objects with a potential rooftop farming area according to use and size in Vienna. Retrieved from *Exploring the possibilities for urban rooftop farming in Vienna* by B. Laa, 2017. Copyrights 2017 by B. Laa.

The districts with the greatest flat roof potential are *Liesing* (176.9 hectares), *Donaustadt* (163.7 hectares) and *Floridsdorf* (121.6 hectares).

The existing urban green infrastructure of Vienna could be substantially extended with the implementation of rooftop gardens. It is estimated that greening all the flat roof surfaces of Vienna would increase by 10% the total surface of the green areas of the densely built-up districts of *Wieden, Neubau* or *Alsergrund* (Vali, 2011).

4.3. The potential for rooftop agriculture in the city of Rio de Janeiro

4.3.1. Collection of the data

The municipality provides digital maps about the roof landscape of RJC and its potential benefits: the Solar potential map *Mapa Solar da Cidade do Rio de Janeiro*, and the Rainwater harvesting map *Uso de Água de Chuva no Rio de Janeiro*. However, these maps do not have information regarding the inclination of the roofs.

To identify the flat roof surfaces, a LIDAR 3D point cloud was collected and analyzed. The mapping results give an accurate representation of the flat roof landscape, which is one of the

products of the present research. This map will be available online on the digital platform *Sistema Municipal de Informações Urbanas* (SIURB) of the municipality of Rio de Janeiro by 2019. In the frame of the study, the *Instituto Pereira Passos* (*Prefeitura Rio*) provided the following datasets:

- 1. **The Land use map** *Cobertura Vegetal e Uso da Terra* generated in 2014. The map gives information about the location, the shape and the type of green surface and the built environment of RJC.
- 2. **The Building footprints map** generated in 2013. The map provides the roof footprints polygons (with details on the building height).
- 3. **The Social development index** *Índice de Desenvolvimento Social* (IDS) calculated for each district (*"Bairro"*) of RJC and dated from 2008.
- 4. The LIDAR 3D Point cloud covering only 69.2% of RJC (.las data) generated in 2013. The laser scanned aerial survey provides a dataset with a point density of 2 points per square meters and a basis for the roof slope analysis. The survey did not cover the whole city but exclusively the areas of RJC in urban expansion, which represents 830,93 km² as shown in Figure 27.



Figure 27. Area of Rio de Janeiro City covered by the LIDAR data survey in 2013 and analyzed in the present study. The map was created by the author of the present thesis based on the GIS data of the municipality of Rio de Janeiro City.

The characteristics of the LIDAR data are: Sensor type: Sistema LIDAR ALS60; Opening angle (FOV): 25°; Average flight altitude: 2.000 m; Point density: 2pto/m²; Lateral Overlap: 20%; Number of strips: 75; Projection: UTM; Zone: 23; Reference: SIRGAS 2000.

To compare the two roofscapes (Vienna and RJC), the flat roofs polygons were calculated based on the same parameters. As described in Chapter 4.2.1, these parameters are: a roof pitch angle inferior the 5 degrees, roof surface larger than 5 square meters and a quotient Area / Perimeter superior to 0.3 per flat roof unit. To calculate the angle of the roofs, it was necessary to create a high-resolution Digital Terrain Model and Digital Surface Model:

 The Digital Terrain Model (DTM) gives a bare earth representation of terrain or surface topography. It includes heights, elevations and other geographical elements such as rivers, ridgelines etc. - **The Digital Surface Model (DSM)** provides coded elevation points of the earth's surface, including all items located upon it (buildings, roads, vegetation growth, etc.).

Figure 28 illustrates the differences between the two types of models:



Figure 28. Representation of a DSM and a DTM. From *Developing an algorithm for enhancement of a digital terrain model for a densely vegetated floodplain wetland.* by Mirosław-Świątek, D., Szporak-Wasilewska, S., Michałowski, R., Kardel, I. & Grygoruk, M., 2016: J. Appl. Rem. Sens. Copyrights 2016 by Mirosław-Świątek.

4.3.2. Quality Checking

Before generating the two elevation models, the .GIS data (.las) must be inspected. The program LAStools was used to reveal the errors within the dataset (Isenburg, 2018). By using the command **lasoverlap**, it was possible to check the zones with potential poor flightlines and to ensure that the point cloud was "correct" before converting it into a DTM and a DSM.

The study detected 4 error zones: Figure 29 shows the misalignment of the data and some long and bright stripes of "noise":



Figure 29. View of the white "noise stripes" and the roof surfaces (depicted in purple) observed in the east of the district of *Guaratiba* in RJC.

These zones were identified and gathered within a file in order to keep track of the error polygons. Figure 30 gives an overview of the error zones.



Figure 30. The red zones correspond to the error flight lines areas within the LIDAR point cloud boundaries. These corrupted zones were observed in the districts of *Guaratiba, Campo Grande, Jacarepagua and Anil in RJC.*

The corrupted areas concerned 3'460 roofs from the dataset. This represents only 0.23% of all the roofs analyzed. Unfortunately, this data cannot be corrected and these areas should be scanned a second time. All the roofs which were overlapping these zones were withdrawn from

the datasets and immediately notified to the institute *Pereira Passos*. The rest of the point cloud was transferred for further analysis.

4.3.3. Creation of the DTMs and the DSMs using LAStools

LAStools is a collection of command line tools to classify, tiles, contour, convert, filter, clip or polygonize LIDAR data (non-exhaustive list of the capacities of the tool) (Isenburg, 2018). An academic LAStools license was also generously provided by to the LASmoons program for the research study. Below the workflow for the generation of the DTMs and DSMs based on LIDAR data (Figure 31):



Figure 31. Description of the workflow in LAStools used for the present study.

Due to the size of the data, the DTMs & DSMs were divided into 13 different regions (Figure 32):



Figure 32. Processing of the LIDAR data divided into regions with the use of LAStools in RJC.

6 Steps were iterated for each of the 13 "Regions":

Step 1. LASTILE > Step 2. LASGROUND_new > Step 3. LASHEIGHT > Step 4.
LASCLASSIFY > Step 5. LAS2DEM > Step 6. LASGRID

Appendix 5 – "Processing of the LIDAR Data into a DTM and a DSM using LAStools"

illustrates the processing of one example tile in the region of Bangu using Lastools.

According to the pulse spacing of the initial data, it was decided to create the DTMs and DSMs based on a step size of 0.5 meters, which corresponds to a pixel resolution of 0.25 m². The Digital Surface Models were based on the first returns.

• Step 1. LASTILE

Input: Raw Lidar Data provided by the IPP (Region*.las)

Goal: to tile a very large amount of LAS points from many files into square non-overlapping tiles of a specified size and to save them into LAZ format.

The first step was to tile the data into tiles that are typically 1000 by 1000 or, for higher density surveys, 500 by 500 meters in size. In the present study, the tiling was made with 1000 by 1000 squares tiles (Figure 33).

Command: C:\LAStools\bin>lastile -i strips_raw\Region*.las ^

-utm 23S ^ -tile_size 1000 -buffer 50 ^ -tile_II 500 500 ^ -odir tiles_raw -o fitch.laz



Figure 33.Tiling of the raw LIDAR data using the command lastile

• Step 2. LASGROUND_new

Input: Lastile output (from step 1)

Goal: to classify the LIDAR points into ground points (defined as class = 2) and non-ground points (defined as class = 1).

Lasground_new was chosen over lasground because the command is more efficient for areas with high contrasts of steep mountains and buildings, which was the case of RJC. The setting '-metro' (ie. "Metropolis") was selected.

If very large buildings fall fully into the predefined grid, these buildings may be classified as ground. To avoid this mistake, a large step of 50 meters was set as security. A visualization of the classification results is shown on Figures 34 and 35.

Command: lasground_new -fitch.laz ^

-metro -hyper_fine ^ -compute_height ^ -odir tiles_ground -olaz ^



Figure 34. Examples of outputs of step 2 "Lasground_new" for the present study. (a) Points classified as ground points; (b) Points classified as non-ground points.



Figure 35. Visualization of the ground points as a Triangulated Irregular Network (TIN).

• Step 3. LASHEIGHT

Input: Lasground_new output (from step 2)

Goal: to compute the height of each point above and below the ground and to drop the points with a height below 3 meters or above X meters. The value X depends on the maximal building height observed within the study zone. To set appropriately this value, the maximum building

height for each region was evaluated based on the Building footprints map provided by the municipality. The objective was to "clean" the point cloud and to ensure the good quality of the final DTMs and DSMs. All the detected points (ie. falling out of the height range) were removed from the compressed tiles. Figure 36 shows an example of solitary points which were removed using the command Lasheight.



Figure 36. View of 4 outliers points observed within a tile during step 3.

Command : C:\LAStools\bin>lasheight -i tiles_ground\fitch*.laz ^

-drop_below -3 -drop_above X ^

-odir tiles_height -olaz ^

In most cases, the points of the electrical installations remained into the dataset after step 3 (Figure 37). However, this was not an issue since these points were filtered on the last step of the processing.



Figure 37. View of the point cloud with the points of an electrical installation which remain after step 3.

• Step 4. LASCLASSIFY

Input: Lasheight output (from step 3)

Goal: to classify the points as "Building" and "High vegetation" (i.e. trees)

Settings: Search area 2; Building planarity = 0.1; Forest ruggedness = 0.4; "include gutters"; "no tree overhang". The points were classified as follows: (1) unclassified points; (2) ground; (5) high vegetation; (6) building (Figure 38).

Command : C:\LAStools\bin>lasclassify -i tiles_height\fitch*.laz ^

-step 2 ^

-odir tiles_classified -olaz ^



Figure 38. Visualization of an example of points classified as vegetation (green), buildings (orange), ground (brown) and non-classified (grey) after step 4 for the present study.

Note: After the processing of the data with Lasclassify, some of the points remained unclassified. RJC has a very complex and irregular urban structure. The settings were chosen as an adjustment between the flat and steep topography (which was observed in the region of *Meier* and *Jacare*), the urban areas with high towers (in the region of *Barra da Tijuca*) and the regions with impervious forests and small buildings (in the regions of *Vargem Grande* and

Pequena). In addition, the point density of the LIDAR data was not very high (2 points per square meters).

• Step 5. LAS2DEM

Input: Lasclassify output (from step 4)

Goal: to triangulate the LIDAR points from the LAZ format into a temporary Triangulated Irregular Network (TIN) and to raster the TIN to create a DTM and a DSM.

Notes:

- The lasinfo command generated a report about the characteristics of the LIDAR data. Based on this document, the data presented an average of 1.6 laser pulses / last returns per square meter which translated into an average spacing of 0.79 meters between the laser pulses / last returns. It was not necessary to thin this low-density data on-the-fly onto a 10-centimeter grid by using the option '-thin with grid 0.1'. This option would not have increase the quality of the output but would have cost computation and memory resources.

- Considering the pulse spacing, it would have been possible to get a satisfying 1-meter DTM and DSM using a step size of '-step 1.0'. More information could have been gained by setting the step size to 0.8 or 0.5. However, a lower step such as 0.3 would not be a useful raster resolution for this low point density of the dataset. The tiles have a dimension of 1000x1000 (as mentioned in step 1 lastile). Therefore, 0.2, 0.25, 0.4, 0.5, 0.8, or 1.0 should be the only considered choices for the creation of the models when diving a 1000x1000 tile.

Below the command for the creation of the DTMs based on classification 2 (ground points) (Figure 39).

Command : C:\LAStools\bin>las2dem -i tiles_classified*.laz ^

-keep_class 2^
-extra_pass^
-use_tile_bb^

-odir tiles_dtm -obil^



Figure 39. Visualizations of an example of DTM generated with Las2dem for the present study. The surface is coloured by height.

The DSMs were generated based on the first returns. An example of TIN output of a DSM in the

region of Bangu is shown on Figure 40.

Command : C:\lastools\bin>las2dem -i tiles_classified\fitch*.laz ^

-first_only ^

-extra_pass ^

-use_tile_bb ^

-odir tiles_dsm -obil ^



Figure 40. Visualization of a TIN of the Digital Surface Model in the district of *Bangu* in RJC.

• Step 6. LASGRID

Input: Las2dem output (from step 5)

Goal: to read data from a .bil format and to grid it onto a raster format.

Command 1 : C:\lastools\bin>lasgrid -i tiles_dsm\fitch*.bil -merged ^

-utm 23S ^

-o dsm.tif

Command 2 : C:\lastools\bin>lasgrid -i tiles_dtm\fitch*.bil -merged ^

-utm 23S ^

-o dtm.tif

Figure 41 shows the differences between a DTM (terrain) and a DSM (includes tree canopy, buildings, objects, and terrain) generated on a tile of the region of Bangu.



Figure 41. The caption illustrates the differences between the DTM and DSM in the region of Bangu. The DSM includes tree canopy, buildings, objects and terrain. The DTM only provides information on the terrain.

4.3.4. Slope calculation and mapping with GIS applications

The last step of the data processing consisted in calculating the slope of the roofs. As a preliminary step, the DTMs and the DSMs were merged together into one DTM and one DSM, both projected into UTM23S.

Step 1. Combination of the DTM and DSM using the raster calculator

Since the terrain of RJC presents great variations in elevation (the range is comprised between 0 to 1,020 m above sea level), it was not possible to conclude immediately on the respective absolute roof height. For this purpose, a Normalized Digital Surface Model NDSM was required (the terrain is set to a standard of zero). The NDSM was generated by subtracting the Digital Terrain Model (DTM) from the Digital Surface Model (DSM) (Figure 42).

NDSM = DSM - DTM



Figure 42. Graphic illustrating the differences between a DSM, a DTM, and a NDSM. From *Developing an algorithm for enhancement of a digital terrain model for a densely vegetated floodplain wetland.* by Mirosław-Świątek, D., Szporak-Wasilewska, S., Michałowski, R., Kardel, I. & Grygoruk, M., 2016: J. Appl. Rem. Sens. Copyright 2016 by Mirosław-Świątek.

This procedure simplifies the distinction between elevated and non-elevated objects and allows the direct measurement of the object heights. The NDSM gives a clear distinction between streets, elevated vegetation and structures, with height information (Berlin, 2019). The raster calculator was used to generate the NDSMs (Figure 43).



Figure 43. View of a NDSM generated for the region of Bangu for the present study.

• Step 2. Slope calculation using the "DEM – Terrain Model" tool

The tool "DEM - Terrain model" was used to calculate the slopes of the NDSMs. The outputs "NDSM_Slope" were raster images with a black to white color ramp. Each pixel is colored according to the slope: the colour white corresponds to vertical surfaces such as the lines around the walls of the buildings and the colour black corresponds to the flat areas (Figure 44).



Figure 44. Example of a result of slope calculation in the region of north Bangu for the present study.

• Step 3. Finding the flat roofs

The study aimed to identify all the roofs, which are located on buildings with a minimum height of 2 meters (ie. off the ground-level). The mapping was based on the same parameters than the ones used to generate the green roof cadastre of the city of Vienna. Therefore, the roofs were considered flat when their slope was inferior to 5 degrees. The following formula was used into the raster calculator:

"DSM-DTM@1" >= 2 AND "NDSM_Slope@1" <= 5

Figure 45 gives a first visualization of the flat areas within the study region.



Figure 45. Example of a result of roofs with a slope inferior to 5 degree and a minimum elevation of 2 meters in the region of North Bangu.

• Step 4. Cleaning up the raster map with the "sieve" command

It was necessary to refine the data to remove unwanted elements such as white speckles (which were often trees) and long thin lines (which corresponded to roof peaks). The command "sieve" was used with a threshold of 5 pixels. "Sieve" removed all raster polygons smaller than 5 pixels and replaced them with the pixel value of the largest neighbor polygon. The pixel values were 0 (black, unwanted surfaces) and 1 (white, flat roofs).

• Step 5. Conversion from Raster to vector and filtering of the data

The objective was to convert the raster image to a vector format to get the flat roof polygons. It was also important to identify the roofs with a "donut" shape which could have been filled with an extra surface in their core (Figure 46).



Figure 46. "Donut" filled due to the raster to vector conversion.

This "filling error" was corrected with an automated workflow (zonal statistics). For the removal of the roof peaks, the following query filter was applied:

U = Shape Area / Shape Length > 0.3

All features with a U value inferior or equal to 0.3 were removed from the dataset. A last filter was applied to keep exclusively the roof areas which were superior or equal to 5 square meters. Last but not least, the last phase consisted in intersecting the remaining flat surfaces with the building footprints provided by the Instituto *Pereira Passos*. A roof unit may have several flat surfaces. It is important to highlight the fact that the map displays each of the flat surfaces located on each roof. Therefore, it does not give an estimation of the flat roof potential per roof unit. This could not be made due to the structure of the data "Building footprints map" which is composed of overlapping roof polygons. Since, it was not possible to provide an evaluation of the flat areas per roof unit. It was necessary to dissolve all the building footprints in order to remove all the overlapping roof units. Figure 47 gives an example of the final output.



Figure 47. Final mapping of the RA potential on a tile of North Bangu in RJC. The flat surfaces are coloured in green and the building footprints are coloured in grey.

4.3.5. Analysis of the rooftop agriculture potential

4.3.5.1. Availability and distribution

The map integrated all the flat roofs with a minimum size of 5 square meters and a minimum height of 2 meters. As a result, smaller areas were not reported as a potential. The map did not include the structural conditions of the roofs; this criterion requires an on-site investigation. The Lidar-based mapping shows there are 1'384.5 hectares of flat roof surfaces within the studied area of RJC. This represents 11.2% of all the roofs surfaces considered in the present study area. The mapping results can be found in **Appendix 6. "Results of the Lidar-based mapping for the present study". Appendix 7. "Summary of the results of the Lidar-based mapping for the present study"** gives an overview of the numerical results.

• Results of the LIDAR-based mapping on a 1 km² grid

To better analyze the spatial distribution of the flat roof landscape, the political borders of the districts *Bairros* were not considered as relevant. Some districts were "cut" by the area covered by the LIDAR Scanning survey, therefore summarizing the results per district would not give an accurate representation of the potential. The sum of all the flat roofs within each 1km² cell of the grid was calculated and categorized into 5 different classes:

- very high potential ≥ 64'000 m²
- high potential 64'000 $m^2 > X \ge 48'000 m^2$
- medium potential 48'000 m² > X \ge 31'000 m²
- low potential 31'000 m² > X \ge 16'000 m²
- very low potential 16'000 m² > X \ge 5 m²

An overview of the mapping is available in **Appendix 8.** "**Results of the LIDAR-based mapping on a 1km² grid**". The results show several clusters with a very high flat roof potential ($\geq 64'000 \text{ m}^2$) located in the highly urbanized areas of the north zone of RJC. This is not a surprising result since this region is highly populated with a lot of buildings. Here some important findings:

- Vila Kennedy presents the highest number of flat roof surfaces: 22,5% of the overall roof surface is flat, which represents 12.7 hectares of roofs.
- Cidade de Deus is the district with the second highest amount of flat roof surfaces: 17.6% of the roof landscape is flat which represents 11.4 hectares.
- "Very high flat roof potential" zones (\geq 64'000 m² per grid cell) are exclusively in areas where the population density is high or very high (> 12'000 hab/km²). This shows that RA could be targeted in these key zones and benefits to a high density of consumers within a relatively short distance, providing local and fresh food directly to the households.
- 4.3.5.2. Characteristics of the clusters with a high potential of flat roofs

The analysis focuses on four clusters, evaluated as key zones. These areas hold a flat roof potential superior than $48'000 \text{ m}^2 \text{ per 1 km}^2 \text{ grid cell}$:

- cluster 1 covering Bangu, Senador Camara, Gericino and Vila Kennedy;
- cluster 2 with Magalhães Bastos, Padre Miguel, and Realengo;
- cluster 3 is Cidade de Deus;
- cluster 4 covering Cosmos and Inhoaiba

These clusters are identified in Figure 48.



Figure 48. Clusters as key areas for rooftop agriculture in RJC based on the mapping results.

The 4 clusters represent 355.44 hectares of flat surfaces, which corresponds to 26% of the overall flat roof potential. Land uses are mainly residential, including slums areas (shaped with blockhouses and small flat roof terraces). Other land uses with a high amount of flat roofs are

commercial and service areas (such as Shopping Bangu), industrial areas (with large flat roofs units) and zones with public infrastructure (such as the prison complex in the north of Bangu).

Cluster regions and Social Development Indexes (IDS)

Defined by the municipality of RJC, the Social Development Indexes (IDS) combine indicators of educational level, income, housing quality and level of basic sanitation (Cavallieri & Peres Lopes, 2008). The region of Lagoa has the highest IDS (0,786) and Guaratiba the lowest IDS (0.446). In the cluster regions, the IDS are among the lowest of RJC with only 0.520 for Bangu or 0.498 for Cidade de Deus. The cluster regions correspond to areas with a high social vulnerability. Holding a high flat roof potential, these zones could benefit greatly from RA.

Building characteristics of the cluster regions

Table 2 gives a summary of the building characteristics and the flat roofs dimensions observed in the cluster regions based on the GIS data "Building footprints map" provided by the municipality of RJC.

Clusters	Building Characteristics	Flat roof Dimensions
1, 2, 3, 4	Average value building height: 4.5m Median value of the building footprint area: 71.4m²	Minimum flat roof: 5 m² Largest flat roof: 6,142.8 m² Median flat roof area: 14.31 m²

Table 2. Statistics of the buildings and the flat roofs characteristics in the cluster regions presented in this study for RJC

The most common building typology observed in the cluster regions corresponds to single to two-story building blocks, with a height of 4.5 meters and a median building footprint around 71.4 m². Figure 49 shows example of buildings in Cidade de Deus (cluster 3) and Realengo (part of cluster 2) (Google Maps, 2018).



Figure 49. Rio de Janeiro City. (a) The roofscape of Cidade de Deus; (b) Front view of building blocks in Realengo. Captions from Google maps, Cidade de Deus 22° 57' 1.8" S 43° 21' 37.188" W; Realengo 22° 52' 20.172" S 43° 26' 6.864" W. Retrieved 2018 from: google.com/maps. Copyright 2018 by Google Street View.

The structure of the single to two-story building blocks is usually composed of concrete pillars and the floors are floor beams and slabs. The rooftop terraces are covered by a corrugated iron roof or left open. Water tanks may be placed on the roof to provide running water. The houses are often constructed over years: the first two floors may be completed in the future by an extra floor for rental to a family member or an external person (Veysseyre, 2014). For this reason, the structure is conceived robust in the perspective of a vertical extension. This constitutes a great opportunity since the structural conditions of the building have a strong impact on the implementation costs of the rooftop gardens.

Low building height is an important parameter for maximizing the potential cooling effect of the rooftop gardens on the pedestrian level (Peng & Jim, 2013). In the case of the clusters (with a very low average building height of 4.5m), it could be interesting to simulate the cooling effects of green roofs, taking into account further parameters such as wind direction, construction materials and building density. In addition, the advantage of green roofs on low-rise site is that the green roof surfaces are situated closer to the urban green infrastructure on the street-level, thus enhancing the connectivity potential. Roof greening policies should be addressed particularly within the four clusters since these areas hold a great flat roof potential, a low amount of green areas and low social development indexes.

The suitable agriculture typology for these residential areas would be informal RA since the roofs are essentially private with a low median area of 14.2 square meters. Simple production systems could be used such as small containers, boxes or bags filled with soil and compost. The small gardens would enrich the diet of the families with fresh vegetables and save on food expenditure. Nonetheless, rooftop gardens are not only valuable for food production but can also benefit the community. The large flat rooftop surfaces located on public buildings could be transformed into community garden hubs, serving as a platform for the neighborhood activities and increasing food education.

4.3.5.3. Spatial distribution of the flat roofs surfaces

The flat roof density map displays the density of flat roofs within the study area (**Appendix 9**. "**Map of the density of flat roof surfaces**"). To get more details on these results, two heat maps were created: **Appendix 10**. "**Map of the regions with the highest amount of small** flat roofs (<500m²)" and **Appendix 11**. "**Map of the regions with the highest amount of** large flat roofs (\geq 1'000m²)".

The zones mapped in Appendix 10 correspond greatly to the cluster regions identified previously: clusters 1 and 2 show a high density of flat roof surfaces as well as clusters 3 and 4. In clusters 1 and 2, the high number of small flat roof units may be caused by the large amount of residential buildings with a building block typology. Appendix 11 shows that the spatial distribution of the large flat roof surfaces. The map demonstrates that large flat roofs are not exclusively concentrated into the cluster areas. The key large flat roofs are identified in:

- the industrial zone of Barra da Tijuca,
- the commercial areas near the former Olympic parc
- the industrial area in the south of the district of Taquara
- the commercial zone in the district of Gardenia Azul
- the industrial complex of the Fabrica Michelin in the north of Guaratiba

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- within *Campo Grande*, the industrial zone of *Jardim São Pedro* and the Brewery *Cervejaria Ambev*
- the commercial zone of north Cachambi and the shopping complex of Del Castilho
- the southern zone of Manguinhos
- the bus station Rodoviária Novo Rio and its surroundings in Gamboa

These large roof surfaces present a great potential for the implementation of large urban agriculture projects such as commercial rooftop farms.

4.3.5.4. Description and characteristics of the largest flat roofs

Below a list of the largest flat roofs elements based on the results of the Lidar-based mapping. For each figure, the area coloured in green corresponds to the flat surface areas of the roof units.

1. Leroy Merlin, Commercial use (Figure 50)

R. Afonso Projetada, 550 - Del Castilho, Rio de Janeiro - RJ, 20730-140

Flat roof potential Area = 10'463.75m²



Figure 50. Aerial view of the Leroy Merlin building from Google Maps and on the results of the mapping. Retrieved 2018 from: google.com/maps. Copyright 2018 by GoogleMaps.

2. Américas Shopping, Commercial use (Figure 51)

Av. das Américas, 15500 - Recreio dos Bandeirantes, Rio de Janeiro - RJ, 22790-702 Flat roof potential Area = $9'755m^2$



Figure 51. Aerial view of the Shopping center from Google Maps and on the results of the mapping. Retrieved 2018 from: google.com/maps. Copyright 2018 by GoogleMaps.

3. TIVIT, Telemarketing (Figure 52)

Estr. dos Bandeirantes, 10916 - Sala B - Vargem Pequena, Rio de Janeiro - RJ, 22783-

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Flat roof potential Area = 8'429m²



Figure 52. Aerial view of the TIVIT industrial building from Google Maps and on the results of the mapping. Retrieved 2018 from: google.com/maps. Copyright 2018 by GoogleMaps.

4. Cervejaria Ambev Rio de Janeiro RJ, industrial use (Figure 53)

Estr. Rio São Paulo, 6011, 4421 - Campo Grande, Rio de Janeiro - RJ, 23087-005

Flat roof potential Area = $7'984m^2$



Figure 53. Aerial view of the industrial building from Google Maps and with the results of the mapping. Retrieved 2018 from: google.com/maps. Copyright 2018 by GoogleMaps.

Note: The Brewery possesses several industrial buildings with large flat roof units.

5. Comercial Gerdau, industrial use (Figure 54)

Estr. do Pedregoso, 900 - Campo Grande, Rio de Janeiro - RJ, 23095-250 Flat roof potential Area = 7'796.17 m^2



Figure 54. Aerial view of the industrial building from Google Maps and with the results of the mapping. Retrieved 2018 from: google.com/maps. Copyright 2018 by GoogleMaps.

6. Assaí Atacadista, industrial use (Figure 55)

Av. Dom Hélder Câmara, 6350 - Pilares, Rio de Janeiro - RJ, 20771-001

Flat roof potential Area = $7'082m^2$



Figure 55. Aerial view of the industrial building from Google Maps and with the results of the mapping. Retrieved 2018 from: google.com/maps. Copyright 2018 by GoogleMaps.

Note: The map was generated based on LIDAR data collected in 2013. At the time of the present research (2018-2019), the building with the largest flat roof potential (15'187.2m²; located in *Santa Cruz*) does not exist anymore.

The typology "Industrial building" presents the largest flat roof surfaces, which are mostly used for retail, production or commercial purposes. These buildings are commonly owned by private companies and located on the periphery of highly urbanized areas. The roofs of *Américas Shopping* and *Leroy Merlin* show a great flat roof potential. Implementing a commercial rooftop farms (indoor or outdoor) combined with the commercial use of the building could be an upgrading of the existing commercial use. The rooftop gardens could provide fresh and local food which could be directly distributed in the shopping areas and restaurants underneath.

4.3.6. Calculation of the overall growing capacity

The yearly vegetable requirement in Brazil was based on official statistics collected by the Food and Agriculture Organization of the United Nations (FAO) and published in 2017 (FAO, 2017). The database FAO Hortivar was chosen as a reference for the evaluation of the vegetable production yield of RA. The production yield of the RA systems fluctuates according to the vegetable species and agricultural techniques. The productivity of the plant species cabbage is 20 kg/m²/year, corn salad 14.6 kg/m²/year and eggplant is around 16.9 kg/m²/year (Hortivar, 2016). For the research, the production yield of the rooftop gardens was set to 15 kg/m²/year. This value seems realistic compared to several project which resulted in a productivity yield of 15.2 kg/m²/year in Bologna, 18 kg/m²/year in Cuba and up to 50 kg/m²/year (Orsini et al. 2014; Altieri et al., 1999; Drescher, 2004). To calculate the net production surface of the roofs, it was estimated that 35% of the overall surface was used for infrastructural spaces, as suggested in a recent study for the city of Bologna (Orsini et al., 2014).

The national and World Health Organization recommends between 73 to 91.5 kilograms of yearly vegetable intake per capita. Brazil is below this recommendation, with only 50.3 kilograms (FAO, 2017). Accordingly, the entire rooftop surface could produce around 134'985 tons of vegetables per year, which represents 39.2% of the evaluated vegetable requirement of RJC (Table 3).

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Element	Value	Unit
Overall roof surfaces	12'354.10	На
Flat roofs	1'384.50	На
Ratio of flat roofs	11.2	%
Net production surface of the rooftop garden	899.9	На
Productivity yield of the rooftop gardens	15	kg.m-².year-1
Potential vegetable production	134'985	t.year-1
Average yearly vegetable consumption per capita	51.5	kg
Average yearly vegetable consumption per capita (recommended)	91.5	kg.year-1
The estimated population in Rio de Janeiro City (2018)	6'688'927	Persons
Overall vegetable demand in Rio de Janeiro City (2018)	344'680.40	tons.year-1
Potential of persons fed per year in Rio de Janeiro City	39.2	%

 Table 3. Estimation of the potential productivity of the flat roofs landscape based on the mapping results for RJC (FAO, 2017; Hortivar, 2016; IBGE, 2018)

In the present study, the calculation was based on the average yearly vegetable consumption per capita, which is the actual consumption pattern and not the consumption recommended by the FAO. The resulting food production would feed 2'608'681 adult persons per year in vegetables. This is the equivalent of 39.2% of the overall population of RJC. In RJC, around **1,4 million** people were living in slums (*favelas*) in 2013. Therefore, the results show that if the city transforms **only 53% of its flat roof landscape** into rooftop gardens, **it would provide enough vegetables to feed annually all the inhabitants of the slums.** In addition, It would stimulate better food education and provides fresh vegetables directly in and by the households. RA in RJC could be a valuable contribution to food security as well as providing other benefits such as improved city liveability and community building.

4.3.7. Dissemination and publication of the map on the SIURB platform

The results of the mapping were presented during a public talk and workshop at the Federal University of the state of Rio de Janeiro (UNIRIO) on the 11th of October 2018. The aim of the event, called "Thinking of future policies for greening the city", was to bring together planners,
architects, city officials and researchers to learn about the results of the research and to discuss the potential application programs which could support the implementation of the results on-site (Figure 56).



Figure 56. Flyer of the Workshop "Thinking of future policies for greening the city" at the UNIRIO planned on october 11, 2018.

The feedback collected during the workshop showed the great relevance of the mapping work for the development of future roof greening policies. The propositions for the use of the research work were:

1) Building up greening strategies based on the combination of the rooftop agriculture map with the areas identified with a "High vulnerability" (defined as the zones where there is a lack of basic resources, food insecurity);

2) Targeting public buildings and institutions for the implementation on-site of rooftop gardens. The strategy consists in promoting successful cases in order to have a replication effect on further private roof objects.

3) The study outputs should be considered as a support for decision-making in planning urban green infrastructure. It is important to make the results public since the mapping aims to increase awareness among citizens about the potential for RA in RJC. The map should not only be directed to policy-makers and city planners but also to property owners who could start a dialogue with greening experts and potential farm tenants.

From 2019, the map will be available on the digital platform *SIURB* of the municipality of RJC https://siurb.rio. The digital map includes :

- a short description of the mapping methodology;
- a guide "How to grow?": legal framework, standards and certification;
- a guide "What to grow?": types of vegetables and fruits which would be the most suitable to grow on the roofs of RJC.

The map was named "The green roof potential map of the city of Rio de Janeiro" rather than "The rooftop agriculture map of the city of Rio de Janeiro" to suggest a more generic use of the results. Figure 57 shows the final layout.



Figure 57. Screenshot of the final Layout of the map for RJC available on the digital platform SIURB by 2019.

The idea is to motivate owners, organizations, and associations to look at the potential growing capacity of the roofs and promote roof gardening initiatives. The two guides were written in collaboration with the Prefeitura Rio and the socio-environmental association called CARPE. CARPE supervises several gardening projects in public schools and has practical experience on the types of crops and plants which are the easiest to grow on roofs in the context of humid tropical climates.

Chapter 5. Parametric modelling

5.1. Parametric design and urban acupuncture

Confronted to the plurality and uncertainty of urban transformations, cities seek for adaptive greening strategies, which would be suitable for a multiplicity of scenarios; especially providing sustainable solutions. Jane Jacobs wrote that cities are categorized as "organized complexity" with "several dozen quantities [...] all varying simultaneously and in subtly interconnected ways" (Jacobs, 2011). As a matter of fact, cities should not be designed as fixed structures, but evolutive systems (Padoa, 2013). In the context of the rapidly evolving climatic change and exponential growth of the built environment, a shift from static design towards specific and dynamic design of generic solutions is essential (Beirão, 2011). The use of adaptive strategies would ensure the long-term of the planned interventions into the city fabric, which is in a continuous transformation process.

Although the value of parametric modelling is widely acknowledged among architects, parametric design on the city scale remains a marginal approach. Grasshopper is a visual programming tool for designers and architects to generate new shapes using generative algorithms and it does not require any knowledge of coding. It has been chosen because it is a platform which integrates multidisciplinary modules for interdisciplinary projects. Grasshopper gives an alternative to the usual GIS Software because it proposes several free-access Plugins such as Meerkat GIS, Heron (generates Grasshopper geometry from GIS shapefiles) and Elk (generates a map and topographical surfaces using open source data from OpenStreetMap) (Lowe, 2015; Washburn, 2015; Logan, 2016).

For the present study, it was relevant to use the plugin Meerkat GIS to import the polygons from a shapefile to the grasshopper platform. This process preserves the scale, the size and the attributes of the green spaces and the flat roofs. Parametric design enables flexibility in the modelization process and the possibility to work on an interdisciplinary level. Since this research is based on different domains such as city planning, applied mathematics, geo-information analysis and landscape ecology, the need of this parametric design platform seemed like a selfevident requirement. By exploring various green roofscapes possibilities with the use of generative algorithms, the study investigates the spatial potentials and tendencies for RA by combining GIS data with urban parametric modelling techniques. The objective is to provide a support for decision-making in developing small-scale and prioritized RA strategies.

5.2. Roadmap: the creation of the parametric models based on the roofscape of Vienna

The roadmap displayed in Appendix 1. gives an overview of the different parametric tools created in the frame of this study. Three levels of analysis were identified:

Level A: Analysis of the existing urban green landscape. The products of this level are named "Products green landscapes analysis" and are Products 1 / 2 / 3. This level focuses exclusively on investigating the opportunities and vulnerabilities within an existing urban green envelope. The parametric models which have been developed for level A are:

PM "Green desert" - Chapter 5.4.

PM "Location Density" - Chapter 5.5.1.

- Level B: Analysis of the key roofs surfaces for RA "From green areas to flat roofs". The products of this level are named "Products Flat roof landscape analysis" and are Products 4 / 5 / 6. Based on the zones of opportunities identified in Level A, level B integrates the flat roofs landscape polygons and points out how and which flat roofs could be used to reconnect or strengthen the existing urban green cover. The parametric models which have been developed for level B are:

PM "Green desert" (extension) – Chapter 5.4.

PM "Minimum Spanning Tree" - Chapter 5.5.2.

PM "Food Production" – Chapter 5.6.

Level C: Proof of concept on the region of Bangu & Analysis of the key scenarios
 "From flat roofs to combination scenarios". The products of this level are named
 "Products roof greening scenarios proposals" and are products 7 / 8 / 9. This level
 focuses on generating combination scenarios based on the results of Levels A and B.
 The PMs which were developed for level C are:

PM "Minimum Spanning Tree" - Chapter 5.5.2.

PM "Detecting spatial synergies" - Chapter 5.8.1.

PM "Wallacei" - Chapter 5.8.2.

Level C also includes the testing and optimization of the PMs on the case study area of Bangu in RJC (Proof of concept).

5.3. Case study area in Vienna

The city of Vienna contains 23 districts of different sizes and degrees of urbanization. Figure 58 shows the spatial distribution of the green and blue areas in Vienna. This map was generated based on the GIS data "Land Use map - *Realnutzungskartierung*" dated from 2009 and provided by the Magistrate 22 Umwelt.



Figure 58. The distribution of the green spaces in the city of Vienna. The map was created by the author of the present thesis based on the GIS data of the Stadt Wien.

The green and blue elements were extracted based on their potential for providing substantial pollen and nectars for insect pollinators. The focus of the research was made on a highly urbanized zone that regroups fully or partly the 1st, 2nd, 3rd, 4th, 5th, 6th, 7th, 8th, 9th, 15th, 16th, 17th and 18th Districts of Vienna (Figure 59).



Figure 59. Figure : Definition of the case study area in the city of Vienna: (A) Focus area (B) Green spaces & rooftops locations within the selected focus area.

The area of the case study was defined according to the mapping results of the workshop conducted at the *Kunsthalle Wien* and described in Chapter 3.4.4. "Mapping the opportunities for community gardening in Vienna". The goal was to extract an urban space that the participants of the collective mapping identified as very suitable for urban agriculture. 30 out of 50 key locations obtained during the workshop were enclosed by the present case study area. Another parameter for defining the case study location was the high degree of urbanization and the lack of green spaces. The characteristics of the case study area are presented in Table 4.

		Elements	Area (in ha)
Total surface			5'027
Green surfaces		149	263
Largest green space	Volksgarten &		18.6

Heldenplatz

Smallest green space	Neusserplatz	0.1
Flat rooftops	10'210	

Table 4. Characteristics of the case study area

Inside the case study area, 149 green spaces were identified and 10'210 flat rooftops elements were considered as "opportunity" for implementing RA. The polygons of the green and urban areas were transferred into Rhinoceros 3D and Grasshopper using the Meerkat plugin. After the implementation of the pre-filtered geoformation data into Grasshopper, the data was processed and analyzed using several parametric models.

5.4. Parametric model "Green desert'

5.4.1. Definition of the Grasshopper model

The parametric definition aims to identify the urban areas where there is a deficit of green spaces. The objective is to target all the sectors where rooftop gardens could provide additional green areas in highly grey and urbanized sectors, thus increasing the even distribution of green spaces.

The necessary geometrical inputs are:

- **the green spaces polygons:** These are transferred to the grasshopper platform through the plugin Meerkat (converts shapefile into a set of polygons and lists);
- **a focus boundary (optional):** this polygon allows the planner to focus and run the model on a certain area of the city. This function is useful in the case of large urban areas where the processing of the data may become too slow.

The model was conceived in a way that planners can set the following parameters:

The accuracy of the outputs ("smoothness" of the boundaries of the key zones): the number of reference points for the calculation of the distances;

- The categorization of the zones as a "low", "medium" and "high priority" zone for greening: by setting the distance from the reference point to the boundaries of the green areas;
- **The accuracy and the quality of the final visualization**: by setting the distance between each contour line.

The outputs of the model are:

- A map which categorizes the different urban areas according to their distance to the existing green spaces: this is the visual display in the Rhinoceros 3D panel;
- The contour lines which delimitate the different urban space categories;
- the key roofs for increasing the even distribution of green spaces.

The PM was built in Grasshopper and offers a responsive visualization of the key zones with less green spaces. The goal of the mapping was to integrate the green roofs (elevated areas) as a substantial addition for a multi-levels green matrix. For this reason, the calculation of Air distances were chosen over Road distances. A grid of points was generated within a chosen focus area and delimited by a curve. The amount and distance between the points can be set accordingly. The more points the grid has, the more accurate and smooth will be the key zone boundaries. A buffer area was created around the focus in order to include into the calculation the nearest green areas which are located outside the study boundaries. The grasshopper model definition is shown in Figure 60.



Figure 60. Grasshopper definition of the PM "Green Desert": inputs (in red), parameter settings (in yellow) and the outputs (in green).

5.4.2. Case study

The case study zone is described in chapter 5.3. "Case study area in Vienna". The zone comprised 144 green spaces polygons with a total surface area of 308 hectares. 5'022 reference points were generated on a circular focus of 5'027 hectares (Figure 61). The accuracy of the model was 1 reference point per hectare.



Figure 61. The generated points grid on the circular focus area in the city of Vienna. The distances calculated from the reference points to the nearest green areas were comprised between 0 and 825 meters. The results are categorized as follows:

- "Low priority" zones (coloured in green): the distance from each reference point to the nearest green area is less 300 meters.
- "Medium priority" zones (coloured in yellow): the distance from each reference point to the nearest green area is comprised between 300 and 600 meters.
- **"High priority" zones** (coloured in red): the distance from each reference point to the nearest green area is greater than 600 meters.

The distance between each contour line was set to 25 meters. To highlight the key zones with fewer green areas, the contour lines were shifted on the z-axis based on their distance from each reference point to the nearest green area. Therefore, high peaks indicate the deficit of green spaces. After setting the parameters as mentioned previously, the visual output was displayed simultaneously into the Rhinoceros 3D panel (Figure 62).



Figure 62. (a) Panel for the visualization of the results; (b) Panel for the settings of the parameters.

5.4.3. Results of the mapping

The final mapping results are illustrated in Figure 63 below.



Figure 63. Study results for the case study of the city of Vienna (a) Visualization of the results; (b) Zoning of the case study area into 3 priority zones.

Among the 6 areas categorized as "High priority" zones, the model detected:

- 1) the surroundings of the "Stephansdom" (1st district);
- 2) the area on the west side of the station "Alser Strasse" (17th district);
- the zones on the south and west sides of the subway station "Wien Währinger Straße - Volksoper" (9th and 18th districts).

The flat roofs landscape was transferred into the PM in order to identify the key surface areas which were located within the priority zones. Figure 64 shows the identification results for the "high priority" zones and "medium priority" zones.



Figure 64. Study results for the case study of the city of Vienna. (a) Identification of the key flat roofs located within the "Medium" and "High priority" zones, (b) Identification of the flat roofs located within the "High priority" zones.

The results can be assessed visually using the mapping results. In the present case study, the height of the roofs was not considered. However, it is possible to import the key flat roofs into an

excel sheet which provides information about the roofs and the buildings (roof height, address, district,...).

5.4.4. Discussions

The PM "Green Desert" supports planners for the detection of the zones with a deficit of green areas. Since the PM is parametric, planners can rapidly adapt the parameters and conditions of the calculation. However, several points could improve this investigation process:

- The PM could be extended to more detailed datasets. The more accurate the GIS inputs are, the more precise would be the final output of the PM. As an example, the initial GIS data "Land use map" provided by the municipality of Vienna, does not include the location of green inner-courtyards, trees, existing green facades and green roofs. The integration of this information would provide a more accurate assessment of the urban areas with a deficit of green surfaces.
- Some errors were detected such as the Schutzhaus Zukunft auf der Schmelz in the 15th district of Vienna. Although this area comprises small houses with garden plots and allotment gardens, it was evaluated as a "high priority" zone for greening by the PM. This is the result of its initial classification as "Building Land use Residential area" by the Municipality of Vienna. Allotment gardens provide important ecosystem services to urban communities, including local climate and water regulation as well as habitat provision for biodiversity (Cabral, 2017). Privately owned green spaces play a role in enhancing the urban green infrastructure (Tahvonen, 2018). This shows that the land use map *Realnutzungskartierung* could be substantially improved by including information on the spatial qualities of the urban public and private spaces like in the present case, their function as a green corridor and stepping stone.
- According to the purpose of the investigation (ie. enhancing permeability in urban areas, habitat for biodiversity,...), planners could import different types of space opportunities

like roofs, facades, private spaces, or street areas. The PM can be a support for detecting the zones with a deficit of recreational areas. In this case, it would be relevant to use Road distances as a parameter for the evaluation.

5.5. Reconnecting the Green Corridors network

5.5.1. Parametric model "Location Density"

5.5.1.1. Definition of the Grasshopper model

The connectivity of the green patches is highly important for the resilience of the ecosystem. To calculate the connectivity of the green spaces, the research used the Location Density (LD) measure. The LD is considered as the most effective indicator for bee resilience and pollination (Marcus et al., 2014). The LD is a distance-based indicator which calculates the number of opportunities accessible within a fixed cost limit (Breheny, 1978). The LD is defined by the formula:

$$LD_i = \sum_j B_j h(C_{ij})$$

 B_i = the number of opportunities in zone j

$$h(C_{ij}) = \begin{array}{c} 1 & if \ C_{ij} \leq C \\ 0 & if \ C_{ij} \geq C \end{array}$$

 $C_{ij} = distance from origin i to destination$

$$C = con$$

The present chapter shows how to evaluate the Location Density of green spaces with the use of urban parametric design. The objective is to get a parametric mapping of the green areas based on their LD and size.

The necessary geometrical inputs are:

- the green spaces polygons (geometry and size): these are transferred to the grasshopper platform through the plugin Meerkat (converts shapefile into a set of polygons and lists).
- a focus boundary (optional): this polygon allows the planner to focus and run the model on a certain area of the city. This function is useful in the case of large urban areas where the processing of the data may become too slow.

The model was conceived in a way that planners can set the following parameters:

- the flight foraging distance (thus, the pollinator species considered): the flight foraging distance of bees varies according to the different species: 250 meters for solitary bees, 500 meters for wild bees, 750 meters for bumblebees and up to 3 km for honey bees (Steffan-Dewenter et al., 2002). In the case of the present case study, the flight foraging distance parameter was set to 500 meters, which is a suitable distance for most common pollinators (Gathmann & Tscharntke, 2002).
- the categorization settings of the Priority indicator, which combines the LD with the size of the green space: the size of the green area is the second important criterion for the parametric definition. Since the LD does not include the size of the patch of origin, the parametric mapping was based on a Priority Indicator, which associates the LD value with the size of the green areas. Table 5 illustrates the ranking matrix of the Priority indicator.

Priority indicator		Location Density (LD)			
		≥ 3	2	1	< 1
Size of	small <10'000	very low	Low	Medium	Critical
the green patches	e medium en 10'000 ≤ X < 40'000	Low	medium	High	Critical
(m²)	large ≥ 40'000	Medium	high	very high	Critical

 Table 5. Ranking matrix of the Priority Indicator based on the Location Density and the size of the green patches.

The green areas with a LD smaller than 1 were ranked as "critical" since these elements

do not have any connexion with the existing green corridors network.

The outputs of the model are:

- a map which categorizes the different green patches based on the Priority Indicator (as defined in Table 5);

a map of the existing Green Corridors Network (GCN)

To build the graph, the model integrated several components of the Spider Web Plugin (Schaffranek, 2016):

- "Graph from Points (undirected)": creates a graph from a set of points and connection distance;
- "Graph to Data tree (to Vertex List)": converts a graph to a data tree.

The Meerkat Plugin enables the transfer of the GIS data into the grasshopper platform (Lowe, 2015). Figure 65 displays the structure of the parametric model.



Figure 65. Structure of the parametric model "Location Density": inputs (in red), parameter settings (in yellow) and the outputs (in green).

5.5.1.2. Case study

The case study zone is described in chapter 5.4. "Case study area in Vienna". Figure 66 shows the process of mapping the existing GCN:



Figure 66. Modelling of the GCN for the present case study area; (a) Import of the green areas into the PM; (b) Delaunay triangulation; (c) Visualization of the existing GCN.

(a) the green spaces are imported into the model;

(b) the GCN is modeled by connecting the centers of each green space using the Delaunay triangulation method;

(c) the linkages with a length greater than 500 meters are removed.

The PM offers a visualization of the existing linkages between each green space and for a flight foraging distance of 500 meters. The existing GCN consists of a fragmented network of green patches inside the studied area. Several green elements are disconnected from the rest of the network as shown in Figure 67:



Figure 67. Fragmented green corridors network (generated using the Delaunay triangulation method).

The next step of the modelling consists in calculating and categorizing each green element based on the Priority Indicator.

5.5.1.3. Results of the mapping

Based on the previous outputs and the Priority Indicator, the PM mapped the following result (Figure 68).



Figure 68. Spatial distribution of the green elements based on their location density and size.

- The identification of the existing GCN in a highly urbanized zone of Vienna revealed a significant degree of fragmentation. 20 out of 149 objects were ranked as critical (this represents 13.42% of all the green spaces) and 21 objects were ranked with a high or very high Priority Indicator. For a location density equal to 0, the size of the green spaces remained smaller than 40'000m² (medium size).
- The PM "Minimum Spanning Tree" proposes one solution to reconnect the fragmented GCN based on a Minimum Spanning Tree and with the use of rooftop gardens as extra stepping stones. The objective is to create a network where no green areas are ranked as critical. Since the research focuses on the flat roof landscape, only these areas were considered as a potential addition to the existing network. Nonetheless, it is important to highlight that ground-level green areas could be also be considered as a complement to the GCN (as illustrated in STEP 2025).
- An additional weight could be specifically assigned based on the type of plants and vegetation cover of each green area. This aspect was not considered as relevant for the present case study. However, the parametric definition allows planners to integrate this factor into weighing system of the PM.
- 5.5.2. Parametric Model "Minimum Spanning Tree"
- 5.5.2.1. Definition of the Grasshopper model

To optimize the current GCN of Vienna 3 potential options were considered:

• Increasing the weight and/or attraction potential of the nodes :

by increasing the size of the green patches (enlarging the green areas); and by growing a diversity of native and pollinator-friendly plants

• Enlarging the network by creating new bridges (or stepping stones) between the isolated green nodes.

• Strengthening the nodes connectivity by increasing the LD value of the green spaces (ie. offering further possibilities to access a green node).

The present modelling phase focuses on studying the second and third options. In particular, the parametric model investigates how green patches can be all connected to allow a higher dispersion potential of pollinators with the use of extra "stepping stones", which are the rooftop gardens. More specifically, the objective is to increase the LD of the green areas which are ranked as "critical" (as identified in chapter 5.5.1.3. "Results of the mapping").

A few potential network typologies could be generated in order to close the green corridors network. The purpose of the present case study is to build up a set of edges connecting all nodes (green spaces) such that the overall sum of the edge length is minimized. To achieve this objective, the Minimum Spanning Tree with the greedy Kruskal's algorithm is chosen. Kruskal first described it in 1956: "Perform the following step as many times as possible: Among the edges [...] not yet chosen, choose the shortest edge, which does not form any loops with those edges already chosen" (Kruskal, 1956). This means that the algorithm finds an edge of the least possible weight that connects any two trees in the forest (Cormen et al., 2009).

This modelling process adapts the idea suggested in the research of 2014 for the city of Bologna, where scientists analyzed the potential impact of a GCN by connecting all flat rooftops with a predefined flight foraging distance (Orsini et al., 2014). Here, the PM detects the key positions for implementing RA in the perspective of simultaneously enlarging the existing GCN and strengthening the nodes connectivity. The parametric modelling process includes 3 consecutive steps:

- Step 1. Designing the Minimum Spanning Tree Network
- Step 2. Finding suitable flat roofs
- Step 3. Detecting the closest flat roofs to create the shortest bridges (ie. finding out the minimum amount of flat roofs which would be necessary to close the existing green corridors network).

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The results should be considered as a support for the further development of greening strategies. This approach gives the basics of a reflection on how green roofs can be linked to the green corridors network and can enlarge the existing urban biological system.

5.5.2.2. Step 1: Designing the Minimum Spanning Tree

The Spider Web Plugin generated the Minimum Spanning Tree network typology in Grasshopper. Figure 69 shows the fragmented network and the minimum spanning tree obtained after the application of the algorithm.



Figure 69. (a) Fragmented GCN based on the Delaunay triangulation method; (b) GCN based on the Minimum Spanning Tree.

The PM provides a visualization of the potential additional green corridors (ie. "Missing bridges" coloured in red in Figure 70). 40 Missing bridges (with a total length of 25.9 km) are necessary to close the minimum spanning tree network. Table 6 gives further details on the characteristics of the Minimum Spanning Tree GCN, the existing bridges and the missing bridges.

	Bridges (objects)	Length (km)
Minimum Spanning Tree GCN (Kruskal's algorithm)	148	54.42
existing bridges (length between 2 nearby green units ≤ 500m)	108	
Existing Network length		28.52
missing bridges (length between 2 nearby green units > 500m)	40	
Length of the missing bridges		25.9

Table 6. Characteristics of the generated green corridors network with Kruskal's Algorithm.

5.5.2.3. Step 2: Finding the suitable flat roofs

Figure 70 shows the process of filtering and identifying the suitable flat roofs that would be necessary to connect the isolated green nodes. This filter is adjusted on the proximity of the so-called "missing bridges".



Figure 70. (a) Implementation of the flat roofs filter, (b) Visualization of the selected roofs (in yellow) that could be used as "bridges".

3'492 flat roofs out of the 10'210 roofs of the studied area are identified as "suitable" (ie. within 500 meters from the center of the green areas). It is therefore interesting to find out which roofs would create the smallest bridge between the solitary green nodes.

5.5.2.4. Step 3: Selecting the closest flat roofs to create the shortest bridges

By generating a graph from the green spaces centers with the Spider Web plugin, it is possible to calculate the shortest path between the critical points. It was previously calculated that 40 bridges (with an overall distance of 25.9 km) are missing to close up the network. Since one stop is calculated per rooftop between each isolated green area, each constructed bridge is composed of two small bridges. In this "shortest path" simulation, 83 bridges with an overall distance of 25.9 km were identified to construct the Minimum spanning tree GCN. The length of the GCN was 54.42 km long. Results can be seen in Figures 71 and 72 and Table 6.



Figure 71. Final Minimum spanning Tree GCN according to the case study.



Figure 72. Zoom on the flat roofs identification.

Results

ftops 43	Selected Flat Rooftops	Elements
dges 83	New Bridges	Elements
roof 80	Bridges created with 1 roof	Elements
roofs 3	Bridges created with 2 roofs	Elements
dges 25.9	overall length of the new bridges	Km
dges 108	Existing bridges	Elements
dges 28.52	overall length of the existing bridges	Km
work 54.42	Final Green Corridors Network	Km

Table 7. Results of the case study.

5.5.2.5. Results and observations

The aim of the present study was to build up a set of edges connecting all nodes (or green spaces) such that the overall sum of the edge length is minimized. The model gives one possible solution, the Minimum spanning tree GCN, for selecting the hotspots rooftops. Only 43 flat roofs have been identified on 5'027 hectares of a highly urbanized area in Vienna. These results highlight the opportunities within the case study area and give a clear quantification of the green areas that are lacking to close the existing GCN. This amount of roofs to convert into gardens seems realistic and feasible on the scale of 5'000 hectares built area. It would be interesting to investigate the application of this PM in reality in order to monitor the possible improvements on site.

Figure 73 illustrates how the existing network "Initial green corridors network - **Initial GCN**" (a) was extended with the use of the key flat roofs and converted to a "Minimum Spanning Tree GCN - **MST GCN**" (b).



(B) Mapping of the green spaces based on the Priority Indicator





(C) Distribution of the green areas of the initial GCN and the MST GCN according to the LD value, the size and the Priority Indicator

Figure 73. (a) Initial GCN and MST GCN; (b) Categorization of the green spaces for the Initial GCN and the MST GCN based on the Priority Indicator; (c) Distribution of the green areas of the initial GCN and the MST GCN according to the LD value, the size and the Priority Indicator.

• Compared to the initial GCN, several green areas of the MST GCN performed higher LD scores (ie. the green patches increased their connectivity performance). The evolution between the initial GCN and MST GCN shows a decrease of -100% of green areas with a LD equal to 0. Green areas with a low LD indicator (LD=1) decreased by -41.18% compared to the initial GCN. There is also an increase of +14.47% of green areas which perform as high LD indicator, +26.47% of green areas with a medium LD indicator. Figure 74 illustrates the proportion of green spaces objects according to the Priority Indicator in the case of the initial GCN and MST GCN.



Figure 74. Distribution of the number of objects according to the Priority Indicator.

Although the size of the green spaces did not change, the results show that fewer green spaces have been ranked with a critical, high or very high Priority Indicator.

Two measures could be combined in the perspective of maximizing the performance of the GCN:

- enhancing the connectivity of the network by conceiving a MST GCN (as shown previously);
- increasing the size of the green areas in order to increase the weight potential of the green patches.
- The minimum spanning tree was chosen for this study. However, different network typologies could have been generated according to other simulation's objectives such as the Hierarchical network or the Least Cost to User (Hellmund & Cawood, 1989).
- The final GCN should be further analyzed and assessed by planners in order to complement the model with some additional key points. As an example, the MST GCN could be efficiently enhanced by adding a few more potential bridges as illustrated in Figure 75.



Figure 75. Final mapping and visual assessment of the potential green bridges.

 Apart from the results, it is important to underline a non-negligible aspect of the green corridors: the problematic of invasive species. When the dispersion of beneficial species such as pollinators can be facilitated by the improvement of green nodes connectivity, it also allows pest organisms to move around the green patches. When modifying any existing ecosystem structure and organization, other consequences have to be considered and managed.

The PM "Minimum Spanning Tree" should be considered as a support for decision-making. It is now important to extend the analysis to other influence domains such as food production.

5.6. Parametric Model "Food Production"

5.6.1. Definition of the Grasshopper model

The objective of the PM "Food Production" is to calculate the growing capacity of a given roofscape by combining GIS data with parametric modelling techniques. The model can be set according to two types of RA: **Open air and soil-based system** and **Rooftop hydroponic greenhouse (exclusively for flat roofs larger than 1'000m²).** More than just a visualization of the food production potential for each roof, the model also evaluates the best scenarios for maximizing the overall food production according to a selected number of roof units. The necessary geometrical inputs for the modelling phase are:

- **the urban flat roofs landscape:** each polygon is associated with a value from the GIS data which gives information on the size of the flat area on each roof (in m²);
- **a focus boundary (optional):** this polygon allows the planner to focus and run the model on a certain area of the city. This function is useful in the case of large urban areas where the processing of the data may become too slow.

The model was conceived in a way that the planners can set the following parameters:

- the number of roofs to be converted with the use of RA;
- the productivity yield of the two different urban agriculture techniques (in kg/m²);
- the minimum roof surface area of the flat roofs (in m²);
- the gross to net production area (in %): this factor relates to the areas on the roofs which would be necessary for non-productive purposes (access, corridors, ...). Its value varies according to the type of production (Soil-based system or Rooftop hydroponic greenhouse).

The outputs of the model are:

- the growing capacity (in kg/year);
- the key roofs location for maximizing the rooftop food production: these roof locations are divided into two categories 1) roofs with soil-based cultures and 2) roofs with hydroponic greenhouses.

Figure 76 displays the structure of the parametric model.

Food production model



Figure 76. Structure of the parametric model "Food Production": inputs (in red), parameter settings (in yellow) and the outputs (in green).

5.6.2. Case study

The case study zone is described in chapter 5.3. "Case study area in Vienna". The goal of the PM is to analyze the potential of the roof landscape surface for food production. Imported are every roof with a flat roof area superior or equal to 500 m² (ie. roofs with a smaller potential were considered too small for maximizing food production). Within the study focus, 4'491 roofs matched this condition. The following settings of the parameters were chosen based on Chapter 3.2. "Types of rooftop agriculture considered in the present research":

- the system "Rooftop hydroponics greenhouses" can produce around 29 kg/m² per year of vegetables;
- the system "Open air and soil-based" can produce around 5 kg/m² per year of vegetables;
- the gross to net production area factor was set to 0.65 for soil-based production and 0.73 for hydroponics production. The study considered that all surfaces dedicated for the personal, packaging, potential photovoltaic panels and food processing are not located on roof, but in rooms in the building below;

- the flat roof areas larger or equal to 1'000m², are associated with a Rooftop hydroponics greenhouse system. The flat roofs smaller than 1'000m², are associated with an open air and soil-based system.

5.6.3. Results of the mapping

Figure 77 shows a "Full use Scenario" which includes all the flat roofs larger than 500m² located within the focus. The height of the bars shows the amount of vegetables produced per year. The colour of the bars designate the type of rooftop agriculture assigned by the PM: in pink the hydroponic greenhouses and in blue the open and soil-based rooftop gardens.



Figure 77. "Full use" scenario: Visualization of the food production potential for the roofs with a flat surface potential greater than 500m².

In total, the implementation of rooftop agriculture (both hydroponics and soil-based cultures) would produce approximately **8'780 tons of vegetables per year for the full use scenario (ie.**

4'491 roofs are converted into rooftop agricultural surfaces). Based on the previous settings (yields, surface conditions,...), the following flat roofs are considered with the highest productive potential:

- Allgemeines Krankenhaus der Stadt Wien with a potential vegetable production of 633'290 kg/m² per year
- 2) The Ottakringer Brewery with a potential vegetable production of 237'351 kg/m² per year

3) The Wiener Stadthalle with a potential vegetable production of 224'961 kg/m² per year The successful implementation of a rooftop farm highly depends on the owner of the building, the structural condition of the roof and the existing building use. In the next chapter, the study includes a Feasibility indicator for the implementation of RA and integrates more information into the PM "Food Production".

5.6.4. Extension of the PM "Food production" with the Feasibility indicator

As described previously, due to a lack of data it was not possible to cross reference the flat roofs based on their date of construction and structural condition. However, the parametric definition of the PM allows the integration of this parameter if data is provided in the future. The Feasibility indicator was defined based on the building use, the size of the flat roof and the type of ownership (public or private). Since the two types of RA have very different kind of requirements, acceptability and benefits, the indicator was very dependent on the type of project:

• Feasibility indicator for the system "Rooftop Hydroponics greenhouse"

As described previously, this type of rooftop farming is profitable only for roof surfaces larger than 1'000m². Within the study area, 126 roofs were identified as larger than 1'000m² (Figure 78):



Figure 78. Visualization of the flat roofs larger than 1'000 m² and suitable for a hydroponic greenhouse in the case study area.

The Feasibility indicator was based on the suitability and potential acceptance of the hydroponics greenhouse projects on existing buildings. In the context of Vienna, the buildings were classified into 5 categories:

- Parking Use: usually has the highest potential for such a project because they have already an access to the roof, strong structural conditions and do not possess a high occupancy rate on the top of the building. Another strong advantage is the accessibility of the rooftop farm for the distribution of the products to the surrounding areas.
- Industrial and Retail Use: holds a great potential for the implementation of rooftop farms. Especially buildings with a food retailing use may have a higher acceptance rate and could use their roof as a productive area and the ground-level to sell directly the products to the customers.
- Education, Health, Sports, Culture Use: possesses a relatively high potential for rooftop farming. These buildings are usually owned by public institutions, thus the acceptance rate may be higher that private buildings especially when the project is planned as an educative and research space for children and seniors.
- Office Use: is considered as more limited for the implementation of rooftop farms than the other uses since the rooftop terraces are usually shared among the different private owners and it may be more difficult to negotiate the use of the space. If implemented, the rooftop project tends to be soil-based agriculture so that workers can enjoy a green rooftop. Hydroponic greenhouses would not be a priority.
- Housing & Mixed Use: has a low rate of acceptance for the implementation of such project. Multiple private owners and the preference towards soil-based gardening are the reasons why the suitability score remains "low" to "very low".

Based on these observations and the size of the roof units, the following matrix was defined (Table 8):

Feasibility indicator "Hydroponic greenhouse"		Building use					
		Housing & Mixed use	Office	Education Health Sport & Culture	Industrial & Retail	Parking	
Flat roof size in m ²	Small ≤ 2'000	very low (1)	Low (2)	Medium (3)	Medium (3)	High (4)	
	medium 2'000 <x≤6'000< td=""><td>Low (2)</td><td>Medium (3)</td><td>High (4)</td><td>High (4)</td><td>very high (5)</td></x≤6'000<>	Low (2)	Medium (3)	High (4)	High (4)	very high (5)	
	large > 6'000	Low (2)	Medium (3)	High (4)	very high (5)	very high (5)	

 Table 8. Ranking matrix of the Feasibility indicator for the implementation of rooftop gardens with a "Hydroponic greenhouses system" based on the building use and the size of the flat roof.

For each of the 15 categories, a feasibility criterion was associated and linked to the building polygons. The results aimed to prioritize the selection of roofs with a high feasibility criterion. The feasibility score was extracted and used for further analysis in Chapter 5.6.5.

• Feasibility Indicator for the system "Open air and Soil-based systems"

Soil-based and open air production are commonly preferred for self-initiated projects such as community gardens. This type of garderning does not require a very deep technical knowledge compared to hydroponic technologies. The production yield is much lower than hydroponics culture but the objective is usually oriented towards food education, social inclusion and community building. This type of projects allows the creation of additional green stepping stones which enhances the connectivity of the GCN and the urban green cover. The different values of the Feasibility indicator were associated with the 5 building use classes (Table 9).

Feasibility indicator "soil-based & open air system"		Building use						
		Housing & Mixed use	Office	Education Health Sport & Culture	Industrial & Retail	Parking		
Flat roof size in m ²	small ≤500	low (2)	very low (1)	medium (3)	very low (1)	high (4)		
	medium 500 <s≤2'000< td=""><td>medium (3)</td><td>low (2)</td><td>high (4)</td><td>low (2)</td><td>very high (5)</td></s≤2'000<>	medium (3)	low (2)	high (4)	low (2)	very high (5)		
	large > 2'000	medium (3)	medium (3)	high (4)	medium (3)	very high (5)		

Table 9. Ranking matrix of the Feasibility indicator for the implementation of rooftop gardens with a "soil-based and on building use and flat roof size.

The Feasibility indicator "Soil-based & open air system" will be further investigated in Chapter 5.8. "Integrated design of combined scenarios".

5.6.5. Integration of the feasibility indicator "Rooftop Hydroponics greenhouse"

To refine the results of the food production model, the feasibility criterion was integrated into the parametric definition. The objective was to identify the 100 most suitable roofs for maximizing food production with the use of hydroponic greenhouses. Figure 79 illustrates the mapping results:



the bars is proportional to the growing capacity and the colors corresponds to the feasibility indicator matrix. The colour attributed to each bar gives information of whether the roof has a very high, high, medium, low or very low feasibility indicator. The overall growing capacity is also measured: the implementation of this solution (100 largest roofs with a rooftop hydroponic greenhouse) would produce around 5'380 tons of vegetable per year. The view in perspective allows the user to visualize both the potential growing capacity (height of the bars) and the feasibility indicator for each roof unit.

Figure 79. Visualization (top and perspective) of the 100 roof units with the greatest growing capacity: The height of

5.6.6. Limitations

- The ranking of the Feasibility indicator was defined arbitrary and in the context of the city of Vienna. The values may change according to the urban context, the cultural background, the populations needs and interest in implementing RA. In addition, it is important to consider incentives program or policies existing in the city: commercial and industrial buildings may have the obligation to possess a green roof or photovoltaic panels. In this case, the Feasibility indicator should be ranked as "very high". These values can be adjusted accordingly and modified in the PM definition.
- The combination of the two systems (hydroponics and soil-based) on the same roof unit was not investigated in the present case study. The PM could be extended to this option.
- If available, the Feasibility indicator could be improved with the incorporation of the structural conditions of the roofs. As explained in the previous chapters, the GIS data of the construction dates in Vienna should be more detailed in order to have this level of detail in the calculations.
- The PM "Food production" showed only one potential of the flat roofs. It is now important to overlap the previous results with the outputs of the other PMs "Green Desert" and "Minimum Spanning Tree GCN". The objective is to detect spatial synergies where

selected flat roofs can provide multiple benefits simultaneously (ie. producing vegetables, closing the existing green corridors network and enhancing the green cover of highly urbanized urban areas). The next step consists in incorporating this parametric definition into a more developed PM which has the capacity to compute multi-objectives optimization (Chapter 5.8).

5.7. Optimization of the model on the roofscape of the region of Bangu and proof of concept

5.7.1. Case study area: the region of Bangu

Defining urban parametric tools requires the consideration of multiple criteria: cities are complex dynamic systems which differ highly according to their size, climate, conditions, and organization. Since the research aimed to produce a set of PMs which would work for a diversity of city roofscapes, it was necessary to test and optimize them on a different urban context. Among other aspects, the cities of Vienna and RJC differ on the size, the shape, the topography and the climatic conditions. The Lidar-based mapping showed that 1,384.5 hectares of flat surfaces located on roofs are available on 69% of the surface of RJC. This represents 11.2% of all the roofs considered. Based on a parametric models created for the city of Vienna, the present chapter investigates further this surface potential for the region of Bangu in RJC.

The Laboratory of Sustainable Actions (UNIRIO) hosted the research and the region of Bangu was chosen for the optimization of the models. The location of Bangu is illustrated in Figure 80.



Figure 80. The region of Bangu (including Vila Kennedy and Gericino) in 2018. From basemap Bing Maps Aerial 2018, https://www.bing.com/maps.

Bangu faces multiple challenges:

- very high temperatures: Bangu holds the record of 43.1°C in 1984, which is the highest temperature ever registered by the National Meteorological Institute or Brazil (INMET, 2019);
- the worst air quality in RJC in 2012 registered by MonitorAr-Rio (Silbar, 2013);
- a low Social development index (IDS) of 0.520. The IDS refers to the educational level, income, housing quality and level of basic sanitation (Cavallieri & Peres Lopes, 2008).

Bangu is one of the most populated districts of RJC with around 244'518 residents (in 2000) and presents an overall surface of 4'570.69 ha (IBGE, 2013). Although 58.2% of the surface area of Bangu was covered by vegetation in 2014, the spatial distribution of the green spaces is very uneven (Rio Prefeitura, 2014). The region presents large forests on the North and South zones (with the *Pedra Branca* state park) and a very dense urban center with little green spaces. In addition, Bangu also has high contrast of flat urban land with hilly green areas. A recent study showed that the region presents a very unique, dry and hot wind form due to the surrounding

mountains. The state park of *Pedra Branca* (on the south part of Bangu) creates a natural wall which blocks the cooling effect of the sea (Lucena, 2005).

The region needs to implement better greening strategies in order to improve the existing urban environment. As evaluated in Chapter 4.3. "The potential for rooftop agriculture in the city of Rio de Janeiro", the region of Bangu presents a relatively high flat roof potential of 158.8 ha. These surfaces could play a key role in constructing a larger and denser urban green infrastructure. Figure 81 shows the existing roofs of the region (a) and the flat roof landscape after filtering of the roof surfaces with an inclinaison inferior or equal to 5 degrees (b).



Figure 81. (a) View of the roof landscape of the region of Bangu including the zones of Vila Kennedy and Gericino, (b) The flat roofs landscape. From basemap Bing Maps Aerial 2018, https://www.bing.com/maps.

Due to the short research stay in RJC and the time required to detect the flat roofs based on the

LIDAR data, only two PMs were tested:

1) **The PM Model "Green Desert"**: detects and categorizes the zones with a lack of green

spaces;

 The PM "Minimum Spanning Tree": designs an optimized green corridors network based on the Minimum Spanning Tree.

The case study had 3 main objectives: detecting the areas in Bangu where there is a lack of green spaces (using the PM "Green desert"), proposing an optimized green corridors network solution using the flat roof landscape (using the PM "Minimum Spanning Tree") and simultaneously optimizing the existing PMs developed in Vienna.

5.7.2. Test of the PM "Green Desert"

• Settings of the PM

The workflow and the structure of the PM "Green desert" were described in Chapter 5.4. The categorization of the priority zones was based on the following settings:

- "Low priority" zones (coloured in green): the distance from each reference point to the nearest green area is less 320 meters;
- "Medium priority" zones (coloured in yellow): the distance from each reference point to the nearest green area is comprised between 320 and 680 meters;
- **"High priority" zones** (coloured in red): the distance from each reference point to the nearest green area is greater than 680 meters.

Parametric modelling process

Figure 82 shows the different steps of the parametric process for the case study of Bangu (from a perspective view).



Figure 82. Modelling process of the PM "Green desert" on a focus area of Bangu (Perspective View): (a) Selection of the green spaces; (b) Creation of a mesh: the height of each point of the mesh corresponds to its distance to the nearest green space; (c) Generation of the contours; (d) Categorization of the contours.

Based on the categorization of the contours, the model detected the 3 priority zones "low", "medium" and "high priority" (Figure 83(a)). Figure 83(b) presents the overlapping of the flat roofs landscape with the detected Priority zones.



Figure 83. (a) Detection of the 3 priority zones "low", "medium" and "high priority" with a lack of green spaces in the region of Bangu; (b) overlapping of the flat roofs landscape with the detected Priority zones.

Figure 84 illustrates the process of extracting the key flat roofs located within the "High Priority"

zones (ie. the distance from each reference point to the nearest green area is greater than 680

meters).



Figure 84. (a) identification of the flat roofs located within the High Priority zones; (b) extraction of the flat roofs polygons.

An excel sheet can be exported and gives further information concerning the flat roof such as the amount of square meters available for greenery per unit.

Results of the parametric modelling

The model highlighted 251 key flat roofs within the "High Priority" zones (ie. the distance to the nearest green area is greater than 680m):

- 1. The eastern side of Bangu in the proximity of *"Vila Vintem"* and at the border between Bangu and *Padre Miguel*
- 2. The surroundings of the Commercial center "Bangu Shopping"
- 3. The surroundings of the railway station "Senador Camara"

It is highly recommended to consider these zones for greenery (highly urbanized with little green spaces). The use of the PM "Green desert" on the region of Bangu did not require any major changes in its initial definition.

5.7.3. Test of the PM "Minimum Spanning Tree"

Settings of the parameters

For the parametric design of the GCN of the region of Bangu, the PM "Minimum Spanning Tree" was tested based on the pollination and seed dispersal requirements of bats. Frugivorous bats play a key role in the dispersal of seeds and support the plant recolonization of fragmented habitats and forests. They are able to transport seeds on long distances and therefore are considered as efficient seed dispersers (Fleming, 1986; Fleming & Williams, 1990; Galletti & Morellato, 1994). Flower-visiting bats have to capacity to carry large amounts of pollen and can travel great distances (Fleming et al., 2009). Implementing a network of biodiverse roofs provides bat habitat enhancement, key foraging locations and benefits urban bat populations on a long-term perspective (Pearce & Charlotte, 2012).

Brazil has one of the largest diversity of bat species in the world (Nunes et. al., 2017). The state of Rio de Janeiro is the home of 8 of the 9 bat families existing in Brazil, including 41 genera and 71 species (Esberard & Bergallo, 2005). The selection of the bats for the study was based on a personal interview with Prof. Avilla, Professor at the Faculty of Zoology, at the Federal University of the State of Rio de Janeiro. The chosen bat species were:

- the *Glossophaga Soricina* and the *Anoura Caudifera* (two common pollinator bats in RJC);
- the Artibeus lituratus and the Carollia perspicillata (two common fruit bats in RJC).

Figure 85 shows portraits of the selected bat species.



Figure 85. Portraits of the bats considered in the present case study. (a) Glossophaga Soricina; (b) Anoura Caudifera; (c) Artibeus lituratus; (d) Carollia perspicillata. From *Temporal variation in the organization of a neotropical assemblage of leaf-nosed bats (Chiroptera: Phyllostomidae)* by M. Mello, Acta Oecologia, 35(2), 280-286. Copyrights 2019 by Tuttle Merlin's bat conservation merlintuttle.org; 2009 by M. Mello.

The Artibeus lituratus and the Carollia perspicillata can travel relatively far away from their nest and disperse seeds on a wide perimeter, which is a great support for the reconstruction of green areas destroyed by human activities in RJC (Avilla, 2018). Carollia perspicillata has an average flight foraging distance of 1.6 km (Heithaus & Fleming, 1978). The Glossophaga Soricina have routes of approximately 250 meters, though some individuals were recorded up to 1.4 kilometers (Lemke, 1984). Unfortunately, data regarding the flight foraging distance of the Anoura Caudifera was not found. A flight foraging distance of 500 meters was chosen as a suitable distance for the dispersion of the selected bat species for the present case study. The types of green areas in Bangu listed as attractive for these bat species are mapped in **Appendix 12. "Distribution of the selected green areas for the design of the green corridors network in the region of Bangu**" (Avilla, 2018).

Modelling the existing GCN in Bangu

The selected green areas (ie. considered as profitable for the bat species) were extracted in ARCGIS and imported as a shapefile into the PM "Minimum Spanning Tree". The existing GCN

was designed by connecting all the green spaces within a maximal distance of 500 meters from each other. Since several polygons had a very large size, a series of points on the boundaries of the areas were taken as reference points for the connexion between the polygons. Figure 86 shows the results of the modelling process.



Figure 86. Modelling of the existing GCN of the region of Bangu. (a) spatial distribution of the green areas; (b) Existing GCN connecting every green area within 500 meters.

Connecting every green space with a flight foraging distance of 500 meters resulted in a green corridors network of 67.1 km. The existing GCN links two large green areas (the forest of Bangu North and the *Parque Estadual da Pedra Branca* in the south) with a few green patches and a long river stripe. Mostly scattered and thin, this network could be enhanced with the strategic implementation of rooftop gardens. The objective of the further modelling steps was to define scenarios for:

- modelling and/or closing the existing GCN for the region of Bangu by connecting all the green patches with the use of the flat roof landscape

- detecting the key flat roofs which would densify the existing GCN.

• Scenario 1: "Full use" scenario by using all the flat roofs larger than 100 m²

Based on the previous modelling settings, the roofs landscape of Bangu was imported into the PM (Figure 87).



Figure 87. Network modelling using all the flat roofs larger than 100m².

The PM estimated that greening all the flat roofs larger than 100 m² (which represents 1'064 roofs), would extend the existing network with an extra length of 77.2 km. The network would be 2.15 times longer than the initial one and would sprawl across a larger region (Figure 93). However, this amount of rooftop gardens is very high and it would be very challenging to apply this scenario in Bangu.

• Scenario 2: "Closed GCN" scenario

As described in Chapter 5.5.2., the PM uses a Minimum Spanning tree network typology for the detection of the "isolated green patches" and the definition of the "missing bridges". Figure 88 illustrates this process on the region of Bangu.



Figure 88. Identification of the isolated green patches and detection of the flat roofs (>100m²) which are suitable for reconnecting the GCN.

The model identified two isolated green areas within the network: *Praca da Fe* (1) and the children's playground of the *Escola Municipal Professor Celia Martins Menna Barreto* (2). To connect these two green areas to the rest of the GCN, 2 roofs would be theoretically necessary. Depending on the desired density of the green connexion, the planner can select more roofs in proximity of the two missing bridges in order to densify the connexion between the patches. This scenario shows that the current definition of the PM "Minimum Spanning tree" is not very adapted for the region of Bangu, since the process of closing the network would only lead to minor changes in the spatial configuration of the GCN. The network of Bangu is very thin and it would be interesting to look at ways for densifying the network rather than finding scenarios which connect every isolated green patch into one large network. Scenario 3 explores this solution.

• Scenario 3: "Densified green corridors network" scenario in the proximity of the river of Bangu

The long river stripe crossing Bangu appears to be a strategic route for connecting the two large forests of South and North of Bangu. This route could be improved by enhancing the width of the corridor or the density of the green patches in its proximity. Figure 89 shows a test example on how the GCN could be strategically densified by using all the roofs larger than 100 m² and located within 500 meters from the river stripe.



Figure 89. Test for the densification of the GCN. (a) Selection of the flat roofs located within 500 meters of the river and visualization of the connectivity of the existing GCN; (b) Visualization of the newly generated GCN using the key flat roofs.

In this case, the network was densified by using 172 flat roofs. The design is parametric and can be easily adapted by selecting fewer flat roofs and observing directly the network scenario outputs. The PM also offers the possibility to import street-level surfaces (ie. unused areas which could be greened and support densification of the existing GCN).

• Scenario 4: Extension of the GCN based on the GIS data "key hot areas":

Since the region of Bangu experiences frequent heat waves, a test was also made for integrating the "key hot areas", which were identified by the municipality of RJC based on the Land Surface Temperature recorded in Bangu in september 2015 (Rio Prefeitura, 2015). The results presented the flat roofs located within these hot areas and how the greening of these roofs would enhance the existing GCN connectivity. The results are displayed on Figure 90.



Figure 90. (a) Integration of the land surface temperature information into the PM; (b) Results of the GCN connecting green areas and the roofs located in the key hot areas.

The model considers that every edge touching these areas should be prioritized. The network is remodeled accordingly and 1'021 flat roofs out of 1'064 roofs are filtered. This represents 40.75 hectares of additional green surfaces distributed on 1'021 flat roofs.

5.7.4. Discussions and conclusions

These 4 scenarios could be considered as a support for decision-making in planning the urban green infrastructure of Bangu. The PM gives the basics of a reflection on how rooftop gardens can be linked to the existing green corridors network and enlarge the urban biological system of Bangu. Since the definition of the grasshopper model is fully parametric, it is possible for planners to generate other networks by setting differently the three following parameters: the size and the amount of flat roofs, the flight foraging distance (thus the type of pollinators considered) and the minimum land-surface temperature (defined as key "hot areas"). The increase of connexions between the green patches would allow a higher dispersion potential of the bats. Below a few observations and recommendations regarding the outputs of the tests of the PMs on Bangu:

Improvements of the parametric definition of the PMs

The design of the scenarios for the GCN in Bangu as well as the analysis of the "green desert" led to the following improvements of the program capacity such as:

- accuracy of the system to define the starting and ending points of the corridors;
- automated separation of the large and small green spaces into two groups for a specific processing of the PM from small parks to large forests. Bangu presents very large green polygons. Since the model was initially based on the center of the polygons, some forests were ignored in the first test calculation. Therefore, the model was optimized by using the control points of the polygons rather than their center to identify and target more precisely the large green areas;

evaluation of the key surfaces for densifying an existing GCN (first prototypes);

Besides these points, the processing of the data did not encounter major obstacles. The 2 PMs proved to be capable to process a larger amount of GIS data than in the case study of Vienna. By combining and confronting the results for another urban system, the modelling process

improved the model definition; and hence developed its capacity to larger and more complex city shapes.

• Recommendations and further steps

- The region of Bangu has high contrast of flat land with hilly green areas. The topography of Bangu has an influence on the cooling effect of the green areas in the district and increases the distances between the green areas. It would be interesting to import the topography of the area (DTM) in order to get a more accurate response of the PMs (ie. distance-based calculation).
- The PM "Food Production" was not tested on the Bangu. However, it seems relevant to analyze the contribution of RA in the perspective of tackling food security challenges in Bangu. In addition, the use of roof greenery should integrate edible plant species which are resistant to high temperatures.
- It would be interesting **to combine the results of the different scenarios**. This would give an idea of which flat roofs are simultaneously within the zones with a high land surface temperature and the zones with fewer green spaces. This approach will be explored in a multi-objective model in the last chapter of the present thesis with the case study of Vienna.
- Finding opportunities to close the network is important and the use of street-level areas and unused spaces is strongly recommended in the region of Bangu. Vienna has a really dense city center where such spaces are not usually available, reason why the model integrated only the GIS-data of the flat roofs. On the contrary, in Bangu, the strategy of greening roofs should be secondary compared to the implementation of green parks. It would be now interesting to combine the roof greening solution with ground-level greening. Parks, green facades, rooftop gardens are potential extensions of the green cover. Acquiring GIS data about the unused spaces on the street level

would give a more complete approach to the greening capacity of Bangu. Since the PM can compute any kind of zones or surfaces considered as a potential interest by the user, this integration of data could be performed. The area possesses quite a few areas with no clear purpose. Based on the crucial zones mapped by the model, these street-level areas could be greened and provide large extra green surfaces in the region.

Finally, the outputs of the PMs should be approached from two perspectives:

(1) Empty and unused spaces on the street-level in the key identified zones should be prioritized since these areas are cheaper and more accessible to green than flat roofs. These actions could be initiated by the municipality and coordinated with the inhabitants in order to better understand the social context of the defined areas.

(2) As a complement to the greening of the street-level key zones, roof greening should **be considered**. Revealing the potential on roofs to increase the greening coverage in the area could be a key indicator for the municipality to develop roof greening incentives. Most of the buildings have a residential use, therefore a bottom-up approach is strongly recommended.

5.8. Integrated design of combined scenarios

5.8.1. The PM "Detecting spatial synergies"

The goal of the PM "Detecting Spatial Synergies (DSS)" was to combine and identify the spatial opportunities within the flat roof landscape by overlapping the results of the three parametric models: 1) PM "green desert", 2) PM "food production" and 3) the PM "Minimum Spanning Tree". The superposition of the different layers revealed a set of roofs which have, simultaneously, a high potential for maximizing the food production, for rebinding the fragmented green corridors network and for creating an even distribution of the green areas in the city. The present case study was based on the results of the PMs obtained for the city of Vienna in the previous chapters. Concerning the PM "Food production", the results analyzed in the present modelling test corresponded to the outputs which were obtained with a "soil-based and open air system".

Results of the PM "DSS" for the matching conditions PM "Green Desert" and PM "Minimum Spanning Tree"

The model tested the overlap of the results of the PM "Green Desert" and "Minimum Spanning tree". Within the case study area:

- 1'287 roof units were identified as key surfaces for an even distribution of the green cover
- **3'492 roof units** were detected as opportunity to close the fragmented GCN.

The goal was to identify if some roof units match simultaneously the two conditions. These two maps presented very different results: the first one identified the roofs that were as far away as possible from the existing green areas; on the opposite the second model model calculated the closest way to rebind the green corridor (ie. the selected roofs were often located in the surroundings of green parks). This overlapping process showed that only **215 roof units** are suitable for both conditions. Figure 91 illustrates the mapping results:



Figure 91. Identification of the 215 roof locations matching the conditions of the PM "Green Desert" and PM "Minimum Spanning Tree".

• Results of the PM "DSS" for the matching conditions of PM "Green Desert", PM

"Minimum Spanning Tree" and PM "Food Production"

Similarly, the 215 outputs of the previous identification were matched with the results of the PM "Food production" (Figure 92).



Figure 92. Mapping of the 3 roof locations matching the conditions of the PM "Green Desert", PM "Minimum Spanning Tree" and PM "Food Production".

Only three roof units matched with the conditions of the three parametric models:

- The school Kooperative Mittelschule at Pfeilgasse
- The main building of the Department of Pediatrics and Adolescent Medicine at the Universitätsklinik für Kinder- und Jugendheilkunde at the Währinger Gürtel
- The storage warehouse of the Wiener Linien tramways at Wattgasse

According to these settings, it was also possible to include or exclude some of the roofs based on feasibility, structural conditions as well as if the buildings are under monument protection. A suitability matrix was created accordingly: if a roof scored 0 condition, 1 condition, 2 conditions or 3 conditions. Each condition related to the output of one of the PMs (GCN, Green topography and Food production). The final mapping is presented in Figure 93.



Figure 93. Locations of the key roofs for RA according to the modelisation results (Top and Perspective Views). The PM "Detecting Spatial Synergies" overlapped the different results outputs of the 3 PMs and provided accurate results of the key locations for RA.

These results are satisfying for supporting decision-making in selecting the best roofs based on the growing capacity. However, this "roof per roof" analysis does not have a very large outlook of the potential influence on a larger scale: this method gives results per roof unit and does not take into account the potential of scenarios as the combination of several roofs greened simultaneously. This is an important point since the outputs of the model "Green Desert" and "Minimum Spanning Tree" highly depend on roof combinations rather than single roof unit solutions. The PM "Wallacei", based on a multi-objective optimization definition, was therefore created and aims to define the best combination strategies for RA.

5.8.2. The PM "Wallacei"

5.8.2.1. Definition of the multi-objective optimization program using Wallacei

The PM "Wallacei" was created with the plug-in Wallacei in Grasshopper. This plugin is an evolutionary engine that allows users to run evolutionary simulations and solve complex multiobjectives optimization problems. Wallacei requires several inputs in order to calculate and find the best sets of scenarios from a large amount of scenarios (Wallacei, 2019). Each scenario is distinct and defined by the combination of a fixed number of flat roofs units to be converted into rooftop gardens. The PM objective was to find the key scenarios which presented the greatest growing capacity (in kg/m² per year), the highest feasibility (calculated as the average value of the feasibility indicator of every roof of the scenario) and the largest extension of the existing GCN (in meters).

The "Gene" used for the multi-objective optimization was the indice of a list of pre-generated scenarios. The larger the test sample size is, the more accurate the overview of the key scenarios will be. For this purpose, the PM generated random and distinct scenarios in order to reach a test sample size large enough for getting the best combinations. In the present case study, the size of the test samples was set to 1'000 solutions. This amount of scenarios was considered as sufficient for the test. However, the PM"Wallacei" is a test model and should be improved in order to increase its capacity to calculate a larger amount of scenarios. The case study was based on a focus area of the city of Vienna, which was used for the previous PMs. The multiobjective optimization process was based on:

1. Inputs

- The flat roofs polygons with their attributes:
- Monument protection and World Heritage ("P_WELKULT"),
- Building Use (as defined in Chapter 5.6),
- Feasibility indicator (as defined in Chapter 5.6.4)

- Flat roofs surface area ("GREEN_AR05")
- a focus boundary (optional): this polygon allows the planner to focus and run the model on a certain area of the city. This function is useful in the case of large urban areas where the processing of the data may become too slow.

2. Filters by boolean

The PM "Wallacei" allows the user to filter the flat roofs units based on selected attributes such as "World Heritage Site", Building Use" and "Structural Conditions". The boolean values are the two constant objects "True" and "False". The 3 filters were triggered thanks to the creation of several gates which can be activated or deactivated using a boolean toggle. Additional filters can be inserted into the definition according to the city context, the data available and the requirements of the user. Below an overview of the filters which were created:

• FILTER 1. World Heritage Site and Protected Zones (optional, triggered with a True/False):

Corresponds to the GIS Attribute "P_WELTKULT" =100 *"Weltkulturerbe und Schutzzonen"*; Null if = -1. This filter enables the selection between:

"true": only non-protected buildings,

"false": both protected and non-protected buildings.

The filter is relevant in the case of the city of Vienna where 4.7% of the building stock is protected (3'548 buildings). The recommendation on Historic Urban Landscape of the Unesco World Heritage includes the following statement:

"Concern for the environment, in particular for water and energy consumption, calls for approaches and new models for urban living and ecologically sensitive policies and practices aims at strengthening sustainability and the quality of urban life. Many of these initiatives, however, should integrate natural and cultural heritage as resources for sustainable development" (UNESCO 2011, sec. II, para. 17). This illustrates the "legitimacy" for rooftop gardens projects to be constructed on protected buildings in Vienna if they comply with the requirements concerning environmental sustainability of the UNESCO committee. The question of monument protection was not highlighted as a major barrier during the interviews with the municipality of RJC (Prefeitura Rio, 2018).

• FILTER 2. Building Use (optional, triggered with a True/False combined with a code for each building use):

The filter allows the selection between:

"true + Code of the Building Use": includes only the buildings classified in the category of the Code. The codes are for the uses Housing & Mixed use; Office; Education Health Sport & Culture; Industrial & Retail; Parking.

"false": includes all buildings without taking into account the building use.

These criteria remain crucial for the implementation of RA initiatives, both in Vienna and RJC. For example, it has been largely acknowledged during interviews that public buildings (such as the category "Education Health Sport & Culture") are more likely to be converted into rooftop gardens than private buildings.

FILTER 3. Structural conditions of the roofs (optional, triggered with a True/False)
Based on the date of construction, the constructive feasibility could be deduced based
on the building use classes, the construction date of the buildings and the requirements
of the associated building legislation. The structural condition of roofs always requires an
on-site investigation. In the present case study, accurate GIS-data was lacking for the
integration of this indicator into the PM (as described in "Chapter 3.4.3. Building and roof
structure"). Therefore Filter 3 could not be used for the present case study. However, if

the *Magistrat Wien* provides more detailed data about the date of construction, the PM could easily integrates this condition.

3. Parameters

- The number of roofs per scenario (in unit): the planner can adapt the length of the scenarios to be tested
- The maximal connexion distance of the green corridors network (in m)
- Productivity yield of the open-air & soil-based system (kg/m²/year) and the gross to net production area (in %)

4. Gene: the indice of a list of pre-generated scenarios

The gene is the numerical value that Wallacei tests in order to produce the various scenarios. In the present case study, the gene was the indice of the scenario tested and its value varies between 0 and 999 (since 1'000 solutions are tested). The list of scenarios was conceived in a way that the population of random number had distinct values (ie. no identical values). A grasshopper definition was created in order to generate this set of combination scenarios. Here are the two conditions for the generation of the scenarios:

• there are no repetitive indices within each set. For instance, the set (1,4,1) is not correct because there are two times the index "1",

AND

each scenario is unique (hence the position of the indices in the list does not matter). For instance: if the set (1,2,3) appears, the model won't generate the sets (2,1,3) or (3,1,2) or (2,3,1). Hence, if the numbers 1, 2 and 3 appeared together, the next possible set could be (1,2,4), (4,2,3), etc.

In combinatorics, these scenarios (also referred as r-combination) can be calculated based on the binomial coefficient formula:

$$\mathcal{C}(\boldsymbol{n},\boldsymbol{r}) = \frac{\boldsymbol{n}!}{(\boldsymbol{r}!\,(\boldsymbol{n}-\boldsymbol{r})!)}$$

For $n \ge r \ge 0$: The number of "r" elements in the sample has to be inferior to "n" elements and superior or equal to 0.

The formula shows us the number of ways a sample of "r" elements can be obtained from a larger set of "n" distinguishable objects where order does not matter and repetitions are not allowed. "The number of ways of picking r unordered outcomes from n possibilities." (Zwillinger, 2003).

Since there is a large number of potential scenarios, the planner must frame the selection of the roofs according to the 3 filters previously listed.

5. Fitness Objectives: The goals of the optimization

The Fitness Objectives (FO) is the "score" by which Wallacei will rank each scenario. The present case study included 3 different FOs:

- FO1 / Fitness Objective 1 "Maximizing the average feasibility indicator" (as defined in Chapter 5.6.4.)
- FO2 / Fitness Objective 2 "Maximizing the length of the GCN" (in meters)
- FO3 / Fitness Objective 3 "Maximizing the growing capacity" (in kg/m²/year)

All scenarios were ranked according to the combination of the 3 fitness values.

6. Outputs

 A set of key scenarios for RA based on a target urban area and the rankings of the 3 FOs. For each combination scenario:

- The amount of square meters of additional green surfaces (in m²)
- The growing capacity (in kg/m²/year)
- The extension of the green corridors network (in m)
- The average of the feasibility indicator of each selected roof

Figure 94 gives an overview of the structure of the model.



Figure 94. Overview of the multi-objective model setup. (a) Visualization of the selected combination scenario, (b) Structure of the parametric model.

5.8.2.2. Case Study

Every roof with a flat area larger or equal to 1'000 m² were imported. In Vienna, the model detected 1'849 roof units which match this condition. The goal of the test was to find out the key combination scenarios for greening a set of 15 key flat roofs out of the 1'849 flat roofs stock capacity. The Wallacei plug-in was set up to 50 generations with a size of 20 combinations for each generation. The total population included 1'000 random and distinct scenarios. For each solution, the runtime was around 2 seconds. Several options can be set according to the wishes of the user. In this test, the following settings were taken into account:

- the model focused on the previous case study area defined in Chapter 5.3
- the model included only the roofs where the buildings underneath has an "Housing & Mixed Use" (Filter 2)
- Only 2.6% of the 1'849 roofs were classified as Cultural Heritage or protected monuments. The model included all the flat roofs without taking into account the World Cultural Heritage and Monument protection requirements (Filter 1).

The Multi-objective optimization evaluated the score of the 1'000 scenarios regarding the three Fitness Objectives: capacity of maximizing the growing capacity, maximizing the average feasibility indicator and maximizing the extension of the existing GCN. Figure 95 illustrates the working panel for the present case study.



Figure 95. Screenshot of the working panels for the multiobjective test. For the calculation, the following parameters were applied: the "Gene" is the index of the tested scenario and the 3 "Fitness Objectives" are (1) maximizing the average Feasibility, (2) maximizing the length of the GCN and (3) maximizing the Growing Capacity.

5.8.2.3. Results of the parametric modelling

Wallacei computed the 1'000 combination scenarios and provided a visualisation of the results

(Figure 96).



Figure 96. (a) Standard deviation graphs of the first and last 50 tested generations based on the 3 fitness objectives. The standard deviation graphs show for each fitness objective how the values are changing around the mean of the dataset. This graphs give information on how the scenarios for each FO are spread out from the average (mean) value; (b) Distribution of the solutions within the "Objective Space".

From left to right (Figure 96(a)):

- FO1 / Fitness objective 1 "Maximizing the average feasibility indicator"
- FO2 / Fitness objective 2 "Maximizing the length of the GCN"
- FO3 / Fitness Objective 3 "Maximizing the growing capacity"

The flatter the curves are in each graph, the higher amount of variations exist for each generation. The variation degree was calculated according to the difference between the maximum and minimum results for the whole generation of 20 solutions. In the case of the present study, the variations were rather small between each generation for the fitness objective 1 "Maximizing the average feasibility indicator". This means that there were no significant performance differences for the FO1 between each RA scenario.

The Objective Space gave a spatial visualization of the performance of each scenario based on 3 axis, which were the 3 fitness objectives previously set. Figure 96(b) shows the distribution of the 1'000 combination scenarios according to the 3 fitness objectives. The full report of the 1'000 solutions for each of the fitness objectives is provided in **Appendix 13. "Data Visualisation of the results produced by Wallacei of the 3 fitness objectives".**

The next step consisted in cross referencing the data results and extracting specific solutions from the population. Planners have the possibility to:

- select the combination scenario they would like to evaluate by calling the reference of the scenario (Option 1: Manual selection of the scenarios);
- extract the scenarios with the highest scores within the set (ie. the best performances for the combination of the 3 FOs) (Option 2: Best combination scenarios for the 3 FOs).

Option 1: Manual selection of the scenarios

Figure 97 illustrates the performance of the manually selected scenario № 100 (number 5 of generation 20):



Figure 97. Graphic information of the solution 5|20 according to the modelisation results.

The graph gave a clear visualisation of the performance of the RA scenario for each fitness objective with a "Diamond Fitness Chart". The Diamond Fitness Chart compares to what extend the different fitness objectives for this specific solution are optimized. The closer the FO is close to the center of the triangle, the fitter the scenario is for the selected FO. In this case, the solution № 100 is very fit for FO1 and FO3 but very not optimal for FO2 (the growing capacity is low). The ranking of the scenario for each FO is also given.

Option 2: Best combination scenarios for the 3 FOs

It is possible to extract the best ranked solutions by simply adding the rank of the scenario within the 1'000 solution sample. After evaluating each of the solutions, the model detected 3 combination scenarios which performed the best (Figure 98):






Figure 98. The 3 best combination scenarios according to present case study and with the use of the PM "Wallacei". The scenarios showed that selecting one of the detected combinations of 15 roofs for RA could extend the existing GCN with approximately **11 kilometers** and produce around **73 tons of food per year** (using a traditional soil-based system). The average Feasibility indicator laid around **2.2** which is between "low" a "medium" score. This is not a surprise since the selected type **"Housing & Mixed-use"** present a low feasibility due to the fact that the rooftops are generally a multi-owned property. The calculation also showed that choosing one of the 3 key scenarios could provide approximately **9'200 m²** additional green surfaces in Vienna. This test was run for a scenario of 15 roofs and with the test of 1'000 potential solutions. These settings can be easily modified according to the wishes and budget capacity of the city planner.

Appendix 14. "The 9 best combination solutions according to the Wallacei modelling test" showed the 9 best solutions of the case study. If necessary, the attributes of the flat roofs can be also extracted for complementary information.

5.8.2.3. Further scenario tests

The test proposed the scenario of transforming 15 roof units into rooftop gardens. It is now interesting to look at the full potential of the roof landscape for RA. The model can give a fast and precise feedback on what advantages this conversion would provide. Below some examples with the potential outputs:

1) 100% use of the roofs of the Buildings with a "Housing & Mixed-Use" (flat roof areas are larger than 1'000m²) (Figure 99):



Figure 99. "Full use" Housing Building Scenario for the flat roof surface areas strictly superior than 1'000m².

2) 100% use of the roofs of the "Education Health Sport & Culture" Building Use (flat roofs areas are larger than 1'000m²) (Figure 100):



Figure 100. "Full use" Education Health Sport & Culture Building Scenario for the flat roof surface areas strictly superior than 1'000m²

3) 100% use of all the roofs which are not protected by the Cultural Heritage and monument protection (flat roofs areas are larger than 1'000m²; 98 roofs) (Figure 101):



Figure 101. Scenario for all the buildings which are not protected by the Cultural Heritage & Monument Protection and with a flat roof surface area strictly superior than 1'000m²

The previous results were based on the equal weighing of the fitness objectives. However the PM also offers the possibility to add a coefficient on each of the FO. Therefore, the exploration of the scenarios can be controlled by the user according to configuration of weighted fitness functions.

5.8.2.4. Observations on the PM "Wallacei"

• The study considered that 1'000 solutions is a sufficient number for getting some of the key scenarios for RA. It is important to note that Wallacei is not very adapted for doing

systematic searches since it is a stochastic solver. This means that the order of states its examination process is very unpredictable. However, the plug-in can handle very large test sample in a very short amount of time (each solution was computed with approx. 1 second runtime).

The simultaneous evaluation of multiple and competing goals could support decisionmaking in the development of roof greening strategies in an ever-growing urban environment. Besides supporting greening strategies, the model offers a multiparametric visualization and quantification of what the urban roof landscape can offer in terms of growing capacity, GCN connectivity and green cover expansion. Therefore, the PM aims to trigger ideas and to show what could be achieved with the use of RA. The goal is to encourage the development of policies and incentives which would facilitate the implementation of urban agriculture initiatives.

Chapter 6. Conclusions

6.1. Summary of the research contributions and products

The research project is innovative:

- on a technical level: The work provides an outlook on the different spatial opportunities of the city and how their combination could maximize the potential benefits of the existing urban green infrastructure (Figure 102).



Figure 102. Finding spatial synergies by overlapping the different layers of complexity of the city.

The study provides technical tools for planners, architects and city officials to analyze the urbanscape and define strategies for prioritization mapping and greening policies. The study also describes numerically, the interdependency between several parameters and quantifies the value of each scenario which is tested such as the potential growing capacity, the enhancement of the green corridors network or the feasibility of the project. The two types of green surfaces (upper and ground level) are combined in order to propose relevant pinpoints strategies. This promotes micro-targeting, low cost and selective interventions rather than extensive and expensive greening projects. The idea is to tackle urban problems at appropriate pressure

points and to produce small-scale (the rooftop gardens) but environmentally catalytic interventions.

- on a planning process and decisional level: By investigating the applicability of parametric design optimization processes over the traditional city design process, the research bridges disciplines via the parametric models. The models enable planners to process a multitude of alternatives during the design process by interconnecting and coordinating design components simultaneously. Based on the tool results, the idea is to collectively create plans to green the city roof landscape. This social and ecological sculpture will be crucial support for rebinding the fragmented green infrastructure in highly urbanized cities.

The four main research contributions of the PhD study are:

1) The Lidar-based mapping of the flat roofs and terraces on 69% of the surface area of RJC "Mapping of the potential for rooftop agriculture in the city of Rio de Janeiro". The research explored the multifaceted benefits associated with the implementation of urban agriculture on roofs in RJC. The city has challenges in terms of food security, urban sprawl and the fragmentation of the green infrastructure. Based on the inclination and the geometry of the roof surfaces, the mapping process showed that 1'383 hectares of roofs would be suitable for RA on 69% of the surface of RJC (without taking into consideration the structural conditions of the roof surfaces). This productive roof area could produce enough food to meet the yearly demand for vegetables of 39.2% of the inhabitants of the city. The study also demonstrated the great relevance of implementing RA in the poorest communities of RJC in the perspective of tackling food insecurity. In RJC, around **1,4 million** people were living in slums (*favelas*) in 2013. Therefore, the results show that if the city transforms **only 53% of its flat roof landscape** into rooftop gardens, **it would provide enough vegetables to feed annually all the inhabitants of the slums.** In addition, It would stimulate better food education and provides fresh vegetables directly in and by the households. From fall 2019, the digital map will be

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available on the platform of the municipality "SIURB.Rio". The map is not only directed to policymakers and city planners but also to property owners who could start a dialogue with greening and potential farm tenants.

2) The elaboration and the successful test of a workflow method which combines GIS applications with parametric modelling techniques. The study provides knowledge on how urban parametric design could be used to detect opportunities within an existing urban landscape and based on GIS data. The analysis of the previous modelling results showed the potential and the limitations of the study workflow. This workflow complements current developments in urban parametric modelling and bridges the gap between landscape ecology, urban biodiversity conservation and city planning.

3) A set of parametric tools which encourages urban planners to analyze green spaces

and integrate rooftop agriculture into their greening planning strategies. The developed set of tools successfully explored the urban green envelope and its potential connexions with the roofscape using Grasshopper, which is an accessible and user-friendly platform for parametric investigations. These tools allow the flexible examination of scenarios based on a large amount of polygons with distinct attributes. By combining the quantitative parameters constituting the design (ie. the green and blue infrastructure, the flat roofs...) and the potential interrelations between these elements, the parametric models generate quickly multiple design variations. Based on a selected area or city, the functions of the parametric models are:

- the parametric mapping of the crucial areas with fewer green spaces (PM "Green **Desert**"). The model definition is based on the proximity of the green spaces;

- the evaluation of the location density and the analysis of the fragmentation (PM "Location Density") of an existing urban green envelope (based on the type, location and size of the green areas);

- the design of an optimized green corridors network (PM "Minimum Spanning Tree") "reinforced" with the use of selected rooftop gardens identified as strategic stepping stones. The model definition is based on the Kruskal's minimum spanning tree algorithm;

- the calculation and the visualization of the growing capacity of the flat roof landscape combined with a feasibility indicator (PM "Food Production"). The settings can be adjusted according to two agricultural techniques: soil-based and rooftop hydroponics systems;

- the identification of the key combination scenarios for rooftop agriculture (PM "Detecting Spatial Synergies" and PM "Wallacei"). The scenarios are evaluated according to the multi-objective optimization of competing fitness objectives such as the extension of the GCN, the growing capacity and the feasibility of the project. Each fitness objectives are weighted and controlled by the designer in order to adapt the analysis to the city context and requirements. In addition, the Proof of Concept investigated the functionality of the PMs "Green desert" and "Minimum Spanning Tree" on the region of Bangu and demonstrated their flexibility for the analysis of further urban landscapes.

4) The starting point of a statement for both citizens and planners to shape collaboratively the social and environmental green structure of cities. With informed design, gardening initiatives conducted by small groups or individual could have a great impact on improving access to green spaces, health and well-being in urban environments. Regarding the design of the GCN, the work reveals and maps the potential flying paths of the urban pollinators. These results invite citizens to poetically rethink different ways of inhabiting the city. The work celebrates new ways of thinking, by uncovering the parallel universes of our urban habitat and by giving a wider dimension to the city's multiple greening potentials. The objective is to go beyond the traditional separation between rural and urban areas. The PMs aim to raise awareness and enhance dialogue on nature-based solutions strategies which join the needs of human society with the integrity of urban biodiversity.

6.3. Answers to research questions and discussions

Below the answers to the sub-questions of the study:

Where to site new rooftop gardens in order to best optimize the distribution of the urban green cover? Consequently, which areas have a relative or absolute lack of green spaces in the case studies of Vienna and Bangu?

These research questions were answered in Chapter 5.4. with the testing of the PM "Green Desert" on the case study areas of Vienna and Bangu. The PM detected 5 zones in Vienna where the distance to the nearest green area is greater than 600 meters and 3 areas in the region of Bangu for a reference distance greater than 680 meters. These zones should be considered as the priority areas for further greening plans.

What are the optimal locations and conditions for rooftop agriculture given an existing fragmentation of the green infrastructure of a city?

It is important to highlight that the same landscape may have different degrees of connectivity for different species (Kindlmann & Burel, 2008). It is a highly complex exercise to create connected green space networks. There are still many issues and questions about the planning strategies and the way they could be optimally designed. The generated parametric models offer a platform for the design and the comparison of different scenarios for rebinding or densifying the existing corridors networks.

For the case study of Vienna: the research generated a solution using the Minimum Spanning Tree network typology, which connects all nodes (or green spaces) such that the overall sum of the edge length is minimized (ie. the location density of every green area is not null). The proposed scenario requires only 43 flat roofs to close the existing green corridors network on 5'027 hectares of a highly urbanized area in Vienna. This amount of roofs to convert into gardens seems realistic and feasible on the scale of 5'000 hectares built area. Based on this

GCN solution, a visual assessment of the results should be nonetheless conducted in order to complement the solution with other potential strategic flat roofs locations.

For the case study of Bangu, the PM gave unsatisfying results with the use of a "Minimum Spanning Tree" network. Rather than closing the GCN, the urban green infrastructure of Bangu would be efficiently improved by increasing the density of the green patches in proximity to the existing GCN. The parametric definition of the PM allowed to quickly generate other network scenarios and to compare the performance of each typology for the region. Therefore, the Proof of Concept demonstrated that the PMs should be used as a tool for comparing greening variations performances with experts in landscape ecology rather than offering a single fixed solution.

What is the flat roof landscape potential in RJC? What would be the associated growing capacity?

The LIDAR-based mapping phase detected all the roofs with an inclination inferior to 5 degrees on 69% of the surface of Rio de Janeiro City. The research showed that 1'383 hectares of roofs would be suitable for RA within the study region (without taking into account the structural conditions of the roofs). This productive roof surface could produce enough food to meet the yearly demand for vegetables of 39.2% of the inhabitants of the city. The study also demonstrated the great relevance of implementing RA in the poorest communities of RJC in the perspective of tackling food insecurity.

What are the key social parameters to be considered for the implementation of rooftop agriculture in Vienna and in Rio de Janeiro City?

The social parameter is an important criterion for the long-term and extensive implementation of agriculture on roofs. The comparison between the two cities was a very interesting process since the cultural contexts, policies and needs are very different.

In Vienna and Austria, local associations such as the *GartenPolylog* support urban and periurban gardening initiatives. More than food production spaces, the gardens serve as community hubs, promoting social integration, education and a collaborative culture. Vienna is more advanced than RJC in terms of financial support for the implementation and management of roof greening initiatives. The importance of community gardening is increasingly being recognized by the municipality and the citizens. However, existing planning and building regulations remain constraints for individuals and associations to use roof areas as gardens. There is no explicit notion of rooftop agriculture and farming in the legal texts, thus efforts should be made to include these as a clear target in regulations and local policies. The results of the workshop confirmed the importance of getting more support from local authorities, especially in facilitating the process of using the public and roof spaces and considering these actions as educational projects. In addition, participants highlighted the need of transforming public spaces into more "engaging" and "active" areas in the city, showing the growing interest in developing community spaces in Vienna.

Although urban gardening plays a key role in creating social links and enhancing urban food security in RJC, the practice is not yet a widespread concept. Food security is an important challenge in the city and rooftop agriculture can be a connector for better practices. One important first step would be to inform the population about the advantages and possibilities of using the roof surfaces for urban gardening. Flat roofs in RJC are valuable for building owners and the benefits of possessing a rooftop garden are not yet widely acknowledged by the population. Therefore the promotion of successful cases on public buildings (schools, institutional buildings, and others) and in communities would expose the multifaceted benefits offered by the green structures and could generate a contagion effect. In the zones with a high density of small flat roofs such as the slum areas of RJC, the research shows great social and environmental potentials. However, the difficulty of access, the violence and the mistrust of the population towards city officials have to be considered. A bottom-up approach is in this case

strongly recommended. Community-based and grassroots associations are the key actors for the promotion and long-term implementation of garden projects. These associations are at the forefront of social innovation in RJC and raise awareness among citizens, families, communities about sustainable agriculture (permaculture, agroforestry,...) and food nutrition. These actions should be better supported by the municipality and on different scales: financially, logistically but also by offering them more public visibility.

The main research question was:

How can parametric modelling methodologies contribute to the spatial analysis and detection of the key locations for rooftop agriculture within an existing urban landscape? Although, the concept of parametric analysis was proven broadly in the architecture and design industry, its capacity to support urban green infrastructure planning was not yet investigated. The study demonstrated the functionality of the parametric models on the two urbanscapes of Vienna and Bangu. The PMs work as a design and negotiation platform, where planners can discuss and be informed of a wide range of greening scenarios with quantified outputs. Generating these scenarios is facilitated by the PMs which allow users to do many iterations and monitor changes during the design process.

The results of the parametric models are very encouraging and show the great possibility to integrate this methodology into the early-stage urban planning. The proposed workflow successfully combines GIS data with parametric modelling techniques and proved to be adaptable to different city contexts. The 2D and 3D outputs give a direct visualization of the vulnerabilities of the urban green infrastructure and the spatial capabilities of the existing roof landscape. This visual result is very important to engage discussions in multidisciplinary planning groups and encourage experts to reflect on both their own and other departments requirements.

However, it is crucial to underline that changing the conventional and complex process of urban planning in municipalities is very challenging and would involve various departments with very different practices. Another difficulty lies in the modelization process and the big amount of information Grasshopper has to compute. The exact GIS locations (street number, district, etc.) of each rooftop, as well as their shape, have been used as initial data. ArcGIS processes quite fast the data but the graphs simulations in Grasshopper can be slow. This is due to the parametrization of the network that requires a calculation of every possible path between the polygons (Figure 103).



Figure 103. Visualization of the flat roofs locations data on ArcGIS & Paths test between the green areas on Grasshopper.

Though several parameters were taken into account, the overall analysis of the flat roofs landscape could be refined. With the acquisition of GIS data concerning the solar radiation, the roof materials and the structural conditions of the roofs, the models could be extended to more accurate results.

6.4. Future steps and recommendations

Below the suggestions and recommendations for further research steps:

• Extending the parametric models to further potential benefits of rooftop agriculture: It is recommended to explore further competing fitness objectives in order

to open the investigation to further potential benefits of the rooftop gardens projects. As an example, it would be very interesting to integrate:

- the potential of the roofs for rainwater harvesting,
- the benefits of combining solar panels with intensive greening,
- the capacity of the rooftop gardens to insulate the buildings underneath
- the potential benefits of combining a building with a hydroponic greenhouse (energy conservation benefits, symbiotic exchange of oxygen and carbon dioxide between crops and building occupants,...)
- Integrating the 3D geometry of the urban terrain as well as the height of the buildings: The experimentation could include the height of the buildings in order to calculate with more accuracy the paths of the pollinators. Due to a lack of computation power, the integration of this parameter was not considered and the building polygons were filtered according to a predefined maximal height. Nonetheless, the PMs were conceived to compute this extra dimension of the built environment. It would be interesting to add this information into the parametric models in order to provide a more accurate and stronger visual result.
- Testing the model with other types of unused surfaces: Although roof surfaces were the focus of the present study, it is very important to integrate other types of surfaces into the greening planning strategies (unused ground-level areas and facades). The parametric definition of the models allows the testing of further surfaces as long as these are provided as a shapefile. Before the integration of this data into the PMs, it is important to filter and classify appropriately the polygons based on their size, type and geometry. The combination of all these greening strategies would give a wider

perspective on the spatial opportunities for greening cities in dense and compact urban centers.

- Including building and management costs into the calculation: Depending on the urban space and the flight foraging distance considered it is possible to get a visualization of the GCN. However this design should include many other aspects (linked to rooftop gardens construction): for instance, the structural and exploitation costs remain crucial parameters. In collaboration with experts from other disciplines, this model should be further developed in order to get more practical and to provide details about the costs of the projects.
- Shaping targeted incentive policies for the implementation of rooftop gardens: The results of the research could give the basis of a strategy targeting directly the owners of the key roofs: for the city of Vienna, the surfaces with the highest potential could be allocated with a higher grants compared to surfaces with lower potential. Therefore citizens and organizations will be included in a global greening strategy of the city; not only considering building scale benefits (insulation, social benefits,...) but also city-scale benefits (inclusion into the green corridors network, heat mitigation,...). This pinpoints strategy would promote micro-targeting and selective interventions. The idea is to produce small-scale (rooftop gardens) but environmentally catalytic actions. The parametric mapping will support a pertinent and efficient greening decision-making process for cities. The Kompetenzzentrum grüne und umwelt-bezogene Infrastruktur, Umwelt (Stadtbaudirektion) & the Magistrate 22 Umwelt showed great interest in the parametric models.

- Dissemination of the results through an online platform and bottom-up approach: The research project should explore a bottom-up approach (information to citizens) and connect directly with policy makers, who have the capacity to transform the results into urban strategies. It is also important to create an online platform which would wider inform and display the tool results for cities. People are often unaware of the potential of cities for protecting biodiversity and how urban agriculture could benefit both to citizens (especially for children & seniors) and nature. Initially, the tool was directed only to city planners and officials, but it appears that there is also a great potential as an educational tool, open to a wider audience. The digital installation would allow citizens to discover these flying paths and invite them to poetically rethink different ways of inhabiting the City.
- Using the growing Smart City trend as an opportunity for the better integration of Food into city plans: Another leverage point for better promoting urban agriculture actions in RJC would be to integrate the topic of Food as an important part of the Rio Smart City initiatives. Large investments are being made by cities to use sensors, satellites and GPS systems to better manage transportation flows, traffic lights, warning systems (extreme weather conditions) or garbage collection. Elected in November 2014 as one of the seven smartest cities in the world, RJC showed great interest in using new technologies for improving city plans, especially in prevision for the Olympic games 2016. Vienna also developed in the last years a department exclusively dedicated to smart cities actions. However, Smart city plans rarely include food, though it is an essential part of the city. So, why not valuing food as much as we value energy, water and Wifi for the smart city plans? The digitalisation of food services (including production and distribution) could be the vector for creating a more sustainable and inclusive food system. Food and Urban agriculture practices should be given a wider recognition

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among cities and the Smart City growing trend could be seen as an opportunity for developing actions in favor of urban agriculture initiatives.

Further optimization of the model based on highly "space-challenging" roofscape and generic GIS-data: The model should be further developed with the collaboration of experts in architecture and landscape ecology. The Ph.D. work provides the first versions of the digital model. The model was successfully built and tested on two different cityscapes: Vienna and Bangu. After analyzing the historical "Gründerzeit" roofscape of Vienna, the irregular and chaotic topography of the roofs of RJC, it is now crucial to adapt and enrich the model definition on the space-challenging and modern townscape such as Tokyo, Hongkong or Shenzen. This step would support the technical optimization of the generic functions of the model on the densest and most populous city in the world, and with a very unique roofscape.

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Appendix 2. Results of the collective mapping "How to grow together": the vulnerable areas of the city of Vienna





"How to grow together?"

Created in the frame of the collective Mapping Map of the vulnerable areas in the city of Vienna

Legend

- Unstimulating
- Unappealing
- Hectic
- Unsafe

OpenStreetMap







Mapping "How to grow together?" collective Created in the frame of the

Legend OpenStreetMap Density of pins medium (1 to 2) high (2 to 4) low (0 to 1)

Heatmap of the

Appendix 4. Preferred locations for community gardening according to the workshop results



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"How to grow together?" Mapping collective frame of the Created in the

Preferred locations for the creation of community gardens in the city of Vienna

Legend

Preferred locations

OpenStreetMap

Appendix 5. Processing of the LIDAR Data into a DTM and a DSM using LAStools

















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Region 8

















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Potential rooftop agriculture

Region 13





Appendix 7. Summary of the results of the Lidar-based mapping

Statistics summary for the districts calculated by the LIDAR-based mapping (95 districts)

		DISTRICT STATISTICS	
Amount of districts included in the calculation (unit)	Total district Surface Area (ha)	Total district Surface Area calculated (ha)	District Surface Area calculated in proportion to the total district surface area (%)
95	102,663.7	83,088.7	80.9

Total district Surface Area noncalculated (19%) Total district Surface Area calculated (81%)

Graphic 1. District surface area calculated in the present study for the 95 districts













90 - 100 : very large	70 - 90 : large	50 - 70 : medium	20 -50 : small	0 - 20 : superficial	

Vila Valque ire	1	00.0
Vila Militar	1	0.00
Vila Kennedy	1	0.00
Vila Isabel	1	0.00
Vasco da Gama	1	0.00
Todos os Santos	1	0.00
Taquara	11	0.00
Tapque		00.0
ranque		00.0
Senador Vasconcelos	1	0.00
Santissimo	1	0.00
Sampaio	1	0.00
São Francisco Xavier	1	0.00
São Cristóvão	1	0.00
Rocha	1	0.00
Riachuelo	1	0.00
Recreio dos Bandeirantes	1	00.0
Quintino Bocaiúva	1	00.0
Dence Com		00.0
Praça Seca	1	0.00
Piedade	1	00.00
Pedra de Guaratiba	1	00.00
Pechincha	1	0.00
Padre Miguel	1	00.00
Maria da Graça	1	0.00
Maracanã	11	0.00
Mangueira	1	00.00
Magalhães Bastos		00.0
Máias		00.0
weier	1	00.0
Lins de Vasconcelos	1	0.00
Jardim Sulacap	1	00.0
Jacarezinho	1	0.00
Jacaré	1	0.00
Inhoaíba	1	0.00
Grajaú	1	0.00
Gardênia Azul	1	00.0
Engenho Novo	1	00.0
Engenno itoto	4	00.0
Encantado	1	0.00
Deodoro	1	00.0
Curicica	1	00.00
Cosmos	1	0.00
Cidade de Deus	1	0.00
Cascadura	1	0.00
Campo dos Afonsos	1	0.00
Campinho	1	00.0
Cachambi	1	00.0
Cacination		00.0
Benfica	1	00.0
Anil	1	0.00
Andaraí	1	0.00
Abolição	1	0.00
Sepetiba	99	9.8
Freguesia (Jacarepaguá)	99	9.6
Praça da Bande ira	99	9.5
Barra da Tijuca		9.2
Engenho de Dentro	07.9	3
Águs Casta	57.5	
Agua Santa	38.0	
Barra de Guaratiba	94.7	
Gericinó	94.6	
De l Castilho	94.5	
Campo Grande	93.8	
Realengo	93.4	
Paciência	92.2	
Vargem Pequena	91.5	
Santa Cruz	91.1	
Manguinhos	86.0	
wangai inos	80.0	
EOL	83.8	
Grumari	82.7	
Pilares	82.2	
Bangu	81.9	
Itanhangá	79.6	
Ricardo de Albuquerque	75.0	
Guaratiba	73.4	
Parque Anchieta	73.4	
Caiu	71 0	
Marsehal Harris		
ware chainermes	/1.0	

Area covered by the LIDAR-based mapping for each district (in %)
0 - 20 : superficial
20 -50 : small
50 - 70 : medium
70 - 90 : large
90 - 100 : very large



%

Statistics summary for the existing roof surfaces and the flat roof potential of the LIDAR-based mapping (95 districts)

	EXIS	TING ROOF SURFACES STAT	TISTICS	
Amount of roof surfaces (unit)	Average size of the roof surfaces (m2)	Max size of the roof surfaces (m2)	Sum of all the roof surfaces (m2)	Sum of all the roof surfaces (ha)
575,948	412	164,365	123,540,999	12,354.10

	FL/	AT ROOF POTENTIAL STATIS	STICS	
Min size of the flat roof surfaces (m2)	Max size of the flat roof surfaces (m2)	Amount of flat roof surfaces (unit)	Total flat roof potential (ha)	Total flat roof potential in proportion to the existing roofs (%)
5	15,187	466,263	1,383.1	11.20



Graphic 2. Flat roof potential results of the LIDAR-based mapping on 69% of the city of Rio de Janeiro





6.53

Total flat roof potential in proportion to the existing roofs (%)

Total flat roof potential in proportion to the existing roofs (%)



Total flat roof potential (ha)

Total flat roof potential (ha)





Gericino	3.4
Todos os Santos	3.3
Jacaré	3.3
Lins de Vasconce los	2.7
Campo dos Afonsos	2.5
Praça da Bande ira	2.4
Riachue lo	2.3
Maria da Graça	2.2
Abolição	2.0
Sampaio	2.0
São Francisco Xavier	1.6
Barra de Guaratiba	1.3
Mangue ira	1.0
Água Santa	0.7
Joá	0.4
Grumari	0.1



		DISTRICT STA	TISTICS		EXIS	TING ROOF SU	JRFACES STATIST	ICS				FLAT ROOF PC	TENTIAL STATIS	TICS	
Districts	Total district Surface Area (ha)	Total district Surface Area calculated (ha)	District Surface Area calculated in proportion to the total district surface area (%)	Amount of roof surfaces (unit)	Average size of the roof surfaces (m2)	Max size of the roof surfaces (m2)	StdDev of the roof surfaces (m2)	Sum of all the roof surfaces (m2)	Sum of all the roof surfaces (ha)	Min size of the flat roof surfaces (m2)	Max size of the flat roof surfaces (m2)	StdDev of the flat roof surfaces (m2)	Amount of flat roof surfaces (unit)	Total flat roof potential (ha)	Total flat roof potential in proportion to the existing roofs (%)
Maria da Graça	82.5	82.5	100.0	930	552	16,687	1,277	397,087	39.71	5	418	32	720	2.2	5.48
Méier	247.1	247.1	100.0	3,826	538	12,831	1,112	1,227,972	122.80	5	2,808	57	2,281	8.4	6.83
Osvaldo Cruz	207.1	77.8	37.5	1,730	344	15,809	854	374,808	37.48	5	306	28	1,090	4.0	10.64
Paciência	2,741.8	2,528.7	92.2	22,862	223	88,087	1,043	3,629,237	362.92	5	4,110	51	16,269	50.2	13.82
Padre Miguel	486.6	486.6	100.0	12,424	365	10,727	812	2,008,393	200.84	5	1,835	35	5,498	27.7	13.79
Parque Anchieta	390.6	286.6	73.4	2,193	336	6,969	659	460,221	46.02	ۍ ا	713	33	1,370	4.9	10.58
Pechincha	283.1	283.1	100.0	2,109	225	6,257	395	818,062	81.81	л С	717	35	3,643	4.8	5.84
Pedra de Guaratiba	363.7	363.7	100.0	2,310	149	3,190	245	601,128	60.11	i U	350	27	4,037	4.8	8.04
Piedade	388.7	388.7	0.001	4,353	697	10,564	642 060	1,339,828	133.98	n ư	756	150	4,981	9.4	7.03
Praca da Randeira	0 COT	21 6 June 21	00 S	2,000 780	1 027	13,451 17 169	1 930	260 737	04.00 26.07	ло	1 444	U8 6CT	1,900 254	2.1 2.4	0 7 <i>1</i>
Praça Seca	650.0	650.0	100.0	5,400	219	25,053	518	1,687,245	168.72	л u	518	28	7,700	11.8	6.97
Quintino Bocaiúva	432.4	432.4	100.0	3,114	297	9,581	719	997,126	99.71	5	636	31	3,360	6.6	6.62
Realengo Recreio dos	2,605.4	2,433.0	93.4	32,525	297	17,809	701	5,208,064	520.81	л	2,756	37	17,559	73.6	14.14
Bandeirantes	3,065.6	3,065.6	100.0	10,585	280	25,865	711	3,104,836	310.48	5	9,755	110	11,091	26.8	8.63
Riachuelo Ricardo de	92.8	92.8	100.0	1,092	576	11,983	1,335	411,626	41.16	л	248	26	715	2.3	5.67
Albuquerque	211.7	158.7	75.0	2,774	227	6,619	441	646,286	64.63	5	411	22	2,845	5.8	8.90
Rio Comprido	334.3	1.5	0.5	26	689	5,290	1,588	7,574	0.76	6	91	22	11	0.1	7.13
Rocha	131.2	131.2	100.0	1,435	568	27,455	1,513	498,075	49.81	S	2,974	94	877	4.2	8.35
Sampaio	88.4	88.4	100.0	706	466	11,983	1,101	321,439	32.14	л	1,115	46	069	2.0	6.32
Santa Cruz	12,504.5	11,389.4	91.1	53,998	202	47,364	634	8,970,125	897.01	ı ر	15,187	86	44,342	131.0	14.60
Santíssimo	832.0	832.0	100.0	7,588	174	30,720	453	1,463,857	146.39	י ט	2,027	42	8,401	17.4	11.90
Santo Cristo	168.5	22.4	13.3	14/	798	17,151	2,337	/3,/11	/.3/	ı u	3,091	312	2000	1.4	19.60
São Cristóvão São Francisco Xavier	410.6 64.9	410.6 64.9	100.0	3,371	793 677	33,433 14.639	2,297	1,616,530 222,197	161.65 22.22	ი თ	6,041 622	124 48	2,038	11.4 1.6	7.07
Senador Camará	1,723.6	1,225.6	71.1	20,288	259	9,895	582	2,878,435	287.84	σ	774	24	11,094	42.8	14.88
Senador Vasconcelos	644.2	644.2	100.0	5.823	210	14.125	447	1.072.979	107.30	S	1.290	40	5.118	14.3	13.31
Sepetiba	1,162.1	1,159.6	99.8	14,471	153	5,843	255	2,344,055	234.41	5	839	26	15,365	32.3	13.77
Tanque	556.8	556.8	100.0	3,162	200	13,146	442	1,071,078	107.11	л	1,569	41	5,366	6.7	6.25
Taquara	1,320.7	1,320.7	100.0	15,485	333	61,603	963	3,618,473	361.85	i U	3,599	76	10,869	42.2	11.66
Todos os Santos	1,006.6	101 3	100.0	5,257	915 915	21,493 11 711	1,462	1,924,457 553 590	192.45	ли	3,342	CE //	3,729	13.4 3.3	6.96
Tomás Coelho	174.8	5.6	3.2	-,	117	2.199	218	14.267	1.43	5	59	11	122	0.0	2.62
Vargem Grande	3,938.0	2,193.1	55.7	2,979	145	9,246	280	1,017,461	101.75	5	1,259	53	6,996	7.8	7.65
Vargem Pequena	1,443.8	1,321.4	91.5	3,517	195	30,239	780	1,069,624	106.96	S	3,205	102	5,495	10.1	9.47
Vasco da Gama	86.3	86.3	100.0	1,715	1,086	32,228	2,831	486,683	48.67	s S	1,162	48	448	3.9	8.06
Vila Isabel	321.7	321.7	100.0	4,216	496	24,491	1,441	1,481,708	148.17	ı ر	1,349	46	2,988	9.7	6.53
Vila Militar	1.075.7	1.075.7	100.0	2,933	355	10,513	712	857,705	85.77	л и	1,197	68	2,417	8.4	9.78
Vila Valqueire	423.2	423.2	100.0	4,096	303	7,999	615	1,227,864	122.79	S	1,414	36	4,047	8.9	7.24


Appendix 8. Results of the LIDAR-based mapping on a 1km² grid





Overview of the potential for rooftop agriculture (on a 1 km² grid) Overall flat roof potential (in m²) Legend very high potential (X≥64000)

low potential (31000>X≥16000) medium potential (48000>X≥31000) high potential (64000>X≥48000)

very low potential (16000>X≥5)



72

Density of flat roof surfaces

Legend

Density of flat roof surfaces

Very low density

Low density

Appendix 9. Map of the density of flat roof surfaces according to the study results



Very high density 8000 ≤ X <11400 elements

High density 6000 ≤ X <8000 elements

Medium density 4000 ≤ X < 6000 elements

Very Low density 300 ≤ X < 2000 elements

Very high density

High density

2

Medium density

Low density 2000 ≤ X < 4000 elements



Appendix 10. Map of the regions with the highest amount of small flat roofs (<500m2) according to the study results



Density of small flat roof surfaces (<500m2)

 $\langle \gamma \rangle$

Legend

Small flat roof elements

7



2



Appendix 11. Map of the regions with the highest amount of large flat roofs ($\geq 1'000m^2$) according to the study results









Amount of large flat roofs



Appendix 12. Distribution of the selected green areas for the design of the green corridors network in the region of Bangu









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Appendix 14. The 9 best combination solutions according to the Wallacei modelling test



