Extensive green roofs in Porto Alegre, Brazil

Effect on indoor thermal comfort in residential buildings

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Keywords

Architecture	Indoor thermal comfort	Social housing
Computer simulations	Leaf area index	Sustainability
Extensive green roofs	Microclimate	Thermal comfort
Housing projects		

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Thesis 11
ISBN 978-91-87866-40-1 (Print)
ISBN 978-91-87866-41-8 (pdf)

ISSN 1652-7666

Layout: by the author
Cover picture by the author and Beatriz Gioielli
Cover layout by Hans Follin
All illustrations made by the author and Carlos Krebs if not otherwise stated
Tables by the author

Printed in Sweden by E-husets tryckeri, Lund, 2018

This Thesis can be ordered from:
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Department of Architecture and Built Environment
Lund University

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This doctoral dissertation is a result of a Double Degree Agreement between

Housing Development and Management, Department of Architecture and Built Environment, Lund University, Sweden,
and

The Programme of Research and Post-graduation in Architecture
Faculty of Architecture and Urbanism,
The Federal University of Rio Grande do Sul, Brazil.

Supervisors at Lund University:
Dr. Erik Johansson
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Supervisors at the Federal University of Rio Grande do Sul:
Dr. Beatriz Maria Fedrizzi
Dr. Eduardo Grala da Cunha

For Brazil, Sweden and a science without borders.

Summary

This research aims to develop further understanding of the effect of extensive green roofs on the indoor thermal comfort in naturally ventilated low-income houses, in the Brazilian subtropical city of Porto Alegre. This is achieved by studying the influence of a set of variables, to comprehend the best combinations of elements to a climate responsive green roof design. Moreover, in order to create more realistic results, different scenarios with green roofs and other elements (as grass on the ground and trees) are created, to evaluate the influence of the local microclimate on the indoor thermal comfort. Additionally, understanding how the extensive green roofs affect the outdoor microclimate in Porto Alegre is also a part of the aim. Evaluations are made for the whole year as well as for the summer and winter seasons.

The study estimates the effect of extensive green roofs on the indoor thermal comfort and on the outdoor microclimate by calculations through computer simulations. The simulations are performed with EnergyPlus for the indoor thermal comfort and with ENVI-met for the microclimate simulations. The studied houses are conceived for urban or suburban areas, to be implemented in any Brazilian city, as long as some adjustments are made to better respond to the climate, complying with the Brazilian Standards 15.575 and 15.220. The indoor thermal comfort is evaluated primarily with the Adaptive thermal comfort model of the ASHRAE Standard 55, and the calculation of heating and cooling degree-hours. For the outdoor microclimate, the variables air temperature and mean radiant temperature are evaluated.

The research shows that green roofs increase the indoor thermal comfort in the studied one-storey houses. For the whole year, the best combination of features is low-density plants and a thick soil layer (150mm). For the winter season, extra-insulation in the building envelope would improve indoor thermal comfort. The extensive green roofs would be beneficial both to new projects, complying with the minimum level of insulation from the Brazilian Standards, and to the existing building stock, which is typically poorly insulated.

The microclimate around the buildings affects the indoor thermal comfort, and this investigation shows that, when the green roofs are integrated in a green strategy at the site (with trees and grass on the ground), their cooling effect increases compared to when they are the only green strategy. This study also confirms the advantages of

performing coupled simulations, where the results of the microclimate simulations are used as input to the building simulations, to have more realistic predictions of the indoor thermal comfort. Concerning the effect of the extensive green roofs on the microclimate, a minor and local cooling effect is observed, especially at pedestrian level. That indicates that the effect of extensive green roofs as a strategy for reducing the outdoor air temperature in an urban context might be overestimated. The study showed that in the climate of Porto Alegre, a trade-off is needed: the best configuration of vegetation for the indoor thermal comfort over the whole year (trees with a lower density) is not the best configuration for providing a cooling effect on the microclimate.

Since the use of green roofs are advantageous to low-income housing projects, this work contributes to meeting the Sustainable Development Goals of the United Nations, especially goal 11: “Make cities and human settlements inclusive, safe, resilient and sustainable”.

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Acknowledgments

Firstly, I would like to thank my supervisor at Housing Development & Management (HDM), Lund University, Dr Erik Johansson who was for me the leading resource for the development of this research, conducting me through the knowledge in the field of thermal comfort, especially as regards outdoor microclimate. I also want to thank my co-supervisor at HDM, Johnny Åstrand, for the productive meetings, discussions and provocations on the development of this work.

I would like to thank my supervisor from the Programme of Research and Post-Graduation in Architecture (PROPAR) of the Federal University of Rio Grande do Sul (UFRGS), Dr. Beatriz Fedrizzi, for all the encouragement to meet my goals, the support throughout the work, and for having inspired me in the field of vegetation and microclimate. I also acknowledge my co-supervisor from PROPAR, Dr Eduardo Grala da Cunha, for the generosity in sharing his knowledge about indoor thermal comfort and simulations, and for his highly contagious optimism.

Special thanks to my beloved husband, Carlos Krebs. His amazing love and partnership make my dreams in life possible and the path, definitely, more creative and fun.

I thank my colleagues at Lund University, with whom I had a great experience of work and friendship, especially to Anh Chu, Laura Liuke, Maria Rasmussen, Marwa Al Khalidi, Moohammed Yahia and Niko Gentile. I would also like to thank Dr Eja Pedersen, for her friendship and for giving me resourceful advice on the presentation of this work.

As the first PhD student in both HDM and PROPAR studying under a double degree agreement, a long organizational path was covered. I am thankful to the administrative staff from both universities who, with their competent and valuable work, helped me in that unknown and not always smooth process. From Lund University, I would like to greatly acknowledge Hans Follin, Katarina Lans, Lena Andersson and Marit Åkesdotter. From UFRGS, I also greatly acknowledge Rosita Borges and Claudia Cabral.

I would like to thank my friends, family and colleagues, everyone that have participated in my life sharing experiences and knowledge.

The financial support provided by the Brazilian National Council for Scientific and Technological Development (CNPq), through the Science Without Borders Programme, is greatly acknowledged.

Erik Johansson and Johnny Åstrand believed in the potential of this research, allowing me to continue my studies in Sweden after the scholarship from the Science Without Borders programme was finished. Moreover, I would also like to thank HDM and Lund University for admitting me as a regular PhD Student, providing excellent conditions for the development of my work, including the exemption from the tuition fee.

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BEM	Building Energy Models
Clo	Clothing
CTF	Conduction Transfer Function
GR	Green roof
LAI	Leaf area index
LAD	Leaf area density
NBR	Brazilian Standard (*Norma Brasileira*)
OR	Original roof
RH	Relative humidity
RTQ-R	Regulation for Energy Efficiency Labelling of Residential Buildings
T_{air}	Air temperature (dry-bulb)
T_{mrt}	Mean radiant temperature
TMY	Typical meteorological year
T_{op}	Operative temperature
TRNSYS	Transient System Simulation Tool
U value	Thermal transmittance

1 Introduction

1.1 Background and problem definition

The desire for living in cities where vegetation integrates landscaping also in other forms than the traditional ones (parks, gardens and trees alongside streets), were early motivations for this investigation. Green roofs align with the idea of urban design and planning where citizens experience benefits from the integration with vegetation. The potential benefits offered by green roofs in urban areas (such as the increase in biodiversity and contribution to flood water management, for instance) are not restricted to its private house owners but extended to the city users.

This research aims to contribute to the knowledge about green roofs in Brazil. More specifically, the investigation intends to explore the potential increase of indoor thermal comfort, under different configurations and microclimate scenarios. A considerable part of the building stock, including new social housing projects, are made by naturally ventilated single-floor houses, which do not achieve good thermal comfort levels. Thus, this investigation aims to estimate the rise in thermal comfort green roofs could provide, for those building projects.

A green roof is a rooftop system with the addition of vegetation in the upper layer. Although “green roof” is the most common name, these roofing systems can also be found with other names like “ecological roof," “vegetated roof," “living roof," "light-weight green roof," “roof garden” and “planted roof". For this research, a green roof is a designed roof. It includes a group of layers (from plants to waterproofing layer), involving a certain level of complexity. Although authors like Köhler et al. (2003) consider spontaneously established plants above the roof as one type of green roof, only a few authors agree with that definition.

The most common type of green roof is the extensive one. An extensive green roof suits well to be implemented for residential projects in large scale. The reasons why they are the first option worldwide is because they weigh less than the intensive green roofs, they have the lowest implementation cost (reduced weight on the roof structure), the lowest maintenance and their construction is technically straightforward. That combination of characteristics results in lower costs involved, being compatible with social housing projects – which has highly motivated the choice of the extensive green roofs for this research. Also, they are suitable for flat to sloped roofs as the ones in this study (as it will be explained in Chapter 3).

A constructive solution that increases indoor thermal comfort can provide lower energy use for the residential sector. That is especially relevant if adopted on a large scale. Furthermore, the lower the building, the more significant the influence of the roof on the indoor thermal comfort.

According to Pinheiro (2015) Brazil had, in 2013, a housing deficit of approximately 6.2 million residences. From that total, almost 697 thousand were in the South Region. Porto Alegre is the capital of the State of Rio Grande do Sul, the southernmost Brazilian state. According to IBGE (2016), Porto Alegre has approximately 1.48 million inhabitants. Pinheiro (2015) states that in 2013 the city was responsible for a deficit of roughly 94 thousand residences. As explained by Braga & Nascimento (2009), social housing programmes in Brazil have historically presented problems - related to urban planning, funding, design, and construction quality. Traditionally, these programmes do not consider indoor thermal comfort as a requirement. Green roofs can be an affordable measure to improve indoor thermal quality through the use of natural, local resources.

In a broader perspective, this work intends to produce background technical knowledge that contributes to meet the goals of the 2030 Agenda for Sustainable Development from the United Nations General Assembly (2015). Specifically, it is associated with the 11^{th} Sustainable Development Goal: "Make cities and human settlements inclusive, safe, resilient and sustainable". Adopting green roofs to increase the indoor thermal comfort and to improve microclimate is a way to raise the environmental sustainability in social housing projects (that is mainly due to the increase in vegetation in the site and the use of local materials for the main components).

By increasing knowledge, this work aims to contribute to the following targets of the 11^{th} United Nations Goal: **11.1** – "By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums; **11.7b** – "By 2020, substantially increase the number of cities and human settlements adopting and implementing integrated policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change…"; and **11.7c** – "Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilising local materials".

Steiner et al. (2013) state green strategies, including green roofs, are highly favourable to increase the resilience in cities. The authors state that an understanding of ecological mechanisms in the urban landscape would help to increase the resiliency in cities through environmental design and planning. In the case of green roofs, that is mainly due to the increase of biodiversity and the flood water retention.

In 2005, the Brazilian Standard NBR15.220 - Thermal Performance of Buildings (ABNT, 2005) was released, being the first step forward to increase the indoor thermal comfort – especially in social housing projects (for which the Standard was created). With the release of the Brazilian Standard NBR 15575 - Performance of Buildings (ABNT, 2013), several quality requirements were defined for the building performance, including the indoor thermal comfort. The compliance with the Standard NBR 15575 is, currently, required by government agencies and banks for funding building projects. Indoor thermal comfort is part of the whole building evaluation, which is pushing construction companies to increase the quality of the building envelope. This includes their response to the local climate.

The need for a significant number of new houses and the requirement of indoor thermal comfort have motivated the choice of a residential typology for this study. The social housing was selected for its relevance to the Brazilian social programmes: according to IBGE (2016), the majority of the Brazilian housing deficit belongs to the most deprived population. The decision to study a naturally ventilated building is aligned with the search for environmental sustainability in architecture, through a climate-responsive design.

The interest for investigating green roofs as a possible solution to increase the thermal comfort is due to the overall benefits they provide to the users and the city, as extensively mentioned in the scientific literature (see Chapter 3 – Literature review). Köhler et al. (2003) argue that Brazil, a country with vast plant biodiversity, has the potential for green roofs using a substantial amount of plant species. It may also improve the indoor climate in dwellings and reduce the need for cooling, due to its good thermal performance (Köhler et al., 2003).

Refahi et al. (2015) claim that green roofs are one of the most effective approaches to reducing energy use in buildings. Boafo et al. (2017) define green roofs as a passive technique, representing a sustainable alternative to enhance roof performance while limiting heat flux through it.

A considerable increase in commercial green roof products has been observed in the last decade. Vijayaraghavan (2016) points out that the focus of developers, however, has been limited to achieving aesthetical benefits of the rooftop gardens, while many other benefits are just as achievable. The author observes that commercialised green roof systems, usually, are not optimised to meet those other interests. Consistent with that, Lehmann (2014) argues that the primary motivation why they are installed is the visual improvement, but the author also adds the aim of achieving a good environmental performance. Thus, more research on the subject is needed, to change that scenario.

There is a growing interest in green roofs in Brazil. However, green roofs are not an ancient roof construction system in the country, as it is in countries like Sweden or Germany, for instance. A more comprehensive understanding of green roof systems in Brazil will help to provide a design appropriate to optimise its benefits.

A green roof interacts more with the site than a conventional roof. As a green roof is a living system, the thermal exchange includes the latent heat from plants and soil. Climate aspects as air temperature, wind speed and direction, solar radiation, air humidity and rain impact the health and the maintenance of green roofs. Thus, a green roof is profoundly influenced by the surrounding microclimate, more than any other building envelope component. The thermal impact of a green roof both on the microclimate and indoor thermal comfort is dynamic, as it is modified during its life-cycle.

The green roof can also be part of a green strategy in an urban centre. As a consequence, it will contribute to an increase in biodiversity in those urban areas. Although the impact of green roofs on microclimate at the neighbourhood scale has not been explored to the same extent as at the building scale, the amount of research conducted in the field is increasing. The growing number of articles being published in the area (Peng & Jim, 2013; Skelhorn et al., 2014; Berardi, 2016; Solcerova et al., 2017) shows an interest in evaluating the cooling effect green roofs can provide for the outdoors.

It is becoming usual to see green roofs as part of recent Brazilian architectural projects. Between 2003 and 2005 Krebs & Sattler (2012) investigated ten green roofs built in Porto Alegre and vicinity, analysing design and maintenance. Since then, the number of constructed green roofs has increased in the city. Academic research, however, is not growing proportionally. A bibliometric study conducted by Blank et al. (2013) in peer-reviewed international journals through the Web of Science database has collected 300 publications about green roofs. Their review showed that, in the international scenario, Brazil is a country with a negligible number of academic publications on the subject (although the specific number was not informed, a graph showed it was around 1% of the total, so, approximately 3 articles).

Brazil has eight climatic zones (ABNT, 2005), each one presenting different challenges to building projects, especially those aiming to give a good climate response. There is very little knowledge about the thermal performance of green roofs in different Brazilian climates. To what extent it is possible for an extensive green roof to respond positively (meaning, providing a reduction in need of space artificial conditioning) both to the warmer air temperatures in the summer and to the colder air temperatures in the winter of Southern Brazil, is a question to be answered.

Research on thermal performance of green roofs in Brazil has dealt almost exclusively with indoor climate, through experiments (Morais & Roriz, 2005; Parizotto & Lamberts, 2011; Cardoso & Vecchia, 2014; Carneiro et al., 2015; Wilkinson & Feitosa, 2015), and by simulations (Rosseti et al., 2015; Dias, 2016; Krebs et al., 2017). Compared to experiments, simulation studies are thus in fewer number. Given the improvements in the types of software able to calculate the physical dynamics of green roofs (as the *Ecoroof* model in EnergyPlus), it can be predicted that the situation will be the opposite within the next years.

To date, international studies about the impact of green roofs on the microclimate are growing in number. In Brazil, only a few studies have investigated this, especially at pedestrian level. As examples, Rosseti et al. (2015) investigated this subject in the city of Cuiabá (Mato Grosso do Sul, Brazil, tropical climate). Similarly, Krebs et al. (2017) simulated the influence of extensive green roofs on the outdoor microclimate at pedestrian level and above the roof in Porto Alegre.

Worldwide, studies on the influence of both microclimate and green roofs on the indoor thermal comfort are in an extremely reduced number. To date, only a few investigations were found on the subject, in a review conducted in scientific peer-reviewed international journals. The lack of studies about how different outdoor scenarios can affect the influence of green roofs on indoor thermal comfort, and about how the green roof modifies thermal aspects of the building surroundings, constitute substantial gaps in knowledge regarding green roofs in Brazil.

1.2 Aim and objectives

This investigation aims to increase knowledge about the thermal performance of extensive green roofs. The main focus is to predict the effect of green roofs on the indoor thermal comfort in naturally ventilated residential buildings in the city of Porto Alegre, Southern Brazil. As it will be described in Chapter 2, that city's climate poses a significant challenge to provide indoor thermal comfort in naturally ventilated buildings. That is especially true for Brazilian social housing projects, which traditionally rely on low budgets and do not consider the indoor thermal comfort as a priority. Aligning to this main objective, the research evaluates the influence of a range of variables, as follows:

- Green roof components (plants and soil);
- Building components (building envelope insulation);

Different from a cool roof (like a white roof, for instance), that reduces heat transfer to the indoors but can increase the heat on the outdoor by its reflection, a green roof provides thermal exchanges of vegetation with the microclimate. Therefore, a second objective was to predict to what extent extensive green roofs directly influence the outdoor microclimate, at pedestrian level and above the roofs.

As previously mentioned, another critical gap in knowledge is the influence of microclimate on the indoor thermal comfort, using green roofs. Thus, considering the environment around the building, the third objective of this investigation is to estimate the potential thermal comfort provided by extensive green roofs under different microclimatic conditions. In this process, the influence of different site scenarios on indoor thermal comfort was investigated by means of coupled microclimate and indoor comfort simulations.

The primary target group for this investigation is the scientific community, but it also seeks to provide information potentially useful to owners, designers, developers and local governments (municipalities, public policies, and so on). It is important to underline that, in the context of this research, a good performance of green roofs is their ability to increase indoor thermal comfort in buildings having natural ventilation.

1.3 Research questions

The research intends to answer the following questions:

- What is the impact of extensive green roofs on the indoor thermal comfort in the studied buildings, in the climate of Porto Alegre?
- What is the influence of the vegetation and substrate layers on the thermal performance of the green roofs?
- How do green roofs perform with different levels of building envelope insulation?
- How does the microclimate influence the impact of green roofs on indoor thermal comfort?
- How do the green roofs impact the microclimate in the surrounding area?

1.4 Research limitations

The study of green roofs is relatively new and belongs to a multidisciplinary field. In the previously cited bibliometric study made by Blank et al. (2013), the authors have found papers about green roofs in 32 research areas. Although architecture and engineering are within the top five leading fields (in the number of studies found), the subject is also explored by urban studies, material sciences, agriculture, public environment and occupational health, for instance. As previously stated, this exploratory study aims to contribute to fulfilling gaps in knowledge in the field of thermal comfort, evaluating the use of extensive green roofs to improve it in residential buildings with natural ventilation. Therefore, it cannot contemplate all the aspects related to the design or the use of that constructive solution.

This research focuses on extensive green roofs with a depth of the substrate layer equal to or lower than 150mm. As it will be detailed in Chapter 3 (Literature Review), this is usually found in commercial green roof companies as the limit of what is considered an extensive green roof (the most common type of green roofs, with the lowest maintenance needs). The thinner substrate layer only allows smaller plants and grass. Consequently, the effect of bigger plants cannot be explored. The chosen typology also represents a limitation, since results can be different in office buildings compared to residential buildings – especially single family houses, the focus of this study.

The evaluation at the building level was limited to the indoor thermal comfort in a naturally ventilated building. The use of weather data from one year-period, and from the typical summer and winter weeks (and days) were adopted, for being considered representative of the climate in Porto Alegre. Those two characteristics (naturally ventilated buildings and weather data from typical and not extreme periods) were considered suitable for the evaluation of changes in indoor thermal comfort. A calculation of energy-efficiency would not be accurate with data from simulations performed in this investigation as, for that purpose, the weather data adopted should also comprehend the extreme periods.

The simulations have been conducted for a residential design typology. It can be representative of a social housing project in Brazil, so there is no specific location for it. The twin-houses have been created to be able to be built in different places around the country. For that reason, simulations were performed with input weather data from a Typical Reference Year of Porto Alegre (TRY from 2001-2010); there were no measurements involved, which means a limitation regarding weather data from a specific site.

As alleged by Peri et al. (2016), there is a lack of a proper database including green roof plant species and information on their phase of growth, to which a technician possibly will refer in the case of lack of field data. That absence can lead to a certain level of inaccuracy as regards the estimations of the thermal cooling and heating needs of buildings equipped with green roofs. In this investigation, data of plant species does not account for the growing and maintenance phases.

A restriction regarding simulation periods was found during the research development. The software ENVI-met was suitable for short-time simulations, while with EnergyPlus, simulations with until one-year can be run. Therefore, simulations involving microclimate were restricted to typical days, representing the summer and the winter seasons.

1.5 Structure of the thesis

This Thesis is divided into eight Chapters. The outline that follows this introduction is described below:

- Chapter 2 explains the climate of Porto Alegre and the studied residential twin-houses;
- Chapter 3 presents the literature review, providing the state-of-the-art in the field and identifying the main niche where this investigation took place: the impact of green roofs on indoor thermal comfort (under different configurations and microclimates);
- Chapter 4 details the method employed throughout the research: computer simulation with the software EnergyPlus for the evaluations made indoors, and with the software ENVI-met, for the evaluations made outdoors. Also, coupled outdoor-indoor simulations were performed, analysing the effect of the surroundings on the indoor thermal comfort using green roofs;
- Chapter 5 answers the question about the impact of extensive green roofs on the indoor thermal comfort in the studied residential twin-houses, in the climate of Porto Alegre. It evaluates the influence of the LAI of plants, the substrate depth and the insulation of the building envelope. Additionally, it provides a discussion on the effect of ground temperature in simulations;
- Chapter 6 answers the research question on how the green roofs impact the microclimate. Also, the chapter presents results on how a more intensive green strategy impacts the microclimate, and compare the results of the two green strategies on the site;
- Chapter 7 answers the research question on how the microclimate influences the impact of green roofs on indoor thermal comfort. Additionally, the chapter presents results on how a more intensive green strategy impacts the indoor thermal comfort. In the end, Chapter 7 discusses the influence of the coupled simulation method on the results;
- Chapter 8 summarises conclusions from the thesis and suggests recommendations for future work in the field.

2 Porto Alegre city and the studied twin-houses

This Chapter aims to introduce the context in which the green roofs were studied. Firstly, it briefly presents the city of Porto Alegre and its climate. That allows an understanding of the challenges posed to provide thermal comfort in naturally ventilated buildings. Secondly, it presents the requirements on the building envelope to achieve thermal comfort according to the Brazilian Standards. Thirdly, it introduces the studied twin-houses, giving an overview of its constructive system.

2.1 Overview and climate of Porto Alegre

Porto Alegre is the capital of the state of Rio Grande do Sul, the southernmost region of Brazil. It is located at the Latitude 30º10’ South; Longitude 51º13’ West; Altitude of 47m; situated at approximately 100 km distance from the Atlantic Ocean and 2,027 km distance from Brasília, the Brazilian capital. The city has about 1.400.000 inhabitants (IBGE, 2016) and an area of 497,000 km^2, with diversified topography, with hills distributed along the city. Figure 2.1 shows Porto Alegre in South America (a) and the contours of the city (b).

(a) (b)

Figure 2.1: Porto Alegre and Brazil highlighted in the South American map (a), and the city contours (adapted from Google Maps) (b)

Since the creation of Porto Alegre, the Guaíba lake is used for commercial transportations and is closely related to the city's economic development. Known for being one of the Brazilian cities with the higher number of trees per inhabitant, Porto Alegre has about 1,3 million trees in public streets. The Porto Alegre Municipality – PMPA (2017) – informs that the city has 14,78m^2 of green area per inhabitant, which is above the minimum recommended by the World Health Organization (of 12 m^2 of green area per inhabitant).

According to the Köppen-Geiger climate classification (Kottek et al. 2006), Porto Alegre is "Cfa": warm temperate, humid with a hot summer (humid subtropical), with distinct heating and cooling seasons. Hasehach (1989) mentions the influence of two air masses on the city's climate: the tropical maritime air masse, responsible for the high temperatures in spring and summer and the polar maritime air masse, responsible for the lower temperatures in autumn and winter. The Guaíba Lake also contributes to the high level of humidity in the city. Another characteristic of Porto Alegre's climate is the high daily thermal amplitude of air temperature. Figure 2.2 shows the mean monthly air temperature and relative humidity for Porto Alegre, and Table 2.1 summarises its values. All weather data are based on statistical data from a 30-year period: the Brazilian Climatological Normals from1981-2010 (INMET, 2018).

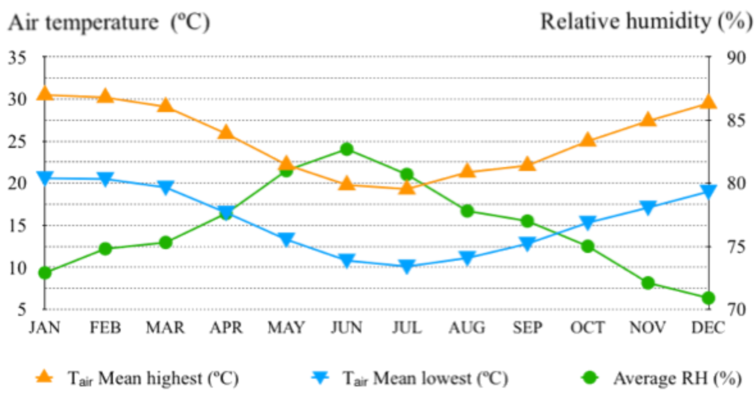


Figure 2.2: Monthly air temperature (minimum, maximum and average) and relative humidity for Porto Alegre (Based on INMET, 2018)

Table 2.1: Values of monthly mean air temperature (minimum, maximum and average) and relative humidity for Porto Alegre (INMET, 2018)

	Mean daily T_{air} (°C)			Mean RH (%)
	Minimum	Average	Maximum	
January	20.6	24.7	30.5	72.9
February	20.5	24.5	30.2	74.8
March	19.5	23.5	29.1	75.3
April	16.5	20.3	25.9	77.6
May	13.3	16.9	22.2	81.0
Jun	10.8	14.4	19.8	82.7
July	10.1	13.8	19.3	80.7
August	11.1	15.3	21.3	77.8
September	12.8	16.7	22.1	77.0
October	15.3	19.4	25.0	75.0
November	17.1	21.5	27.4	72.1
December	19.0	23.6	29.5	70.9
Annual	15.5	19.5	25.2	76.5

The solar radiation in Porto Alegre is high both in the number of sunshine hours and in intensity, especially in summer. This climatic aspect contributes to green strategies in general. Some attention regarding irrigation might be necessary during the summer season, due to the intense solar radiation associated with the higher air temperature. That is especially true for plant species that need more water, like grass. The monthly solar radiation of Porto Alegre is shown in Figure 2.3 and in Table 2.2.

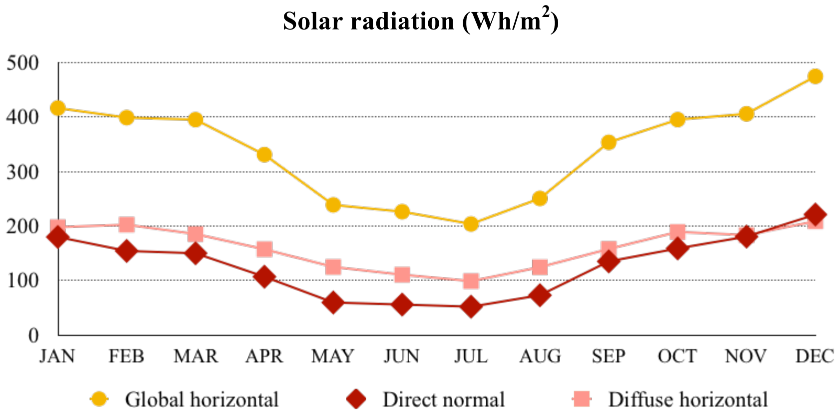


Figure 2.3: Average monthly solar radiation of Porto Alegre (INMET, 2018)

Table 2.2: Solar radiation for Porto Alegre (INMET, 2018)

(Wh/m^2)	Global Horizontal	Normal Direct	Diffuse
January	416	180	198
February	399	154	202
March	395	150	185
April	331	107	157
May	238	59	125
Jun	226	56	110
July	203	52	99
August	250	73	124
September	353	135	158
October	395	159	189
November	406	180	183
December	474	221	208

Figure 2.4 shows the wind speed for Porto Alegre, Table 2.3 shows the wind direction and Figure 2.5 shows the monthly precipitation.

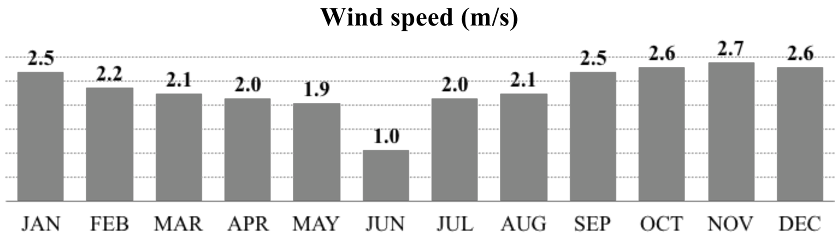


Figure 2.4: Average mean monthly wind speed for Porto Alegre (INMET, 2018)

Table 2.3: Prevailing monthly wind direction (º) for Porto Alegre (INMET, 2018)

January	February	March	April	May	June
134	129	133	145	175	202
July	August	September	October	November	December
164	144	146	139	137	138

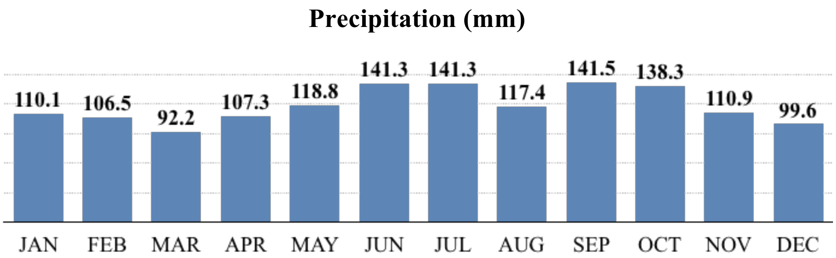


Figure 2.5: Precipitation, monthly (INMET, 2018)

Figure 2.6 presents the psychrometric chart for the EnergyPlus Weather file (EPW weather file) of Porto Alegre. The chart was plotted from the free software Climate Consultant v.6 (DOE, 2017). The chart has hourly values related to temperature and relative humidity of the air, for the 12 months of the year. While 26% of hours in the year are between 20ºC and 24ºC, which is a range compatible with thermal comfort, 74% are above (51%) or below (23%) that range. Therefore, the city presents discomfort by both cold and warmth.

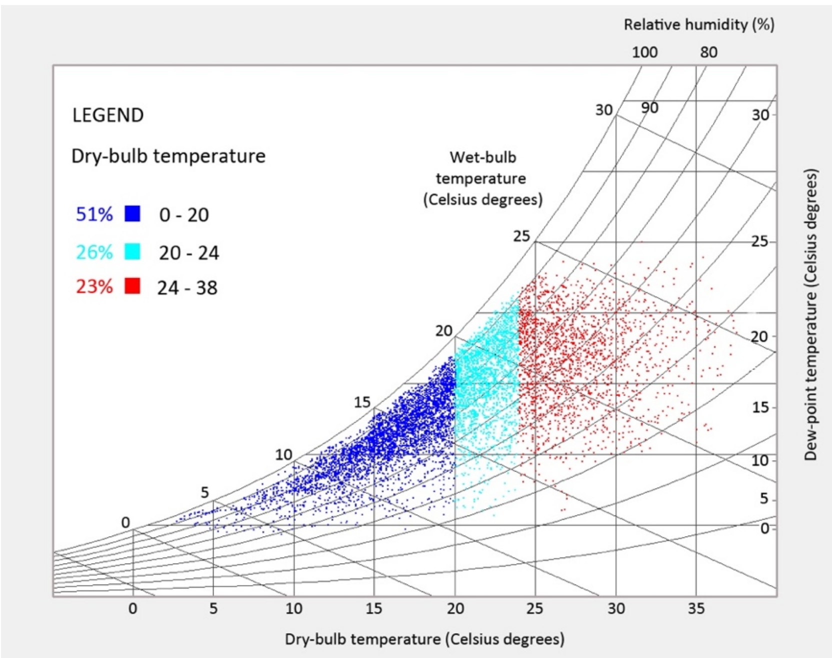


Figure 2.6: Psychrometric chart for the EPW weather file of Porto Alegre (Based on Climate Consultant (DOE, 2017))

This section highlights the challenges posed by Porto Alegre's climate to thermal comfort. The city combines high humidity, high daily amplitude and rain in all months of the year. It presents warm summers and cold winters. The combination of these characteristics represents an extra-effort to provide indoor thermal comfort in housing projects, especially those based exclusively on natural ventilation. The intensity and height of solar radiation, and the rain frequency (typically, all months of the year), are favourable aspects to the use of green roofs in Porto Alegre. The city has neither snow nor extremely high wind speeds, factors that could pose difficulties for the green roof establishment or, at least, would imply on a narrowed option of species selection.

2.2 Requirements of Brazilian Standards

To date, two Brazilian Standards address requirements for the building envelope, regarding thermal comfort: NBR15575 (ABNT, 2013) and NBR 15220 (ABNT, 2005). Since the creation of the NBR 15575[1], several requirements regarding building performance must be met. NBR15220 divides the country into eight climatic zones. It was the first step forward to improve indoor thermal comfort, especially in social housing projects. According to the climatic zone, the Standard defines recommendations for building elements (as the maximum thermal transmittance of walls and roofs). According to NBR15220 – part 3 (ABNT, 2005), Porto Alegre belongs to the Climatic Zone 3, as illustrated in Figure 2.7. Table 2.4 presents the minimum requirements of thermal properties for the building envelope in Zone 3 (to which Porto Alegre belongs), according to NBR 15220 – part 3.

[1] Regarding thermal comfort, this standard complies with the NBR 15220.

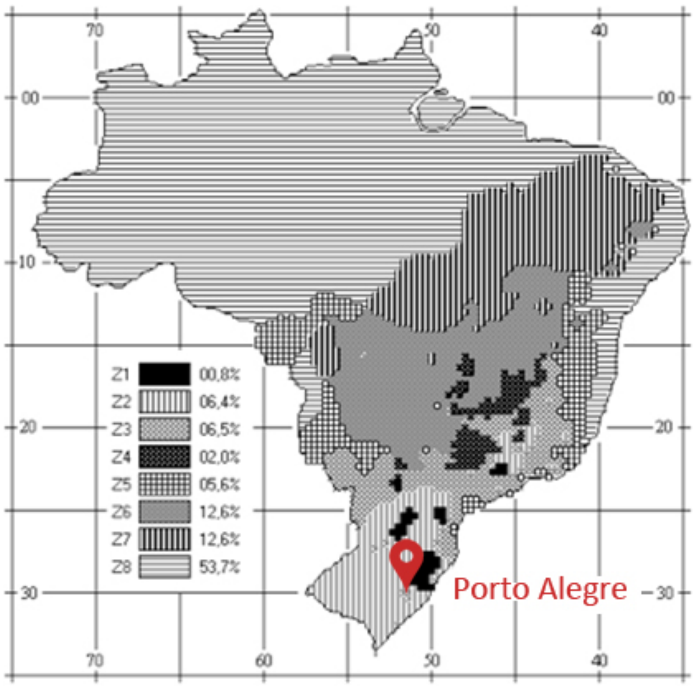


Figure 2.7: Brazilian climatic zones and location of Porto Alegre. Adapted from NBR15.220-3, (ABNT, 2005)

Table 2.4: Brazilian Climatic Zone 3: minimum requirements of thermal properties for the building envelope, according to NBR 15220-3 (ABNT, 2005)

Components	Thermal transmittance U (W/m^{2}K)	Time-lag[2] φ (hours)
Roofs	U ≤ 2,00	φ ≤ 3,3
External walls	U ≤ 3,60	φ ≤ 4,3
Internal walls	With high thermal inertia	
Windows	windows area < 15% room floor area < 25%	
Strategies	Summer	Winter
	Cross-ventilation	Solar heating
	Shaded windows	–

[2] According to the Brazilian Standard NBR 15220-1 (2010), a time-lag is the time lapse between a thermal change in a place and its effect on a surface of a constructive component, under a periodic condition of heat transfer.

Brazil is a developing country that historically has not provided the best possible quality to its social housing programmes. Although technological knowledge exists, it is not reflected in the design or best practices for the houses provided by the government to the low-income population. On the contrary, the cost has usually been the aspect that guide all decisions taken. Since the creation of the NBR 15220, social housing projects need to comply with minimum requirements, regarding thermal comfort. Prior to the standards this was not a concern, as it can be observed in the building stock. Those minimum requirements, however, are not sufficient to provide good thermal insulation on the building envelope – it can be observed, for instance, by the high U values allowed. It is thus relevant to study ways to increase the thermal comfort indoors and green roofs offer a possibility of doing that.

2.3 The studied residential project

The residential project studied in this investigation was selected for its compliance with the following criteria:

- Being naturally ventilated, that is, no space conditioning is used;
- Belonging to a social housing programme: the selected project was approved by the Brazilian social housing programme "*Minha Casa, Minha Vida*", funded by The Brazilian Government. Besides, the project´s typology (one-storey semi-detached houses) is very common in social housing projects in Brazil;
- Being developed to be used (at least, but not only) in the Brazilian Climatic Zone to which Porto Alegre belongs (Climatic zone 3);
- Having a roof slope where it is possible to install a green roof: the roofing in the project has a pitch of 40% (21^{o} 8');
- Presenting a concern about thermal comfort: as a requirement to be approved by the social housing programme named "*Minha Casa, Minha Vida*" the project needed to comply with the Brazilian Standard NBR15.575 (ABNT, 2013), that addresses requirements for residential buildings' performance. In this Standard, the evaluation of thermal performance in naturally ventilated spaces is mandatory.

2.3.1 Overview of the studied residential project

The project is characterised by one-storey, naturally ventilated, single-family semi-detached houses, as shown in Figure 2.8. Figure 2.9 shows the site area partially modelled (as detailed in Chapter 4 (Method)).

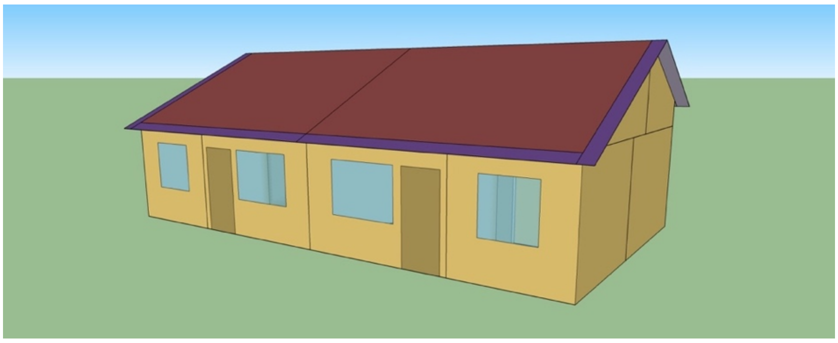


Figure 2.8: The twin-house modelled in SketchUp for the simulation in EnergyPlus – main façade

Figure 2.9: Settlement layout. Based on ACPO (2014) [3]

Although not a requirement for the project selection, it is worth mentioning that the studied project was built in 2014 in the city of Candiota, which belongs to the same state as Porto Alegre (Rio Grande do Sul). Moreover, the external walls of pre-fabricated concrete were considered innovative[4], as the conventional constructive system for

[3] Colours are symbolic.

[4] The "itt Performance" (Technical Institute in Performance and Civil Construction), belonging to The University of Rio dos Sinos has checked the

social housing in Brazil is brick masonry. As so far there is no constructed project in Porto Alegre, the project built in the city of Candiota was selected for the urban configuration. The design concept was created to be implemented in any place in the country as long as adjustments in the project, providing adaptation to climate, are provided. Therefore, for future studies, the design of the urban project is likely to present different configurations.

2.3.2 Constructive system

The external walls of solid concrete are fabricated in an industrial unit and then transported to the building site and assembled (Figure 2.10). In addition to being external walls of the building envelope, they also have a structural role.

Figure 2.10: External walls of the constructive system, being assembled in the city of Candiota, Brazil (ACPO, 2014)

The external walls have a minimum density of 2,300kg/m^3 and 100mm thickness. The internal walls are made of plasterboards fixed to a metallic structure, having a total of 95mm thickness (12.5mm thick plasterboards on both sides). The roofing system is composed of a metallic lattice structure, ceramic tiles and an 8mm polyvinyl chloride (PVC) ceiling. The ceiling height is 2,60m. The external doors are metallic, and the internal doors are made of wood. The windows are aluminum framed 3mm single glass. The living room and bedrooms have two leaf sliding windows; the bedrooms have metallic shutters on

project compliance to the requirements of Directive of the National System of Technical Evaluations (SINAT) n° 002.

the outdoors; kitchen and bathroom have louvre aluminum windows. The floor is composed of a cementitious floor screed and a shallow foundation of 70mm structural lightweight concrete. Figure 2.11 shows the ground plan of a twin-house dwelling. The complete architectural drawings are shown in Appendix A.

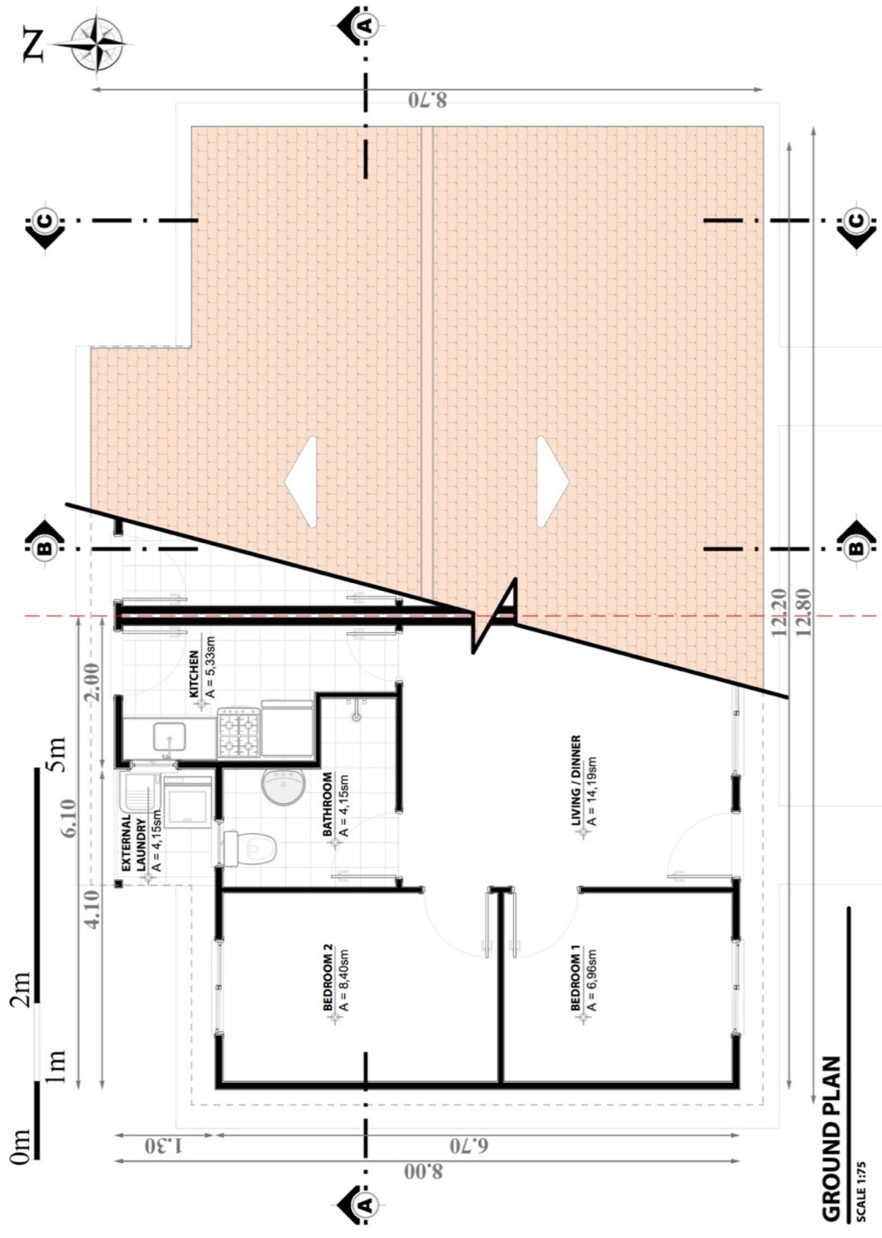


Figure 2.11: Ground Plan

3 Literature review

This Chapter presents a literature review on green roofs and thermal simulations with extensive green roofs. The chapter is divided into six sections. Section 3.1 presents a background about green roofs; Section 3.2 explains the thermal aspects of green roofs; Section 3.3 presents Brazilian studies on extensive green roofs; Section 3.4 discusses the building energy and microclimate simulation tools, followed by Section 3.5, that explores the effect of the microclimate on the impact of extensive green roofs indoor through the coupled outdoor-indoor simulation method; Section 3.6 includes the conclusions from this literature review.

3.1 Background about green roofs

Construction projects aiming to respond to contemporary environmental challenges have, among others, two complementary tasks:

- To revitalise passive design strategies previously employed in a specific climatic and cultural context, but not necessarily in use anymore due to the facilities in providing thermal comfort in active ways; and
- To increase knowledge about technical solutions that might have a positive contribution to the specific climate, but are not yet broadly employed within the particular context – as the case of green roofs in Brazil.

This section gives background information about green roofs. It will start from benefits and concerns, followed by a brief history, the classification and the components of a general extensive green roof.

3.1.1 Benefits and problems with green roofs

Green roofs can be flat or sloped, require different levels of maintenance and can support a wide range of vegetation – depending on the green roof system; it can vary from grass to small trees. Although not representing the most common use of green roofs, they can be designed to be accessible, accommodating human use (serving as a garden or a small park above the building). The same can be observed about food production: several authors have been studying and testing the possibility of food production on rooftops, as illustrated in Figure 3.1 (Colla et al., 2009; Whittinghill et al., 2013; Specht et al., 2014). Due to its complexity, green roofs present both environmental benefits and challenges to its implementation in urban areas.

Figure 3.1: food production on a green roof in Porto Alegre (Krebs, 2005)

Benefits associated with green roofs

Worldwide, several studies identify green roofs as one of the sustainable environmental strategies for both buildings and cities. They offer a broad range of benefits, which explains the growing interest both in the project/construction market and at the academic community. The range of benefits related to green roofs goes from a public perspective (benefits to urban spaces) to private use (increase on indoor thermal comfort). Those benefits include, among others: the improvement in biodiversity in city centers (Gedge & Kadas, 2005; Rowe, 2011; MacIvor, 2015); in air quality (Currie & Bass, 2008; Getter et al., 2009); an improvement in runoff water management (Villarreal, 2007; Berndtsson et al. 2009; Czemiel Berndtsson, 2010); aesthetical qualities (Butler et al. 2012; Blank et al., 2013; Jungels et al., 2013; Berardi et al. 2014; Lehmann 2014; Loder, 2014); and a contribution to reducing the Urban Heat Island effect (Chen et al., 2009; Santamouris, 2014; Alexandri & Jones, 2008; Susca et al., 2011; Wong & Lau, 2013);

Besides water management and retention, the most studied benefit of green roofs is their contribution to low-energy building projects (Jaffal *et al*., 2012; Feng & Hewage, 2014; Langston, 2015). Thermal performance of green roofs has been widely studied both by experiments (Emilsson 2008; Coma *et al.*, 2016; Scharf & Zluwa, 2017) and through simulations (Sailor, 2008; Jaffal *et al*., 2012; Boafo *et al*., 2017). Results have shown a good response regarding a reduction of mechanical cooling and heating needs in several climates. This literature review reveals advantages especially for the summer season when green roofs provide a decrease for the cooling requirements inside buildings (Jaffal et al., 2012; Skelhorn et al., 2016; Boafo et al., 2017).

Problems and concerns associated with green roofs

Green roofs present problems when not appropriately designed, constructed or maintained. Krebs & Sattler (2012) has evaluated the design, construction and maintenance of ten green roofs built in Porto Alegre and its vicinity. Problems associated with design included a lack of detailing in the roof's drainage (Figure 3.2) and the high complexity of the roof planes, incompatible with the capability of craftsmen (Figure 3.3).

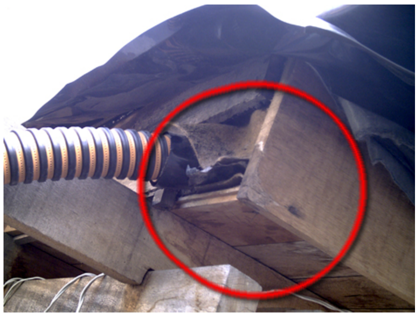


Figure 3.2: The lack of appropriate project detailing of a green roof, resulting in moisture due to drainage (Krebs, 2005)

Figure 3.3: Complex self-constructed green roof (Krebs, 2005)

Correa (2001) states that the self-construction of green roofs is common in Europe in countries like Spain, for instance. She recommends the self-construction only for small green roofs, with a lower level of complexity.

Bad choices regarding the choice of species and the level of plant coverage were found within the studied roofs, as exemplified in Figure 3.4. Additionally, the wrong orientation resulted in problems to the vegetation growth, compromising the health of plants and the performance of the entire green roof system. Figure 3.5 illustrates a green roof oriented to the South, in Porto Alegre (equivalent to the North orientation, in the North Hemisphere).

Figure 3.4: Lack of plant coverage in a green roof built in Porto Alegre (Krebs, 2005)

Figure 3.5: Green roofs oriented to the South (a) with significant areas without plant coverage; and (b): with insufficient plant coverage. (Krebs, 2005)

Concerns about green roofs are also related to the environmental perception. They are divided between a positive and a negative view on increasing nature in urban areas (*biophilia* and *biophobia,* respectively). The term employed to describe the negative view about vegetation, specifically, is *botanophobia*. Ulrich (1993) states that the negative view has a genetic component. According to the author fear, and even full-blown phobias of snakes and spiders, for instance, are quick to develop with very little negative reinforcement.

Krebs et al. (2012) conducted a qualitative study based on interviews, to understand the perception people in Porto Alegre had about green roofs. Results indicated an interest about green roofs, and a strong association with indoor thermal comfort and aesthetical gains to the cities, among other benefits. As negative perceptions, responses pointed mainly to a high maintenance need and infiltration. The fear of insects was also mentioned but by fewer respondents. Findings from that study demonstrated a gap in general information about green roofs in Porto Alegre.

As mentioned, one of the negative perceptions associated with green roofs is related to infiltration, by the idea that the roots will eventually reach and damage the waterproof layer. The combination of plant species with non-aggressive roots together with the inclusion of the anti-roots membrane is, in theory, capable of avoiding the problem. So far, there is no scientific evidence of infiltrations due to the destruction of the anti-roots membrane in adequately designed green roofs.

Regarding the fear of insects, the research conducted by Wong & Jim (2016) explored the temporal and spatial dynamics of vector abundance in urban green space with a particular focus on green roofs in Hong-Kong. After one-year of field study, findings indicated that green roofs were not particularly hospitable to vector mosquitoes. Instead, the study concluded that the availability of water sources is a crucial element for mosquitos' habitat. That was explained by the relatively large number of captured vector mosquitoes at ground level, in blue-green spaces.

3.1.2 Brief history of green roofs

Several authors claim that the Hanging Gardens of Babylon (one of the Seven Wonders of the Ancient World, from approximately 590 B.C.) can be considered as the first register of green roofs in history (**Ascione** et al., 2013; Li & Yeung, 2014; Berardi et al., 2014; Vijayaraghavan, 2016; Ebrahimnejad et al., 2017; He et al., 2017).

It is of a common knowledge that the northern Europe Viking population constructed green roofs to protect their houses against wind, rain, and thermal heat loss. Ascione et al. (2013) speculate that green roofs in Scandinavia probably have existed since prehistory. Examples of old-style green roofs can be found in the ancient dwellings (popularly called turf houses) of the Faroe Islands (Figure 3.6).

Figure 3.6: Example of ancient green roofs in Faroe Islands (Smith, 2016)

Modern green roof technology has its origin in several different countries and various climates (Köhler et al., 2003). Extensive green roofs (see Table 3.1) can be seen as a modern type of the roof-garden concept (Britto, 2001; Oberndorfer et al., 2007). Today's green roof have their origin in the end of the 20^{th} century in Germany, where vegetation was installed on roofs to mitigate the damaging physical effects of solar radiation on the roof structure (Oberndorfer et al., 2007).

In the 1920's Le Corbusier, inspired from Mediterranean vernacular architecture, proposed the idea of the fifth façade or 'living on the roof,' (e.g., in "Ville Radieuse" from 1922 and in "Une Petite Maison" from 1924). Later on, two famous examples of modernist buildings where Le Corbusier has designed a green roof are the "Maison Jaoul" from 1951 at Neuilly-sur-Seine (Figure 3.7) and in "La Tourette" from 1960 in Rhone, France (Figure 3.8).

Figure 3.7: Green roof of Le Corbusier: Maison Jaoul (Hamatany, 2013)

Figure 3.8: Green roof of Le Corbusier: Maison La Tourette (Keagle, 2011)

The roof gardens of the Rockefeller Center (called "Gardens of the Nations"), in New York, are famous examples of green roofs in the USA in the 1940's (Figure 3.9). Köhler et al. (2003) inform these areas require maintenance most similar to gardens.

Figure 3.9: Vintage drawing of a green roof at the Rockefeller Center (AMPLE, 2014)

Lehmann (2014) states that in the 1990's, Germany established acknowledged standards for green roof construction, which are considered the oldest regulations including how to accurately detail green roofs. According to the International Green Roof Association – IGRA (2018), the most known guide is the "Guidelines for the planning, execution, and upkeep of green roof sites" from The Landscaping and

Landscape Development Research Society (FLL) in Bonn, Germany. These guidelines contain suitable vegetation, requirements for construction and maintenance guidelines for different green roof types. The content, however, is mainly suitable to the European climate and the many German green roof system build-ups, as observed by IGRA (2018). Vijayaraghavan (2016) attributes to that first initiative by Germany – followed by other European countries – the growing popularity of green roofs in other parts of the world, in the last three decades. There is still a lack of guidelines for the majority of other climates, including the Brazilian ones.

In Brazil, the first documented green roof was conceived by the landscape designer Roberto Burle Marx at the "Gustavo Capanema Palace"[5], in Rio de Janeiro. The building, designed by the architects Lucio Costa, Oscar Niemeyer and team with the consultancy of Le Corbusier, was inaugurated in 1943 and until now keeps the intensive green roof (Figure 3.10).

Figure 3.10: Intensive green roof at Gustavo Capanema Palace, in Rio de Janeiro (Fracalossi, 2013)

Also from Roberto Burle Marx is the green roof of the Ministry of Foreign Affairs (Figure 3.11). The building design is from Oscar Niemeyer in 1962.

[5] The building is also found in literature by the name given by its use: Building of the Ministry of Education and Culture, or by its abbreviation MEC.

Figure 3.11: Intensive green roof at the Ministry of Foreign Affairs in Brasilia (Raggett, 2018)

The "São Paulo Cultural Center" (Figure 3.12), designed by the architects Eurico Prado Lopes and Luiz Telles, was inaugurated in 1979 in São Paulo. The building is a cultural centre, and the green roof in there is an example of the accessible roof garden.

Figure 3.12: São Paulo Cultural Center (SP Bairros, 2017)

In Porto Alegre, the architect Jorge de Biagi constructed the first green roof in 1978, for his own home and office (Figure 3.13). Although the extensive green roof can be easily accessible, it is not designed for human use.

Figure 3.13: The first green roof in Porto Alegre (Krebs, 2005)

3.1.3 Classifications of green roofs

This section explains the types of green roofs according to the most known classification (maintenance), and according to two other classifications (by slope and by construction technique).

Green roofs classification according to maintenance

For many years, green roofs have been classified into two types: intensive and extensive. Currently, several authors add the semi-intensive form to the other two (Berardi et al., 2014; Li & Yeung; 2014; Hashemi et al., 2015); Karteris et al., 2016; Silva et al., 2016; Vijayaraghavan, 2016). It is worth pointing out that, when classifying a green roof, the primary factor to be considered is the level of maintenance required. Thereby, a green roof with constructive characteristics of the extensive type (like substrate height, for instance), due to a choice of plants and their response to the environment can demand a higher level of maintenance, becoming a semi-intensive or even an intensive green roof (regardless of being a light-weight roof).

The influence of the environment can also change the classification, like for instance: wind velocity; shadowing by trees, buildings or even parts of the building itself; rain frequency (or the lack of it, like in periods of drought). If any of these environmental aspects results in a higher need for maintenance, an extensive green roof can become a semi-intensive or an intensive type. An understanding of the green roof as a complex system will help the designer to be successful in the correct specifications for the different components of the green roof, helping him or her to achieve the initial goals with the proposed green roof project.

Vijayaraghavan (2016) states that shrubs and small trees typically require high maintenance in the form of fertilising, weeding and watering. Minke (2004) observes that (mainly) extensive green roofs usually tend to include plants from the site where they are installed: even if it is not an initial idea, birds bring seeds and, if not removed, they adapt quickly to the roof. Emilsson (2008) corroborate that fact: the author has registered 39 spontaneously established species in the green roofs over a 3.5-year experiment realised in Sweden.

As previously explained in Section 1.1, the extensive green roofs are the most common type of vegetated roofs: they have the lowest initial cost, usually no need to reinforcement in the roof structure and lowest maintenance need. Because of their low weight, they are suitable for renovations (Ferreira, 2014). Besides that, between moss, herb and grass it is possible to have a wide range of plants to specify on a green roof. Extensive green roofs are the type suggested for use from flat to sloped roofs like the ones in the twin-houses selected for this study. Although it can be found in the literature a relatively low energy performance (and rainwater management) of the extensive green roofs, if compared to the intensive type (Lepp, 2008; MacIvor et al., 2013), the majority of studies suggest them as one of the strategies with a good thermal response in several climates. Together, these characteristics have motivated the choice of the extensive green roof for the investigation.

Supported by evidence from a broad literature review, Berardi et al. (2014) have summarised characteristics of intensive and extensive green roofs. Table 3.1 illustrates their results adding to them attributes of semi-intensive green roofs, based on the current classification from the International Green Roof Institute (2017).

Table 3.1: Classification of green roofs and their primary attributes. Based on Berardi et al. (2014).

Main attributes	Extensive	Intensive	Semi-intensive
Thickness of substrate	Below 200mm[6]	Above 200mm	Between 120 and 250mm
Accessibility (use as a garden)	Inaccessible (fragile roots)	Accessible (usable for recreation purpose)	No information
Weight	60–150 kg/m^2	Above 300 kg/m^2	150 - 300 kg/m^2
Diversity of plants	Low (moss, herb, and grass)	High (lawn or perennials, shrub, small trees)	Medium (grass-herbs and shrubs)
Construction	Moderately easy (normal or slightly reinforced structure)	Technically complex (might need a reinforced structure)	Might require a reinforced structure
Irrigation	Often not necessary	Necessity of drainage and irrigation systems	Regularly
Maintenance	Low	High	Periodically
Cost	Low	High	Medium/high
Main commercial use	Ecological thermal protection layer	Park-like garden	Green Roof as a garden

Green roofs classification according to slope

Minke (2004) divides green roofs according to slope into the following four types:

- Up to 5% slope (approximately 3º) – flat roof.
- From 5% to 35% slope (approximately 3º to 20º) – light slope;
- From 35% to 84% (approximately 20º to 40º) – high slope;
- From 84% (approximately 40º) – sloped (or pitched).

[6] Although it is common to have 200mm as a limit for the substrate depth in extensive green roofs, it is also possible to find literature and in commercial green roof companies 150mm as the limit, instead.

Flat roofs are more susceptible to damages if they do not receive the same maintenance level as an ordinary garden. Minke (2004) explains that flat roofs are highly exposed to humidity oscillations. To avoid that problem, they need thicker substrate layers, increasing the weight to the roof structure. Particular attention must be given to the drainage layer: at the same time, it needs to perform proper drainage and to keep a certain level of water in the roof, so it will not become dry. For these reasons, flat roofs are not intended for extensive green roofs according to Minke (2004). Observation must be made, though: due to new technologies, that provide appropriate drainage (as new technological drainage membranes), there are flat extensive green roofs with good resistance to the climate challenges. In Sweden, for instance, it is not rare to see green roofs with approximately 50mm thickness, flat, and extensive.

In light slope roofs, the substrate layer works alone as a drainage layer. For this kind of slope, Minke (2004) suggests the addition of materials with high porosity (as expanded clay or pumice stone) to the substrate layer: they can simultaneously increase the oxygen levels (increasing roots breathing and thermal insulation properties) and decrease the weight to the roof structure.

From high slope to sloped (also called pitched roofs) the drainage layer can be thinner compared to the other slopes, due to the quicker runoff and smaller absorption of rainwater. On the other hand, sloped green roofs require prevention of sliding. Minke (2004) state that these restrictions shall be rounded (smooth), to prevent damages to the waterproofing membrane, as illustrated in Figure 3.14. Another solution is adding an anti-slide membrane supporting the substrate.

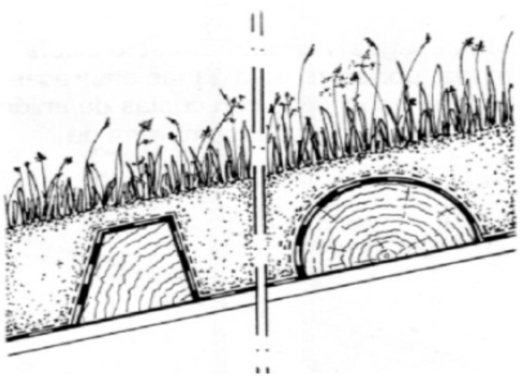
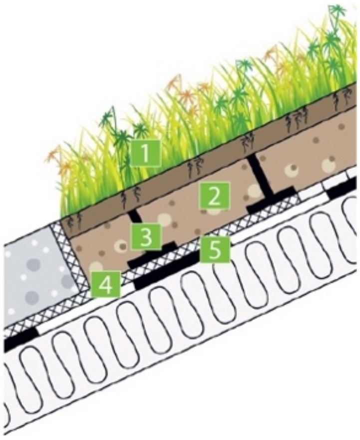


Figure 3.14: Barriers to avoid landslide in high slope and sloped green roofs (Minke, 2004).

Figure 3.15 illustrates a high-tech solution to avoiding sliding when the physical barriers in the substrate are included. Figures 3.16 (a) and (b) illustrate the barriers integrating the concrete slab in a sloped green roof, (44º sloped).



1 – vegetation mat
2 – substrate
3 – anti-slip system
4 – drainage mat
5 – protection and storage mat

Figure 3.15: Physical barriers to avoid landslide in an extensive green roof (Atelier Growenblaun, 2018)

(a) (b)

Figures 3.16 (a) and (b): Roof slab with barriers integrated, in a green roof in Nova Petrópolis, Brazil (The author, 2005)

Green roofs classification according to construction technique

Berardi et al. (2014) divide green roofs according to the construction technique: complete system, a modular system or pre-cultivated blankets, as shown in Table 3.2. The author explains the differences: while a full system encompasses the entire roof, the other two can be planted before being integrated above the rooftop.

Table 3.2: Design construction classification of green roof systems (Berardi et al., 2014).

Aspects	Pre-cultivated system	Modular system	Complete system
System	Pre-planted	Pre-planted	Layered system
Weight	Low	Average	High
Installation	Simple and fast	Simple and fast	Complex
Maintenance	Simple	Simple	Complex
Cost	Low	Average	High

3.1.4 Extensive green roofs' components

The organic components of the green roof are divided into two layers: the vegetation layer and the substrate layer. Together, they are also named "gardening layer". The specification of these layers is a key factor to the green roof´s performance. A general extensive green roof is composed of several layers, as illustrated in Figure 3.17.

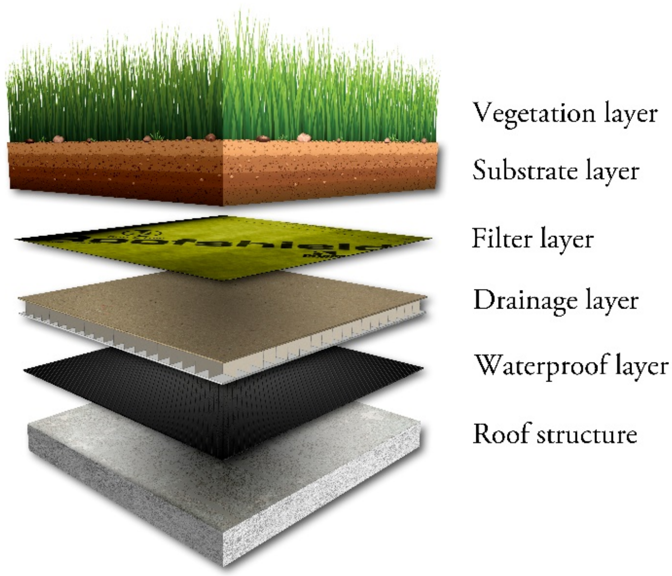


Figure 3.17: Layer scheme of a generic extensive green roof

A description of the layers composing the generic extensive green roof of Figure 3.17 is given as follows:

- Vegetation layer: as the outer part of the green roof, it is the component more exposed to climatic conditions like wind, rain and solar radiation. Depending on the technique employed, the vegetation can be planted on the roof or pre-planted, and then installed on the roof. Because of the thinner substrate layer, extensive green roofs present restrictions for plant species. Particular attention must be given to the roots: species with aggressive roots must be avoided. The most common species with extensive green roofs are moss, herbs and grass as mentioned before (in Table 3.1);
- Substrate layer: although less than the vegetation, it is also exposed to climatic conditions. In extensive green roofs, it varies from 50mm to 200mm (see Table 3.1) and the most common type of substrate is earth. A variety of materials can be added to its composition to improve its thermal performance;
- Filter layer: it has the function of avoiding the earth from the substrate layer to pass to the drainage layer. Commonly it is a geo-textile membrane;
- Drainage layer: it is efficient when it keeps an adequate level of humidity in the roof, compatible with what is needed to the vegetation chosen. Therefore, it is essential to have a lower density and a more significant porosity in the drainage layer, in comparison with the substrate. In more high-tech green roofs systems it is an industrialised material (like geo-textile facings with thermally bonded UV resistant woven nylon loops between). In rustic green roofs, it can be a combination of expanded clay and sand, or of light gravel and sand, for instance.
- Waterproof layer: this membrane avoids water and moisture to leak to the roof structure. Particular attention must be given to the correct specification and installation of this layer. The waterproofing membrane can be asphalt/bitumen or synthetic. Depending on the membrane specified, a root barrier layer can be added above it.

Considering the extreme environment on rooftops, vegetation with extensive green roofs must have the capacity of withstanding rough conditions, while requiring low maintenance. Vijayaraghavan (2016) lists characteristics compatible with those requirements, which can help in the best plant selection:

- Survive under minimal nutrient conditions;
- Rapid multiplication (good ground coverage);
- Short and soft roots;
- Phytoremediation[7].

3.1.5 Concluding remarks

This section showed that the benefits associated with green roofs are many and in different scales: from the building user to the city scale. On the other hand, the problems are related to the small scale, at a constructive level. The environmental perception of green roofs is associated both with benefits (as aesthetics) and concerns (as the fear of insects). That subject, so far, lack a higher number of investigations.

Although green roofs were firstly introduced in colder climates and with a low level of technology involved, this reality has changed since the 20th Century. To date, green roofs are built in several climates around the world, and with different compositions: from low to high level of technology. As previously mentioned, the interest in green roofs has also increased in Brazil, in projects aiming to provide the benefits of a roof garden. This part of the literature review shows there is a lack of systematic studies on the history of green roofs in different climates presenting quantitative data, as the number and location of green roofs built over the years, analysis of detailed design and user's perception, for instance.

[7] Phytoremediation is the process of decontaminating the air, water or soil through the use of plants (or trees), that will absorb or break down pollutants.

3.2 Energy balance of roofs

This section presents the distinct thermal fluxes in a conventional and a green roof energy balances[8]. This analysis helps to understand the influence of the variables on thermal comfort (indoors and outdoors).

3.2.1 Energy balance of conventional roofs

Figure 3.18 shows the energy balance of a conventional[9] roof.

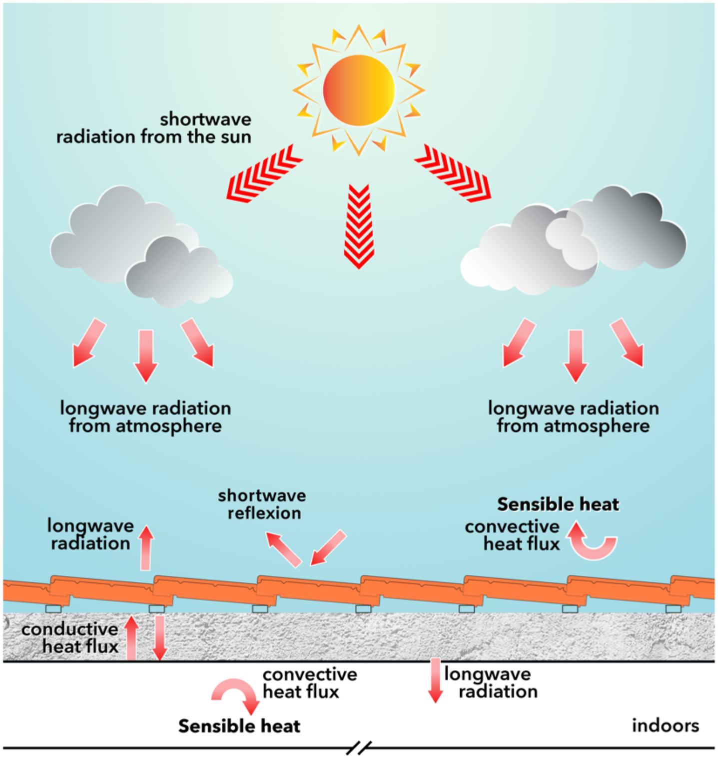


Figure 3.18: Energy balance of a conventional roof

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[8] Energy balance refers to the physical fact that energy cannot be created nor destroyed so that the solar and longwave radiation energy received by a rooftop layer during any time interval must be exactly equal, or 'balance,' the energy gained by that layer minus that lost from the layer during the same time interval (Gaffin et al., 2005).

[9] In the scope of this research, a conventional roof is a non-vegetated roof.

Compared to a green roof, the energy balance of a conventional roof can be considered as simpler, as it does not involve the interaction with the heat fluxes from soil and vegetation. The energy balance (calculation) of a conventional roof takes into account the following factors: incident short-wave radiation from the sun (*I*) and its absorbed portion (depending on the albedo of the outer roof surface); long-wave radiation exchange between the roof and the atmosphere (q *radiant*); convective heat exchange with the outside environment (q_{out} *convective*); heat exchange with the indoor environment (q_{ind} *conductive*, addressing the conduction heat flux); and convective heat exchange with the inside environment (q_{ind} *convective*).

The heat transferred to the indoors through the roof is primarily a function of the difference between the external temperature of the roof and the indoor temperature and takes into account the total thermal resistance (R_{i_se}) of all roof layers plus the inner surface resistance (Gagliano et al. 2015). The energy balance of the conventional roof is explained by Equation (1), adapted from Costanzo et al. (2014):

$$\frac{T_{se}-T_i}{R_{i\_se}} = (1-\propto_r).I_s^{\downarrow} - \left[\sigma.\varepsilon.\left(T_{se}^4 - T_{sky}^4\right) + h_c.(T_{se}-T_o)\right] \qquad \textbf{(1)}$$

Where:

$\frac{T_{se}-T_i}{R_{i\_se}}$ is the heat transferred

T_{se} = outer surface temperature (K)

T_i = indoor temperature (K)

R_{i_se} = thermal resistance of the roof layers plus the internal surface layer[10] ($m^2\,W^{-1}$)

$(1-\propto_r).I_s^{\downarrow}$ is the heat absorbed

$\propto_r$ = albedo (short-wave reflectivity) of the roof's outer surface

$I_s^{\downarrow}$ = net incoming short-wave radiation (W/m^2)

$\sigma.\varepsilon.\left(T_{se}^4 - T_{sky}^4\right)$ is the radiant heat

---

[10] R_{i_se} accounts for the sum of the individual resistances (R) of each roof layer plus the internal surface layer. R = e / λ (W/(m².K)), where "e" is the material thickness (m), and "λ" is the thermal conductivity of the material (W/(m.K)).

σ = Stefan-Boltzmann constant (5.67 x 10^{-8}W/m^2 K^4)
ε = thermal emissivity of the roof's inner surface
T_{sky}^4 = sky temperature (K)

$h_c.(T_{se} - T_o)$ is the convective heat flux (= H_c)
h_c = convective heat transfer coefficient (W m^{-2} K^{-1})
T_o = outdoor dry-bulb temperature (K)

3.2.2 Energy balance of green roofs

Figure 3.19 illustrates the energy balance of a typical green roof.

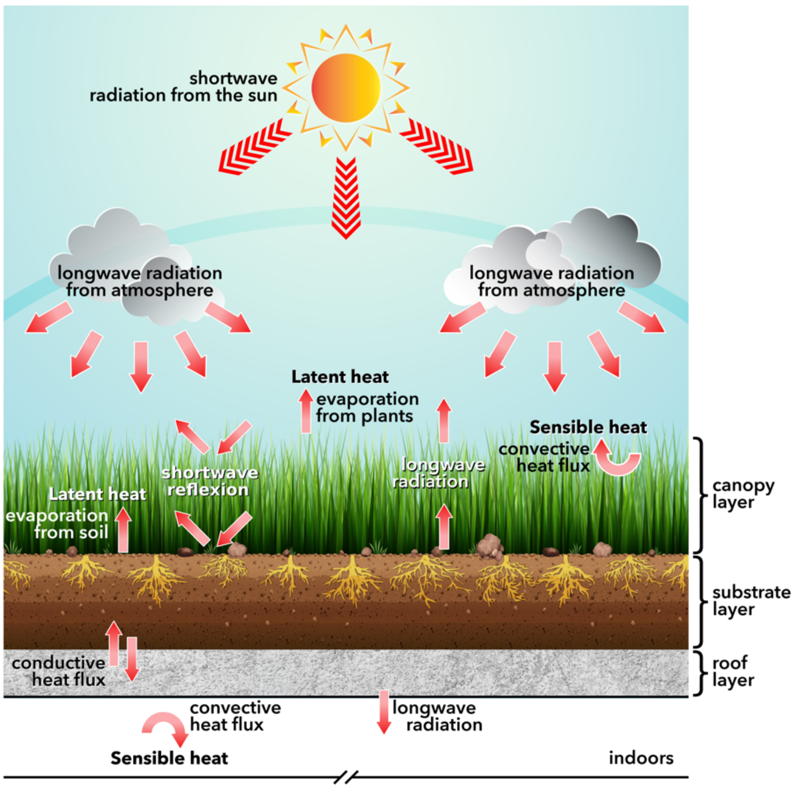

Figure 3.19: Energy balance of a typical green roof

As in a conventional roof, the energy balance of a green roof is dominated by the radiative forcing from the sun. This solar radiation is balanced by sensible (convective), and latent (evaporative) heat fluxes from soil and plant surfaces, combined with conduction of heat into the soil substrate and long-wave (thermal) radiation to and from the soil and leaf surfaces (Sailor 2008).

The heat transfer in a green roof begins to be different from the heat transfer in a conventional roof at its outer layer, where the fractional vegetation coverage determines the percentage of incoming radiation that will reach the soil layer. This shadow from the foliage to the soil layer will provide the first cooling effect from the green roof to the roofing system, through the physical blocking of incoming solar radiation.

The evapotranspiration[11] of plants and soil play a crucial role in the green roof thermal flux. In EnergyPlus, the contribution of the thermal fluxes for the energy balance calculation is divided in two equations: one for the foliage layer and one for the substrate. A green roof thermal flux calculation adds to the roof calculation, though, four new equations[12]: the sensible and the latent heat fluxes in the vegetation layer and the sensible and the latent heat fluxes in the soil layer.

The *foliage* energy balance (F_f) accounts for the sensible and latent heat fluxes in the foliage layer. Its calculation is made by the Equation 2, given by Sailor (2008):

$$F_f = \sigma_f . [\, I_s^{\downarrow} . (1 - \propto_f) + \varepsilon_f . I_{ir}^{\downarrow} - \varepsilon_f . \sigma . T_f^4] + \frac{\sigma_f . \varepsilon_g . \varepsilon_f . \sigma}{\varepsilon_1} . (T_g^4 - T_f^4) + H_f + L_f \quad \textbf{(2)}$$

Where:

F_f = the net heat flux to the foliage layer (W/m^2)

σ_f = fractional vegetation coverage

$I_s^{\downarrow}$ = total incoming short-wave radiation (W/m^2)

$\propto_f$ = albedo (short-wave reflectivity) of the canopy

ε_f = emissivity of the canopy

$I_{ir}^{\downarrow}$ = total incoming long-wave radiation (W/m^2)

---

[11] Evapotranspiration is the water released to the atmosphere from the soil by evaporation and from the plants by transpiration.

[12] All equations detailing the calculation of the green roof energy balance are described in Sailor (2008).

σ = Stefan-Boltzmann constant (5.67 x 10^{-8}W/m^2 K^4)

T_f = foliage temperature (K)

ε_g = emissivity of the ground surface

$\varepsilon_1 = \varepsilon_g + \varepsilon_f - \varepsilon_f . \varepsilon_g$

T_g = ground surface temperature (K)

H_f is the foliage sensible heat flux (W/m^2), that accounts for the convective heat flux between vegetation and air

L_f is the foliage latent heat flux (W/m^2) that accounts for the transpiration of plants

The *soil* energy balance (F_g) accounts for the sensible and latent heat fluxes in the soil layer. Its calculation is made by the Equation 3, given by Sailor (2008):

(3)

$$F_g = (1-\sigma_f).\left[I_s^{\downarrow}.(1-\alpha_g) + \varepsilon_g . I_{ir}^{\downarrow} - \varepsilon_g . \sigma . T_g^4 \right] - \frac{\sigma_f . \varepsilon_g . \varepsilon_f . \sigma}{\varepsilon_1} . (T_g^4 - T_f^4) + H_g + L_g + K_v . \frac{\partial T_g}{\partial_z}$$

Where:

F_g = net heat flux to ground surface (W/m^2)

σ_f = fractional vegetation coverage

$I_s^{\downarrow}$ = or total incoming short-wave radiation (W/m^2)

α_g = albedo (short-wave reflectivity) of ground surface

ε_g = emissivity of the ground surface

$I_{ir}^{\downarrow}$ = total incoming long-wave radiation (W/m^2)

σ = Stefan-Boltzmann constant (5.67 x 10^{-8}W/m^2 K^4)

T_g = ground surface temperature (K)

ε_f = emissivity of canopy

$\varepsilon_1 = \varepsilon_g + \varepsilon_f - \varepsilon_f . \varepsilon_g$

T_f = foliage temperature (K)

H_g is the ground sensible heat flux (W/m^2), that accounts for the convective heat fluxes between the soil and the air

L_g is the ground latent heat flux (W/m^2), that accounts for the evaporation of the soil

K_v is von Karmen constant (0.4)

∂T_g = variation of ground temperature (K)

∂_z = variation of soil thickness (m)

$\frac{\partial T_g}{\partial_z}$ = conduction of heat into the soil layer.

In 2007, Sailor (2008) implemented a physical model of the energy balance into the green roof module incorporated in EnergyPlus called "Ecoroof," which is the algorithm used by this software for green roofs' thermal calculations. The Ecoroof model will be explained further, in Section 3.4.1 (Green roof thermal-energetic simulation model). The energy balance equations previously described are illustrated by Sailor (2008), as shown in Figure 3.20.

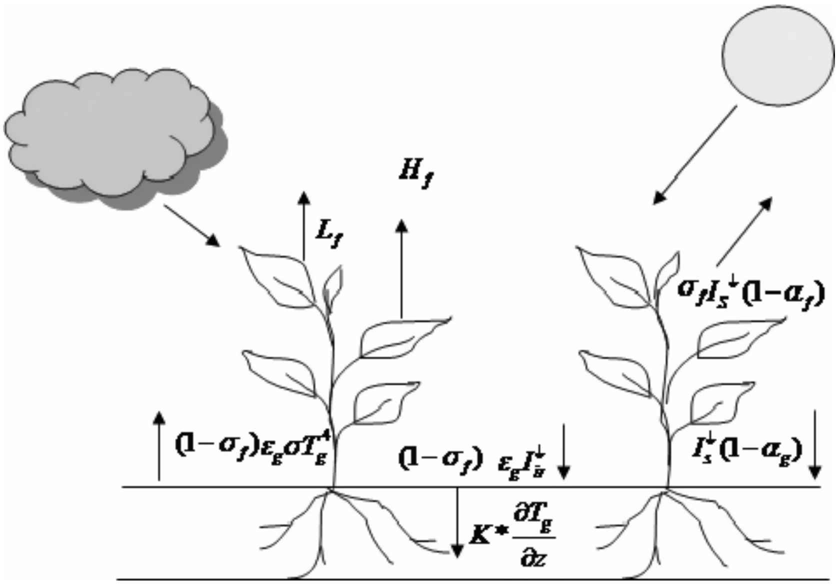

Figure 3.20: Green roof of a generic green roof (Sailor, 2008)

3.2.3 Concluding remarks

This section showed that the energy balance of a green roof includes a far more complicated calculation than a conventional roof. The green roof interacts with the weather conditions, the microclimate in which it is located, and the composition of the organic materials (soil and plants). A comparison between a conventional and a green roof can be like comparing a conventional roof with a garden. Thus, the albedo is not the only aspect to take into consideration when thinking about the effect of the roof on the indoor thermal comfort. Additionally, if an analysis of the microclimate is made, the radiation reflected by a conventional roof with a high albedo to the vicinity might increase the surface temperature of adjacent surfaces. Conversely, the effect of a green roof on the microclimate is similar to the effect of a small garden, thus, a cooling effect.

3.3 Studies on extensive green roofs in Brazil

The literature review on recent studies about extensive green roofs in Brazil focused on peer-reviewed academic journals. The search was carried out in the search engine *Lub Search*, from Lund University. Lub Search is linked to around 200 indexed databases (Lund University, 2018). Among the indexed databases are the ones with the biggest impact in the Built Environment field as "Scopus", "Science Direct", "Engineering Village" and "Scielo". The search was performed with the following terms:

- Brazil* or Brasil* and:
- "green roof*" or "vegetated roof*" or "eco* roof*" or "living roof*" or "planted roof*" or "roof* garden".

The hits were from 2011 to 2017. The search was limited to the English, Portuguese and Spanish languages. Four studies were excluded from results, as they were not focused on green roofs[13]. In total, six studies with extensive green roofs were found in the literature review following the criteria previously described, but only three of them addressed thermal comfort: Wilkinson et al. (2017), Wilkinson & Feitosa (2015) and Parizotto & Lamberts (2011).

The three studies evaluate indoor thermal comfort through experiments. No study with computer simulation or with outdoor microclimate were found in the international peer-reviewed academic journals. Table 3.3 shows the main focus and the research method of the Brazilian studies resulting from the search.

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[13] The four hits excluded from the literature review addressed other subjects as studies of national and international laws and public policies addressing green roofs; and studies of the study of the local legislation (at the municipality level) of Brazilian cities to evaluate the urban sustainability aspects.

Table 3.3: Main focus, method and green roof type of the Brazilian studies on extensive green roofs

Study	Main focus	Method
Noya et al. (2017)	Evaluation of substrate composition for perennial plants	Experiment
De Souza Uhmann & Tavares (2017)	Comparison of the embedded[14] energy and carbon dioxide (CO_2) emissions from a baseline roof with the ones from a green roof	Mathematic simulation
Wilkinson et al. (2017)	Influence of green roofs and green walls on indoor thermal comfort	Experiment
da Rocha & Sattler (2017)	Environmental perception: acceptance of green roofs, but also green walls and composting (or dry) toilets in a small town[15] in Southern Brazil	Surveys
Dias (2016)*	Influence of green roofs on indoor thermal comfort	Simulation
Rosseti et al. (2015)*	Influence of green roofs on outdoor microclimate at pedestrian level	Simulation
Wilkinson & Feitosa (2015)	Influence of green roofs on indoor thermal comfort	Experiment
Parizotto & Lamberts (2011)	Influence of green roofs on indoor thermal comfort	Experiment

* Studies published only in Brazilian literature. Not available in the indexed peer-reviewed academic journals.

Due to the very limited publication of Brazilian studies internationally, A search was made in the Brazilian search engine *Portal de Periódicos Capes*, and also in databases of Ph.D. and Master thesis in Brazilian universities. Therefore, two studies published only in Brazil were selected and added to the literature review. Firstly, a Master Thesis developed by Dias (2016) was included due to its

[14] Embedded energy is the measurement of the energy use in the lifecycle of a product, from its raw material extraction to its disassembly, deconstruction or decomposition. It also evolves all transport between the stages.

[15] The study was developed in the city of Feliz, with has 13,451 inhabitants, according to IBGE (2018).

relevance to the investigation, as it presents a simulation of indoor thermal comfort with extensive green roofs, performed with EnergyPlus. Secondly, an investigation conducted by Rosseti et al. (2015) in Cuiabá, Brazil, was included due to the use of ENVI-met to evaluate the influence of green roofs at pedestrian level. The investigation made by Dias (2016) is discussed in Section 3.4.1, and the investigation made by Rosseti et al. (2015) is discussed in Section 3.4.2.

An experiment study including warmer and colder periods was conducted by Parizotto & Lamberts (2011) in the city of Florianópolis. The city is in the Southern Region of Brazil and belongs to the Brazilian climatic zone 3, like Porto Alegre. Florianópolis has a temperate climate and higher levels of relative humidity. Field measurements took place in a single-family experimental house, assessing data from two periods: from 01 to 07 of March (summer), and from 25 to 31 of May (autumn). An extensive green roof (140mm of substrate and 200mm of plants) was compared to a ceramic roof and a cool roof (metallic, painted white). The ceramic roof consists of white ceramic tiles, wood batten, aluminised polyethene radiant barrier, mineral wool insulation and oriented strand board (OSB) wood ceiling. The metallic roof consists of solar photovoltaic panels, metallic panels of plate folded with white paint, rock wool insulation and OSB wood ceiling. The extensive green roof consists of a *Bulbine frutescens* vegetation layer, a soil substrate, a geotextile filter, gravel and a pebble drainage layer, reinforced mortar, extruded polystyrene insulation, no asphalt sealer and a concrete slab (Parizotto & Lamberts, 2011).

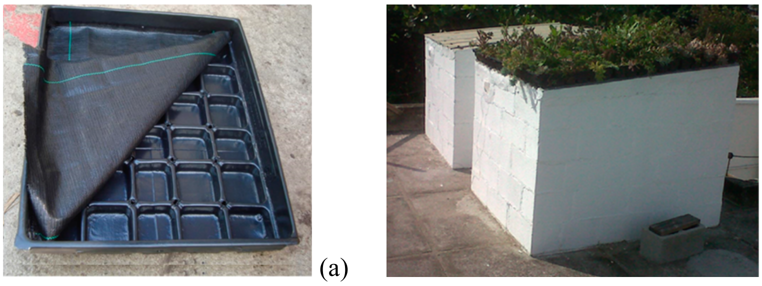
In both periods, the heat gain was reduced with the green roof: by 92% compared to the ceramic roof, and by 97% compared to the cool roof in the summer, and by 70% and 84%, respectively, in the autumn. The heat losses were enhanced in the summer by 49% compared with the ceramic roof, and by 20% compared with the cool roof. In the autumn, the heat losses were reduced by 44% and 52%, respectively. Parizotto & Lamberts (2011) concluded that the extensive green roofs are beneficial to the climate conditions of Florianópolis. According to the authors, in the summer there is a compensation of the lower evapotranspiration rates (due to the high relative humidity) with other beneficial effects: shading, insulation, and thermal mass. The authors claim these factors contribute positively to the green roof thermal fluxes in the warmer period, by reducing the heat gain and enhancing the heat loss.

Parizotto & Lamberts (2011) inform that, although the results showed that the green roof reduced the heat gain in both periods, in autumn the reduction in heat losses compensated the decrease in heat gains, making the energy balance of the green roofs beneficial to the indoors, especially if compared to the other two roofs. The authors point out that, although the three roofs belong to the same building, they were in different room positions and also had different roof slopes, as it can be seen in Figure 3.21. Consequently, the shading is not identical for all the roofs at any time given: the metallic roof is never shaded, while the green and the ceramic roofs receive some degree of shading in the afternoon. Also, the green roof is flat, while the other two are sloped. The shading from the solar panels in the cool roof is also something that should be pointed out, as it certainly influences the roof thermal balance. Although the study results are relevant to a comprehension on the thermal performance of extensive green roofs in the temperate climate of Florianópolis, the different conditions of the three roofs make the evaluation inaccurate, concerning the absolute values compared (surface temperatures, thermal fluxes and indoor T_{air}).

Figure 3.21: Experimental building with the green, ceramic and metal roofs: North façade view (a) and exterior view of bedroom 2 (b) (Source: Parizotto and Lamberts, 2011).

In the second study found, Wilkinson & Feitosa (2015) analysed through experiment the thermal performance of two small-scale portable modules with green roofs. The researchers aimed to evaluate the performance of a low-cost retrofit system, so they tested lightweight removable roofing modules of vegetation for metal tiles roofing. The experiment was developed in Sydney and Rio de Janeiro. As this literature review focuses on studies in the Brazilian context, the discussion will be restricted to the experiment located in Rio de Janeiro, on the roof of an existing building at the Oswaldo Cruz Foundation (Fiocruz).

The modular system was composed by rectangular containers measuring 400mm x 500mm with a low thickness (approximately 50mm), enabling planting and maintenance off-site to be undertaken (Figure 22(a)). The plants were *Sedum*, *Echeveria glauca* and *Kalanchoe quicksilver*, selected mainly because of their higher drought resistance, but also due to their ability of growth in shallow soils. The substrate was separated from the drainage layer by a permeable geotextile fabric (see Figure 3.22(a)). The system was installed on a small-scale prototype blockwork construction, and results on the thermal performance were compared to a traditional metal sheeting roof installed at the same site (Figure 3.22(b)).



(a) (b)

Figure 22: The experiment installed at Fiocruz: plastic module for the green roof (a) and small-scale prototypes (b): one with and the other without the green roof (Source: Wilkinson & Feitosa, 2015)

Data loggers were installed inside each of the prototypes, at 250mm below the top of the structure. The T_{air} was recorded over 194 days (from 17 October 2012 to 29 April 2013), so the warmer periods of the year were covered (the whole Brazilian summer, and part of spring and autumn). Results showed that the green roofs attenuated daily variations of temperature. During the whole period, the highest differences were observed at the daily warmer T_{air}, between 12:00h and 15:00h, where it reached until 5.6ºC. The highest temperature differences between the two roofs were observed at the end of the summer period. Mainly due to the difference in thermal inertia, the green and the metal roofs present a difference in time-lag (the higher differences in delay ranged from 30 to 90 min). Hence, there was a difference between its temperature peaks, which resulted in the green roofs having a slightly warmer T_{air} during the night time and early morning periods.

The modules were installed above a metallic roof and, therefore, this system has air circulating between the modules and the underlying roof. Despite that, the trends of a cooling effect and a thermal delay of were kept, as in a more conventional green roof (meaning, a green roof with all the layers immediately above the structure, and not detached). The authors state a green roof acts as a passive cooler, reducing the U value of the roofing system, increasing the thermal inertia and also having the evapotranspiration effect, helping to reduce the roof surface temperature. Regarding the lightweight modular system, Wilkinson & Feitosa (2015) claim it was observed during 2.5 years, during which no maintenance was required. Although the system does not have a thick substrate, which could improve its thermal performance (due to the aspects previous mentioned).

The third and more recent article on extensive green roofs was published by Wilkinson et al. (2017), combining the effect of the extensive green roof previously analysed by Wilkinson & Feitosa (2015) with added green walls (Figure 3.23). As it was not possible to isolate the cooling effect due to the green roof from the ones due to the green walls, they will not be discussed in this section. One interesting observation, though, is the good development of the succulent plants in the prototype: according to the authors, they did not need maintenance.

Figure 3.23: Green walls added to the former prototype analysed by Wilkinson & Feitosa (2015). (Source: Wilkinson et al., 2017)

3.3.1 Concluding remarks

This section shows how scarce Brazilian studies on thermal performance of green roofs are, both on indoors and outdoors. To date, Brazilian studies are not being published internationally, in peer-reviewed academic journals. In the databases indexed in Lub Search, while a total of three studies analysing the effect of green roofs on indoor thermal comfort were found, none was found about the effect on microclimate. Among those three publications, two experiments were demonstrated and no simulation study. One of the investigations was developed in Florianópolis (Parizotto & Lamberts, 2011), which has a climate similar to Porto Alegre. Results from that study indicate a good performance of green roofs in a subtropical climate, by reducing the heat gain when it is warm and reducing the heat when it is cold.

The second work, developed in Rio de Janeiro, is also interesting due to the low-cost innovation. The green roof modules tested at Fundação Oswaldo Cruz offered flexibility to plant, install and provide maintenance to the green roofs. According to Wilkinson & Feitosa (2015), the modules had a low cost, no necessity of reinforcement of the structure and no need for maintenance evolved during the time of the experiment. The authors claim the system offers a good potential for widespread use at a large scale in urban environments. That would be especially useful in renovations of low-incoming housing, increasing the indoor thermal comfort.

3.4 Building and microclimate simulation tools

3.4.1 The EnergyPlus Ecoroof model

Sailor (2008) informs there was a growing need for comprehensive design tools that could assist the design process, being used by developers and architects to assess the potential benefits of green roofs. Until 2008, studies evaluating green roofs' thermal performance used field measurements to parameterise simplified mathematical models. According to the author, those models presented simplifications concerning the effects of evapotranspiration and time-varying soil thermal properties.

The EnergyPlus is a widely-accepted simulation engine for simulating indoor thermal comfort and building energy use. Developed by the US Department of Energy and released in April 2001, EnergyPlus replaced its predecessors, BLAST and DOE-2, which had some technical and structural limitations (Sailor et al. 2012). EnergyPlus calculates a great number of equations of thermal fluxes happening between the building elements and surrounding climatologic elements. Those equations happen in time-steps stipulated by the user. According to Sailor et al. (2012), a typical EnergyPlus simulation uses time steps of 5–15 min to represent building operation subject to the weather of a typical meteorological year. EnergyPlus' modular architecture also facilitates third-party additions and improvements. The model Ecoroof was incorporated to EnergyPlus in April 2007.

For calculations in Energy Plus, the algorithm used was the Conduction Transfer Function (CFT), which only considers the sensible heat exchanges and does not take into consideration humidity in the building envelope. That means, no latent heat is considered in the calculation within the buildings' thermal zones. The latent heat is calculated, though, in the thermal exchanges in the green roof (through the use of the Ecoroof module).

Since the creation of the Ecoroof model, different compositions of green roofs have been simulated for different climates, testing the influence of a wide range of parameters on the green roof thermal performance including, among others: vegetation LAI and height; substrate depth and compositions, irrigation level and roof insulation.

The Ecoroof model created by the team headed by Professor David Sailor at the Portland University in the USA, is the basis of green roof calculations for the commercial software EnergyPlus. The Ecoroof model is nowadays the most widespread tool used in green roof simulations. The initial validation of the Ecoroof model was made by Sailor (2008), by applying results from EnergyPlus simulations to data gathered from a detailed field study in Florida. The model consistently reproduced the diurnal variation of the near-surface soil temperature (Sailor, 2008). After that first validation, the module was adopted by Sailor to evaluate the energy use for office buildings in Chicago and Houston. Since then, a significant number of studies with the Ecoroof module have validated results with measured data from experiments, reaffirming the tool's reliability on reproducing heat and moisture exchange processes within green roofs.

As previously explained, the energy balance of a green roof takes into account: sensible and latent heat fluxes from plants and soil; conduction of heat into the soil substrate and long-wave radiation to and from the soil and leaf surfaces. All of these physical phenomena were employed by the Ecoroof model to predict the green roof thermal behaviour. The set of equations (accounting for all calculations of the green roof's energy balance) is reduced to the simultaneous solution of two equations: one at the roof foliage surface (Equation 2) and another at the soil surface (Equation 3). These equations involve temperatures of plants and the soil surface, conducting the heat flux to the substrate layer. The sign convention used assumes that all heat fluxes are positive when energy is absorbed into the soil layer (Sailor, 2008).

The green roof module also allows for input of precipitation and irrigation schedules, tracking the resulting diurnal and seasonal variations in soil moisture (Sailor et al. 2012). It is worth mentioning that in EnergyPlus, to date, the heat gained or released due to phase changes of soil moisture are ignored. Therefore, changes in the soil water content due to precipitation heat flux or heat flux due to the vertical transport of water in the soil do not take part in the calculations. The EnergyPlus Ecoroof module inputs include:

- Plant height;
- Substrate density;
- Substrate depth;
- Thermal properties of the substrate: thermal conductivity and specific heat;
- Stomatal resistance (a measure of the resistance of the plant stomata to moisture transport from the plant to the atmosphere);
- Stomatal conductance (the ability of the plant to transpire moisture);
- Soil moisture conditions;
- Irrigation; and
- Precipitation.

3.4.2 Studies with the EnergyPlus Ecoroof model

The search engine *Lub Search* was used to search for peer-reviewed journal papers on extensive green roofs. The aims were to identify (1) the range of variables tested in simulations performed with the use of the EnergyPlus Ecoroof model, and (2) the influence of plant and substrate on the green roofs. The chosen period of time was from 2007 (the date when the Ecoroof module was created) to 2017. The target was articles dealing with the impact of green roofs on indoor thermal comfort. The research question was: “What is the predicted impact of extensive green roofs on the indoor thermal comfort? The criteria for inclusion were:

- Peer-reviewed academic journal articles;
- Simulations using the Energy Plus Ecoroof module;
- Extensive green roofs;
- English, Spanish and Portuguese language.

Studies with intensive or semi-extensive green roofs and simulations performed with other software[16] have been excluded from results. As mentioned in Section 3.3, no journal paper from Brazil was found, on the subject. The search terms used were: "green roof*","vegetated roof*" "eco* roof*" and “simulation*”, “model*” and “indoors” and “thermal comfort”, or “energy efficiency”.

It is important to note that not all extensive green roof research will be found by the databases indexed by the Lub Search engine. Research may also be reported by conference proceedings or technical reports not indexed by the databases. However, in agreement with Blank et al. (2013), the peer-reviewed process was selected as it serves as a reasonable filter for rigorous scientific work. Table 3.4 summarises results from the eleven works selected from the literature review. Ten studies resulted from the systematic literature review. One Brazilian Master thesis (Dias, 2016) was included due to its relevance.

Table 3.4: Parameters in studies adopting the EnergyPlus Ecoroof model

Studies with Energyplus Ecoroof model	Variables				
Authors	Vegetation density (LAI)	Vegetation height	Substrate depth	Irrigation	Roof & envelope insulation
Sailor et al. (2012)	x		x		
Zinzi & Agnoli (2012)				x	
Kolokotsa et al. (2013)	x			x	
Ferreira (2014)	x	x	x		
Refahi & Talkhabi (2015)	x		x		
Yaghoobian & Srebric (2015)	x				
Dias (2016)	x	x	x		
Gargari et al. (2016)	x				x
Peri et al. (2016)	x				
Silva et al. (2016)					x
Boafo et al. (2017)	x				

[16] A few hits appeared with simulations performed with the software TRNSIS.

The list was constructed with the primary parameters analysed in the different studies. A brief discussion about the influence of these parameters (together with other topics from the articles) on the green roof performance is given as follows.

Vegetation density and plant coverage

Berardi et al. (2014) state that the characteristics of plants that influence the heat fluxes are plant height, Leaf Area Index (LAI), fractional coverage[17], albedo and stomatal resistance[18]. Among them, the LAI is the most evaluated aspect of plants. The LAI represents the amount of total one-sided leaf area (m^2) divided by the projection of the vegetation on the ground (m^2). Figure 3.24 shows in a schematic form the LAI of a tree.

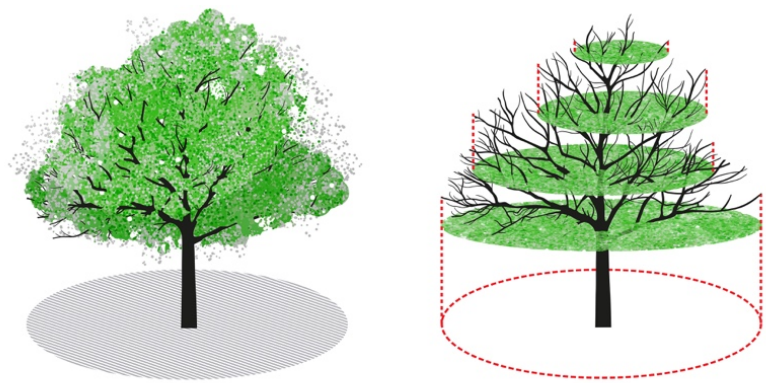


Figure 3.24: Schematic visualization of LAI, defined as the total one-sided leaf area (m^2) divided by the projected surface on the ground (m^2). (Based on Shinzato, 2009)

The LAI is directly associated with the plant species. Authors state that standard values for green roofs vary from 0.5 to 5 (Sailor, 2008; Berardi et al., 2014). Table 3.5 exemplifies the LAI for different trees in Brazil, from field measurements made by Callejas et al. (2014).

[17] (Berardi et al. 2014) define the factional coverage as the fraction of the roof surface that is directly covered by at least one leaf. The author states that, although this parameter is related to LAI, it refers to a different concept.

[18] (Berardi et al. 2014) defines the stomatal resistance as “a biophysical parameter that governs the rate at which the plant transpires moisture (the stomata are the intercellular openings between epidermal cells on the leaf surfaces, and their closing and opening rules of transpiration).”

Regarding grass, the online catalogue NParks Flora & Fauna Web Singapore Government (2013), gives the LAI value of 2.0 for three species commonly used in Brazil: *Zoysia japonica* Steud, *Zoysia tenuifolia* and *Cynodon dactylon.*

Table 3.5: Examples of LAI values (Callejas et al., 2014).

Vegetal species	LAI m^2/m^2
Citrus x limon (Rutaceae) – Lemon tree	6.58
Ficus benjamina (Moraceae) – Ficus tree	5.34
Persea Americana (Lauraceae) – Avocato tree	4.42

Sailor et al. (2012) analysed the effects of roof surface design on building energy use. Simulations were conducted for black and white roofs, and variations of green roofs, in a total of eight cases (new office and new multi-family lodging buildings). Among the green roofs, the variables changed were the LAI (0.5, 2 and 5) and the substrate depths (50mm, 150mm and 300mm). In order to represent diverse climatic conditions in the United States, four cities were chosen: Houston, New York, Phoenix, and Portland, thus, a great variety of climates were covered. The authors found that building energy performance of green roofs improved with the increasing soil depth and vegetative density. The same conclusion was found by Gargari et al. (2016).

Regarding the effect of LAI, Sailor et al. (2012) state the overall annual reduction in energy use increased with an increased LAI. They also observed that the rise in LAI decreased the cooling needs in all cases; conversely, it increased the heating needs. These findings are corroborated by Berardi et al. (2014), who conducted a literature review about the benefits of green roofs. The authors analysed that, for different climates simulated, a high LAI (LAI 5) corresponded to a reduction of energy use in summer, but in an increase in winter. The explanation given by Sailor et al. (2012) is that increasing the LAI rises the shading on the roof reducing the solar heat gain, and also raises the transpiration of plants. The combination of shading and loss of latent heat (through the transpiration of plants) result in a cooling effect that, while beneficial for the cooling needs, is not beneficial for the heating needs.

Ferreira (2014) explored the impact of green roofs on the building energy performance in Lisbon (a Mediterranean climate with four defined seasons). The model was validated by data from three monitored green roofs, and a parametric study tested the substrate depth, plant type, plant height and LAI. The sensitivity analysis was conducted on an adiabatic compartment[19], except the roof. The Baseline green roof had a height of plants of 100mm, LAI of 2 and substrate depth of 250mm. The variations tested were: plant height of 50mm; LAI of 1 and 5; and soil depth of 100mm and 700mm. Results showed that the increase in LAI decreased the cooling energy demand, but increased the heating energy demand.

It is relevant to observe that the climate strongly influences the effect of LAI on the green roof thermal performance. Boafo et al. (2017) state that the LAI must be carefully defined, to minimise energy losses in winter. The authors simulated an extensive green roof in an office building in the Republic of Korea (a humid continental climate), to evaluate the effect of the evapotranspiration on the annual energy use. Although both cooling and heating needs were found, results also showed that when the LAI increased from 20% to 100%, the evapotranspiration flux increased by 10.4% in summer and 80.2% in winter, suggesting that a lower LAI would be more beneficial to avoid heat losses in winter.

A high LAI could be problematic at night. Gargari et al. (2016) remark that a big LAI limits the longwave radiation of the stored heat to be released into the atmosphere during the night. According to the authors, the cooling effect of green roofs in that situation can therefore be reduced. That is especially important in urban centres, often affected by the Urban Heat Island effect.

Dias (2016) showed that the vegetation height has a minor influence on the impact of green roofs on the indoor thermal comfort, if compared to the influence of the LAI and substrate depth. Ferreira (2014), however, observed a similar impact of plant height as with the impact of LAI, regarding the thermal behaviour: the increase in the plant height lead to higher energy use in the heating season and lower energy use in the cooling season. According to the author, the highest plants had the highest transpiration rates, resulting in the highest cooling effect.

Substrate depth

Although the thermal properties of green roofs vary with the moisture content, Sailor et al. (2012) claim that increasing the substrate depth of the green roof results in reductions in heating and cooling needs, for all

[19] An adiabatic environment is defined as not having heat exchanges with spaces outside its external surface boundaries.

buildings. That is attributed to the added insulation value and thermal mass of the deeper soil layer. A general assumption of an average U-value of green roofs, based only on construction thickness, is not entirely reliable, though. It serves to rough calculations, but lack accuracy due to all the changes that occur during the life-cycle of a green roof system (as changes in the LAI value and plant coverage during vegetation growth, for instance, that will have a direct influence on the green roofs' thermal heat fluxes).

Sailor et al. (2012) explain that the added mass helps to even out the diurnal fluctuation of heat flux through the roof. The added mass smooths out the night-and-daytime peak temperatures of the surface adjacent to the conditioned space (in that case, the roof). Similar results have been found by Ferreira (2014), who reports that increasing the soil depth results in lower total energy use for both heating and cooling seasons due to the addition of insulation and thermal mass to the roof.

Irrigation

Kolokotsa et al. (2013) conducted a parametric study comparing green roofs with a conventional roof under various European climatic conditions. The cities chosen for the simulations were: Chania, Athens, Rome, London, Munich and Paris. The effect of green roofs' irrigation rate and vegetation have been examined through the analysis of the sensible heat flux released versus the characteristics of the plants, and the sensible heat flux released versus irrigation rate. With the aim to cover a wide range of vegetation species, the sensitivity analysis was performed for five LAI values: 0.05, 0.5, 1, 2 and 3. The authors concluded that the primary parameter that defines the performance of green roofs is the LAI value. Regarding the irrigation rate, the authors found that, despite playing an essential role in the sensible heat released, it is less significant than the LAI.

Irrigation levels (of 6 mm/day all year, activated only when the soil moisture is below 40%) as suggested by Sailor (2008) have been found valuable in reducing cooling energy demand, while it may increase heating demand. Those results were attributed to the fact that the irrigation enhances the cooling effect from the transpiration of plants and water evaporation from the soil.

Roof & envelope insulation

A recent investigation of Brazilian social housing projects was made by Triana et al. (2015). The authors analysed 108 projects, evaluating their thermal and energy performance, through criteria of the Regulation for Energy Efficiency Labelling of Residential Buildings (RTQ-R). The authors state that current building techniques for social housing show a tendency towards a low performance concerning the thermal and energy performance. To exemplify that, in the Climatic Zone of Porto Alegre (Zone 3) the maximum Thermal transmittance (U) value for roofs and external walls are 2.0 W/m^2K and 3.60 W/m^2K, respectively, which would be considered high for European standards. In Sweden, for instance, a common U value ranges between 0.2 W/m^2K and 0.3 W/m^2K, according to Trä Guiden (2018).

Several authors agree that non-insulated buildings benefit most from the green roof, suggesting them for retrofit use in buildings constructed before building regulations, and in need of renovation (Gagliano et al., 2014; Rakotondramiarana et al., 2015; Dimitrijević et al., 2016).

Silva et al. (2016) suggest extensive green roofs as a good solution for old buildings as they have, typically, low insulation levels and limited structural capacity. Besides, the authors state that well-insulated roofs do not take full advantage of cooling effects by evapotranspiration. In their study, the thermal performance of green roofs was investigated in Lisbon (Mediterranean climatic conditions) during both heating and cooling periods. A simulation was performed for three types of green roofs (intensive, semi-intensive and extensive), with different insulation levels, and were then compared with traditional roof solutions for Portugal. In their study, the walls and floor of the analysed volume were considered adiabatic. Silva et al. (2016) claim extensive green roofs may be a solution to reduce energy use for uninsulated roofs. A comparison in the energy efficiency of the green roofs and the traditional roofs showed that the level of thermal insulation will have an impact on the energy savings obtained with green roof solutions. For low insulation levels, typical in old buildings with limited structural capacity, extensive roofs may be a solution for reducing building energy use since they proved to save around 20% of the energy use (Silva et al., 2016). Conversely, for higher insulation levels, the authors claim extensive green roofs do not appear to have the same extent of energy benefits.

In agreement with Silva et al. (2016), Gargari et al. (2016) concluded that the well-insulated buildings, constructed according to the most recent and restrictive energy regulations, get only moderate benefits from green roof systems. The authors have simulated a green roof under a public housing building in Pisa, under different compositions of external walls, quantifying cooling needs in the summer season. Simulations were carried out for the roof-space thermal zone only and not for lower storeys. In order to assess their energy performances in comparison to the pitched roof, seven different types of green roofs were designed, three extensive and four intensive green roofs. Some of the green roofs were insulated, others were not. Gargari et al. (2016) observed that the T_{op} indoors was, in general, reduced by 0.6ºC with the use of the green roofs, when compared to the traditional pitched roof with the same level of insulation, especially in the warmest days. Results also demonstrated an influence of the insulation layers to the global performances of the green roofs: when compared the insulated version of the traditional pitched roof, the no insulated green roofs registered from 0.25°C to 1.65°C higher T_{op}.

Ground temperature

A procedure found very often in computer simulations is the estimation of ground temperatures with data directly from the weather file. According to the Brazilian regulation for energy efficiency in residential buildings – RTQ-R (INMETRO, 2012), the values of ground temperature from weather file data are not suitable to direct use in buildings' thermal simulations. The regulation suggests, for computer simulations, the use of the pre-processor Slab, which is a tool compatible with EnergyPlus.

Pereira (2009) conducted a study about the influence of the building envelope to the thermal comfort in naturally ventilated houses in Florianópolis, a city belonging to the same climatic zone as Porto Alegre (ZB03). A comparison was made between ground temperatures measured in the field, monthly averaged data from the weather file and ground temperatures corrected by the Slab tool. The conclusion was that the ground temperatures corrected with the Slab tool had more similarity with the measured ground temperature than the ones obtained from the weather file.

A parametrical investigation into variables uncertainties in residential building simulations was conducted by Silva et al. (2015). The authors analysed the sensitivity of building envelope components for a one-storey house in Florianópolis, in the Brazilian climatic zone 3. Simulations were performed in EnergyPlus for a one-year period. For the winter season, the variable having the most significant impact was the monthly average temperature of the ground. In summer, the ground temperature was the second most important parameter[20].

The impact of ground temperature was also demonstrated by Oliveira et al. (2012), in a similar parametrical study for the city of Pelotas, in the Brazilian climatic zone 2. In order to assess the influence of ground temperature on the results, simulations were conducted two times: at first, by configuring the ground temperature with monthly averages from the weather file; secondly, by setting the ground temperature with output data from the Slab tool. Results obtained by Oliveira et al. (2012) indicate the relevance these thermal fluxes between ground and thermal zones have: it was found a difference of up to 6ºC between the ground temperature from the weather file and the ground temperature considering the thermal fluxes.

3.4.3 ENVI-met outdoor microclimate simulations

This section provides an overview of green roof simulation studies performed with ENVI-met. Firstly, an overview about the software is given. Secondly, model calibration and results about the effect of green roofs on microclimate are presented. The studies are classified according to the climate where they were performed, the seasons, and if they have considered or not the influence at pedestrian level.

ENVI-met is a three-dimensional microclimate software with advanced calculations for surface-plant-atmosphere interactions, within or around a complex urban geometry. Morakinyo, Kalani, et al. (2017) state those characteristics make ENVI-met a commonly used tool for modelling different urban atmospheric processes including wind flow, turbulence, urban microclimate, pollutant dispersion, radiation fluxes, and ground temperatures.

The typical horizontal resolution is from 0.5 to 5 meters. The software has a typical time frame of 24 to 48 hours with a time step of 1 to 5 seconds which, according to ENVI-met (2017), allows to analyse small-scale interactions between individual buildings, surfaces and plants. A detailed explanation of the surface–plant–air interaction schemes and its respective equations on ENVI-met were firstly provided by Bruse & Fleer (1998). Since then, newer versions of the software have been released and the calculation procedures have been updated. ENVI-met calculates the influence of vegetation for specific

[20] The most important parameter in summer was, as expected, the albedo of the roof ceramic tiles.

modelled scenarios, including the sensible and latent heat, which makes it a suitable tool to estimate the effect of green roofs to the microclimate. The model is described in more detail in Section 4.4.

Green roof´s effect on microclimate

Aiming to investigate studies performed with ENVI-met to evaluate the green roof contribution on the microclimate, a literature review was made in the search engine Lub Search, from 2007 to 2017. The terms used for the search were: "green roof*","vegetated roof*" "eco* roof*" and “ENVI-met”. The criteria for inclusion were the modelling of green roofs (in a single unit or a cluster) in ENVI-met, and the English, Spanish and Portuguese languages; The criteria adopted for exclusion was the existence of other green strategies together with the green roof, when that made it impossible to evaluate the effect of the green roofs individually. The search focused on peer-reviewed journal articles, and gave 14 results. As explained in Section 3.3, no journal paper from Brazil was found on the subject. To date, they are being published locally, not internationally. As mentioned in Section 3.3, one study published in a Brazilian journal was included to the literature review: Rosseti et al. (2015). That paper is, to date, the first simulation study on the effects of green roofs on microclimate located in a Brazilian city (Cuiabá). Therefore, Table 3.6 present 15 studies from the literature review on the green roof’s effect on microclimate.

The ENVI-met studies on the effect of green roofs on microclimate were performed in different climates, from hot Mediterranean to Temperate. The majority of studies focused on the summer season. The effect at pedestrian level was evaluated in the majority of studies (12 of 15).

Table 3.6: Studies about the effect of green roofs on microclimate, performed with ENVI-met from 2007 to 2017

Authors	Location	Climates (Köppen classification)	Pedestrian	Winter	Summer
Peng & Jim (2013)	Hong Kong	Subtropical	x		x
Ambrosini et al. (2014)	Teramo	Semi-continental temperate	x		x
Perini & Magliocco (2014)	Milan, Genoa, Rome	Marine West Coast, Mediterranean (2x)	x		x
Skelhorn et al. (2014)	Manchester	Temperate maritime	x		
Lobaccaro & Acero (2015)	Bilbao	Humid temperate	x		x
Rosseti et al. (2015)*	Cuiabá (Brazil)	Tropical continental	x	x	x
Alcazar et al. (2016)	Madrid	Mediterranean	x		x
Battista et al. (2016)	Rome	Mediterranean	x		x
Berardi (2016)	Toronto	Warm Summer Continental	x	x	x
Razzaghmanesh et al. (2016)	Adelaide	Hot Mediterranean	x	x	
Skelhorn et al. (2016)	Manchester	Temperate maritime	x		
Taleghani et al. (2016)	Los Angeles	Mediterranean	x		x
Ebrahimnejad et al. (2017)	Tehran	Dry-summer subtropical	x		x
Jamei & Rajagopalan (2017)	Melbourne	Temperate oceanic	x		x
Morakinyo et al. (2017)	Cairo, Hong Kong, Tokyo, Paris	Tropical and subtropical desert, Humid subtropical, Marine west coast	x		x

* Study published only in Brazilian literature. Not available in the indexed peer-reviewed journals.

The cooling effect of green roofs are not restricted to rooftops but can be, in a certain level, extended to a pedestrian level. As with any other green strategy, results depend on the climatic conditions, the urban environment and the green roof composition. Therefore, the values of cooling effect of green roofs at pedestrian level found in literature, although small (if compared with the cooling effect of trees, for instance), can vary considerably. Peng & Jim (2013) investigated the impacts of extensive green roofs in five residential neighbourhoods in Hong Kong. The authors found a reduction from 0.4ºC to 0.7ºC in T_{air}, at pedestrian level. In Toronto, Berardi (2016) found a reduction from 0.2ºC to 0.4ºC of T_{air} at pedestrian level in the summer, at noon. A more pronounced result was found by Alcazar et al. (2016), in Madrid: the authors found up to 1ºC decreased T_{air} at pedestrian level due to the use of green roofs.

Similarly, Rosseti et al. (2015) observed reductions in T_{air} at pedestrian level up to 1ºC in Cuiabá (Brazil), at 13:00h, in the summer season. The study conducted by Rosseti et al. (2015) simulated three scenarios with green roofs in ENVI-met. The scenarios were modelled in a low-density area in the urban perimeter, having 20% of the total area with buildings and 33% with vegetation. The first scenario had 10% of all roofs covered by green roofs, followed by 50% and 100% in the second and the third scenarios, simultaneously. T_{air} and absolute humidity were collected at 1.6m height and results were compared to real data, obtained from measurements (without green roofs). As expected, the maximum differences in the variables were obtained in the third scenario. The main differences occurred in the dry season, at 13:00h: 1.0ºC of reduction in T_{air} and 0.83g/kg of increase in the absolute humidity. Regarding the location, the main influence of the green roofs was observed near the houses, at the leeward side. Rosseti et al. (2015) claim results from the study show the potential of green roofs as a passive strategy to provide thermal comfort in urban environments, at pedestrian level.

Berardi (2016) state the effect of green roofs at the roof level is more expressive than at pedestrian level. Above the rooftop, also the mean radiant temperature (T_{mrt}) is highly influenced by green roofs. Berardi (2016) found a reduction of up to 21.7ºC in the T_{mrt} above green roofs, during the day in Toronto.

The mean radiant temperature (T_{mrt}) is, together with T_{air}, RH and wind speed, one of the variables of the environment influencing thermal comfort. The definition given by ASHRAE (2013) to the mean radiant temperature (T_{mrt}) is the temperature of a uniform, black enclosure that exchanges the same amount of heat by radiation with the occupant as the actual enclosure. It is a single value for the entire body expressed as a spatial average of the temperature of surfaces surrounding the occupant weighted by their view factor with respect to the occupant (ASHRAE, 2013). A simplified way of describing the T_{mrt} indoors is as the average temperature of the surfaces surrounding a particular body, with which thermal radiation will be exchanged.

Determining the T_{mrt} outdoors is more complex than indoors. There is a greater source of elements with whom the human body exchange radiation (e.g. from building façades, trees, ground and other urban components). In addition to the variation of sources, the intensity of their radiation emission varies greatly in space and time, as stated by Johansson (2006). Moreover, outdoors the human body exchange radiation with the sky and may receive solar radiation: direct and diffuse, and reflected from urban surfaces. T_{mrt} can either be measured or calculated (see e.g. Johansson (2006)). In this research, the Tmrt was calculated for the outdoors by ENVI-met. ENVI-met calculates T_{mrt} for a standing person, see Section 4.1.

Agreeing with Berardi (2016), Peng & Jim (2013) state green roofs have a great potential to provide comfortable outdoor recreational and amenity spaces for urban dwellers, however, it can hardly change the thermal comfort at the ground level. In their study in Hong Kong, the authors found up to 0.9ºC decreased in T_{air} with extensive green roofs, 1.2m above the roof.

An interesting investigation was made by Berardi (2016), concerning benefits to the outdoor microclimate and building's energy efficiency, by retrofitting a building located on the university campus of Toronto with extensive green roofs. Outdoor microclimate simulations were performed with ENVI-met and indoor simulations with EnergyPlus. A green roof was simulated, and a comparison was made between the contribution to the outdoor microclimate, and the energy savings due to the increase in thermal comfort, indoors. The study was performed on August 15th (summer, in the Northern Hemisphere), during a 24-hour cycle. Besides, different green roofs were modelled to evaluate the influence of LAI and plant height.

At the rooftop level, results showed a reduction of peak T_{air} values in a range from 0.4ºC to 0.8ºC during the day, due to the substitution of the previous roof[21] for the green roofs. Indoors, the T_{op} was assessed in the last floor of the building and then compared to the comfort zone defined by the ASHRAE Standard 55. According to Berardi (2016), the reduction of the discomfort hours on the last floor of the building was found to be from 22% to 36%. The conclusion was that green roofs were beneficial to a small cooling effect mainly above the roof, but they also had a slight influence (a cooling effect) at pedestrian level. Conversely, the contribution of green roofs on the indoor thermal comfort was considered more relevant. Although performing simulations on both indoors and outdoors, the study made by Berardi (2016) is not considered as a coupled simulation, as it does not employ outputs from the microclimate as inputs to the indoor simulations. The comparison, though, was valid as background knowledge, and also due to the analysis of the influence of green roofs on the microclimate. His work could be classified as a "parallel" outdoor-indoor simulation.

Model calibration

When computer simulations are performed to predict thermal behaviour in a specific environment, model calibration is employed, aiming to achieve results as realistic as possible. This procedure has been widely documented in the literature involving ENVI-met simulations (e.g. Berardi, 2016; Gusson & Duarte 2016; Duarte et al., 2015; Yahia & Johansson 2014; Skelhorn, 2013; Elnabawi et al., 2013). ENVI-met underestimates the daily air temperature amplitude, which is mentioned in previous works (e.g., Ali-Toudert & Mayer, 2006; Johansson, 2006; Yahia, 2014).

In a study to assess the impact of vegetation on urban microclimate in São Paulo, Brazil, Duarte et al. (2015) proposed to discount the first 24 hours simulated, analysing results only from the second day, when calibrating the model. Another example of that strategy is found in Goldberg et al. (2013). In their study in Dresden (Germany), the authors used the first simulation day acted as a "buffer" to dampen model oscillations.

[21] The existing roof consists of a bitumen foil, a variable thickness light concrete layer (50-100mm), cork insulation (50mm), and a structural concrete roof (200mm). The existing roof has a U value of 0.70W/m2K (Berardi, 2016).

ENVI-met v4.0 new features

Gusson & Duarte (2016) adopted the ENVI-met new features *Telescoping grid*, *Simple forcing* and *Albero* to evaluate the effects of built density and urban morphology on urban microclimate, in two areas of the city of São Paulo, Brazil. The model was calibrated with data from field measurements of air temperature and relative humidity, globe temperature, wind speed and direction, among others. Results from field measurements and simulations were very similar in both studied areas, providing the first validation of the ENVI-met new features in a Brazilian context. Shinzatto et al. (2017) also adopted the ENVI-met V.4.0 (and its new features) for new simulations in one of the parks previously analysed by Gusson & Duarte (2016): the Trianon Park, in São Paulo. Shinzato et al. (2017) analysed the microclimatic effects of green infrastructure in the city, with simulations made in ENVI-met v.4.0. Simulations showed a good agreement with field measurements, providing a second validation of the use of ENVI-met new features in a Brazilian context.

3.4.4 Concluding remarks

The first conclusion from the literature review on the effect of extensive green roofs on indoor thermal comfort simulated with EnergyPlus was that there is a lack of Brazilian publications in the international peer-review journals on the subject. Regarding the range of variables influencing the green roofs' thermal performance, the studies showed that the most important ones in the gardening layers were the LAI, fractional plant coverage, stomatal resistance, albedo and substrate depth. About the height of plants there was no consensus: some authors as Ferreira (2014) state it is important while Dias (2016), for instance, claims it is not as relevant as the other aspects.

To calculate the effect of green roofs on the energy use of buildings, having the more accurate information available, is a key factor. Another conclusion from the literature review is that, in the range of information needed for an accurate input in the simulation programme, the correction of the soil temperature, in general, was not mentioned. Some studies, though, showed its relevance to the simulations. Furthermore, the type of plants present different transpiration rates, which is related to the stomatal resistance. Because detailed data of vegetation is difficult to find in the literature, the majority of the studies did not specify the stomatal resistance of plants. Taking that difficulty into consideration, in order to predict the thermal performance of a green roof system, the variables that could be considered as crucial within the gardening layers are the LAI, for the plants, and the depth, for the substrate.

As concerning the effect of extensive green roofs on indoor thermal comfort, the literature described a contribution both to the cooling and heating seasons, and in different climates. Attention must be given to the configuration of the green roof, as dense plants reduce the penetration of solar radiation on the substrate, thus, reducing the efficiency of the green roof of gaining heat in the winter.

It can be concluded that in Europe, studies about extensive green roofs claim they can be beneficial to retrofits, due to the relatively low insulation in existing buildings[22]. In Brazil, Dias (2016) have a similar opinion, but also includes new buildings. That can be explained by the fact that the compliance required for thermal comfort in the Brazilian Standards is still not sufficient to provide a significant insulation level to buildings' envelopes. Therefore, the country has a building stock of poorly insulated houses, especially within social housing, that could benefit from renovations with extensive green roofs.

The literature review on the effect of extensive green roofs on microclimate simulated with ENVI-met showed a lack of consensus regarding the influence of green roofs on the microclimate, at pedestrian level. Some authors claim the influence is significant enough to consider green roofs as a strategy to increase the outdoor thermal comfort at pedestrian level (Rosseti et al., 2015; Alcazar et al., 2016). On the other hand, authors like Berardi (2016) and Peng & Jim (2013) affirm the influence of green roofs is more relevant above the roofs and do not contribute to the outdoor temperature reduction at pedestrian level in a significant manner. As a green strategy, if the interest is on reducing the T_{air} at pedestrian level, the green roofs might not the best option and other measures, as trees and shading devices, could be more effective. If the interest is at the roof level, as in the case of this study[23], green roofs may offer a significant contribution.

[22] Provided before compliance with building energy-efficiency codes.

[23] The indoor thermal comfort in one-story buildings is highly affected by the roof's thermal fluxes, in which the temperature above the roof plays a key role.

3.5 Coupled outdoor-indoor simulations

Martin et al. (2017) state that building energy modelling is one of the leading methods used to predict the interactions between the outdoor environment and a building's energetic performance. According to the authors, Building Energy Models (BEMs) have been coupled for the last years with urban canopy models to study interactions between urban microclimate and building energy use. BEMs can be either simplified – also known as "shoebox" – or detailed, trying to recreate the real world as closely as possible – as the twin-houses modelled in this investigation.

Coupled simulations can be performed in two directions: outdoor-indoor and indoor-outdoor. One example of this kind of study is given by Bueno et al. (2012), who investigated the dominant mechanisms by which the indoor environment of buildings can affect outdoor air temperatures for summer and winter in Toulouse, France.

This section present the literature review on the effect of the outdoor microclimate on the indoor thermal comfort, in buildings with green roofs. That is especially new for the Brazilian context, as no study with coupled simulation was found in literature. Thus, this part of the literature review addresses the effects combinations of green roofs, and outdoor scenarios have on the indoor thermal comfort. It has focused on studies where the coupling process predicted *the effect microclimate scenarios have on a building's indoor thermal comfort* (or energy efficiency).

A literature review was employed in academic research from 2007 to 2017, aiming to provide knowledge about the following subjects:

- A general overview of studies published with coupled simulations;
- The types of software employed to perform outdoor-indoor coupled simulations;
- Variables assessed and methods employed to give input data from the outdoor simulations to the indoor simulations.

The review was performed in the search engine "Lub Search". The terms used for the search were: "coupl* simulation*" and "thermal comfort", reaching 39 results. As criteria for inclusion, publication in peer-reviewed journals in the English, Spanish and Portuguese languages was adopted. However, all studies dealing with coupled simulations and thermal comfort, but with other focus than outdoor microclimate and indoor thermal comfort were excluded. A thorough examination of the abstracts resulted in 16 articles of high relevance to the research. Findings from them are discussed in the next paragraphs. Due to their relevance, one more study was added to the list: a journal article written by Santamouris et al. (2001), which is an earlier study coupling measured data with building simulation.

Table 3.7 summaries result from the 17 studies selected by the literature review.

Table 3.7: Assessed aspects in coupled outdoor-indoor simulations of indoor thermal comfort

Authors	ENVI-met & EnergyPlus	Other combinations of software	Including green roofs	Buildings with natural ventilation	Evaluations in the summer season	Evaluations in the winter season
Santamouris et al. (2001)		x		x	x	x
Bouyer et al. (2011)		x			x	x
Wong et al. (2011)		x				
Yang et al. (2012)	x				x	x
Peng & Elwan (2012)	x				x	
Peng & Elwan (2014)	x			x	x	
Orehounig et al. (2014)	x		x	x	x	x
Yi & Peng (2014)	x				x	
Malys et al. (2015)		x			x	x
Virk et al. (2015)		x	x		x	x
Gros et al. (2016)		x	x		x	
Morakinyo et al. (2016)	x		x	x	x	
Morille et al. (2016)		x	x		x	
Skelhorn et al. (2016)		x		x	x	x
Fahmy et al. (2017)	x		x		x	
Morakinyo et al. (2017)	x		x		x	
Pastore et al. (2017)	x		x	x		

To date, EnergyPlus and ENVI-met represent the highest level of reliability, for indoor (EnergyPlus) and outdoor (ENVI-met) thermal comfort simulations – individually, or combined in a coupled method. Other combinations of software exist, as found in the literature and Table 3.8 details these combinations of software. The main subjects found in the review are discussed in sub-sections 3.5.1 and 3.5.2.

Table 3.8 Combinations of software found in literature, other than ENVI-met and EnergyPlus

Authors	Studies with coupled simulations
Santamouris et al. (2001)	Weather meteorological data[24] and TRNSIS
Wong et al. (2011)	STEVE Tool and TAS Software
Bouyer et al. (2011); Malys et al. (2015) and Morille et al. (2016)	SOLENE-microclimate coupled with its building thermal mode
Virk et al. (2015)	Atmospheric Dispersion Modelling System 4 Temperature and Humidity (ADMS T&H) tool and EnergyPlus
Gros et al. (2016)	EnviBatE and SOLENE thermo-radiative model
Skelhorn et al. (2016)	ENVI-met and Integrated Environmental Solutions, - Virtual Environment (IES-VE)

As previously mentioned, no journal paper from Brazil was found on this subject. That reflects that, if coupled simulation studies like the one conducted in this investigation exist in Brazil, the discussions provided by them are not reaching the international research community, at least through peer-reviewed journals with the highest impact factors.

Table 3.9 shows the places and climates where the coupled simulations with green roofs found in the literature review were located[25]. The only locations with a slightly similar climate to Porto Alegre are Hong Kong and Tokyo, because in the Köppen Climate Classification they are also Humid Subtropical (Csa). However, in both

[24] Instead of simulating weather data, Santamouris et al. (2001) have coupled measured weather data (including surface temperature) with the indoor simulation software TRNSIS.

[25] To date, no coupled simulation was found for the climate of Porto Alegre, nor to an equivalent climate.

Hong Kong and Tokyo the summers are usually more humid than winters, which is the opposite in Porto Alegre – as seen in Chapter 2, the higher rainfall incidence occurs in the winter season[26].

Table 3.9 Studies with coupled simulations including green roofs and its respective climates, according to the Köppen Climate Classification

Authors	Location and climate classification
Orehounig et al. (2014)	Vienna, Austria: Marine West Coast [27](Cfb)
Virk et al. (2015)	London, England: Marine West Coast (Cfb)
Gros et al. (2016)	Lyon, France: Marine West Coast (Cfb)
Morakinyo et al. (2016)	Akure, Nigeria: Tropical Savanna (Aw)
Morille et al. (2016)	Nantes, France: Marine West Coast (Cfb)
Fahmy et al. (2017)	New Borg El-Arab and Giza, Egypt: Tropical and Subtropical Desert (Bwh)
Morakinyo et al. (2017)	Cairo, Egypt: Tropical and Subtropical Desert (Bwh) Hong-Kong, China: Humid Subtropical (Cfa) Tokyo, Japan: Humid Subtropical (Cfa) Paris, France: Marine West Coast (Cfb)
Pastore et al. (2017)	Palermo, Italy: Mediterranean (Csa)

3.5.1 General aspects of coupled simulation models

In the same urban environment, several microclimates coexist, each one influencing and being influenced by nearby elements as buildings, trees, or others. Understanding the impact variables assessed at the neighbourhood scale have on the building's thermal behaviour can give vital information to the architect or engineer, in his or her design process.

The terms "coupling simulations", "coupled simulations" and "co-simulations" are found in the literature to describe the process of studying the effect that urban configurations have on the outdoor environment and vice-versa (as schematically illustrated in Figure 3.25). Coupled simulations can also be used to test different types of future scenarios.

[26] Therefore, even in the same climate classification, those cities have characteristics that differentiate them from the Porto Alegre's climate.
[27] The climate Cfb is also called Oceanic.

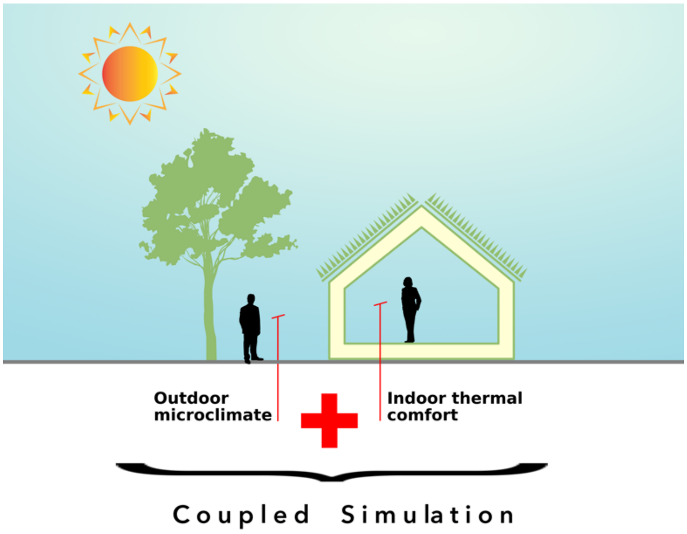


Figure 3.25: Schematic representation of a coupled simulation approach.

The interest in predicting outdoor microclimate and indoor thermal comfort within urban scenarios of green strategies is not new. Already Santamouris et al. (2001) discussed the impact of higher ambient temperatures in the city centres on the building cooling and heating needs. Data were collected from measuring stations in 30 urban and suburban areas, and from ten urban canyons in Athens during a 3-year period. The variables measured were the T_{air}, the exterior surface temperature of the buildings' facades, and the wind speed. The collected data was used to calculate the cooling and heating needs of a typical office building for all locations where climatic data were available (Santamouris et al., 2001). The typical office building was simulated with Transient Systems Simulation Program (TRNSYS) (Solar Energy Laboratory, 1997) and data from the outdoor measurements were used as boundary conditions. It was found that the cooling need at the city centre was about double that of the surrounding Athens region due to higher T_{air}. Apart from increased energy loads for the buildings' cooling, the high ambient temperatures almost doubled the peak cooling load of the reference building.

Yi & Peng (2014) argue that passive design strategies adapted to climate change scenarios are not well understood at the urban scale. The authors claim building design needs to evaluate current and future performance, in order to provide an adaptation and even resilience, toward microclimate changes. The authors performed an outdoor-indoor coupled simulation framework, to assess the effect of microclimate changes on a building's thermal comfort. They tested passive building design in an urban neighbourhood context, within different outdoor scenarios. An existing green building at the University of Sheffield was modelled in ENVI-met and EnergyPlus[28] to predict how a building interacts with the outdoor microclimate scenarios during the summer season, taking into account the seasonal conditions in 2012 and 2050 – as projected by a current climate change scenario[29].

Another example of study attempting to predict a building's thermal behaviour under climate change scenarios, was conducted by Skelhorn et al. (2016). In their case, instead of predicting future climate changes, the scenario focused on the Urban Heat Island effect. However, it has a common point with the studies previously mentioned: the influence of different outdoor configurations on the indoor thermal comfort.

Concluding remarks

This section showed that the majority of the coupled simulation studies conducted in the latest years include green strategies for urban environment (Wong et al., 2011; Skelhorn 2014; Skelhorn et al., 2016; Yang et al., 2012). The climate change and the Urban Heat Island effect studies have been contributing to an interest in developing mitigation alternatives. In this context, coupled simulations offer an appropriate method for investigations with this purpose, by allowing parametrisations of green strategies and evaluations of their results on both the microclimate and the indoor thermal comfort.

3.5.2 Software and procedures in coupled simulations

A certain amount of software combinations was found in the literature review on coupled outdoor-indoor simulations, as registered in Table 3.7. ENVI-met and EnergyPlus, though, are the simulation tools found in the majority of studies: a total of eight, of the 16 studies selected, had this combination. Among the ones not combining ENVI-met and EnergyPlus, at least three of eight adopted a combination with at least

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[28] The software DesignBuilder was used as the interface to EnergyPlus.

[29] For the estimation of the climate change in 2050, the authors predicted a "medium-high" emissions scenario, according to Met Office Hadley Centre (2018).

one of these two tools. The second combination of tools with the highest incidence was SOLENE-microclimate coupled with its building thermal mode, having three studies published on the list. Although not yet being one software, that combination is interesting due to belonging to the same platform, which can facilitate data exchange between outdoors and indoors.

All cases found in the literature review combined two types of software to perform the coupled simulation. Hence, it is vital to guarantee that the strength of one software overcomes a possible limitation of the other. Morakinyo et al. (2016) explain the complementarity of ENVI-met and EnergyPlus in a coupled simulation process: Although widely adopted, to date ENVI-met cannot simulate indoor thermal conditions, which is one of the strengths of EnergyPlus. On the other hand, EnergyPlus cannot simulate the effect of a group of buildings, reproducing a microclimate. Concerning the modelling of trees, EnergyPlus only construct them as conventional shading elements (detached from the building, in the newest versions like 8.7, employed in this research). Thus, EnergyPlus is unable to simulate the real thermal impacts created by the vegetation in the immediate environment. ENVI-met, on the other hand, includes a realistic vegetation module that calculates physiological plant and soil heat exchanges. Both ENVI-met and EnergyPlus are well established in the academic and professional communities, and both were extensively validated with field measurements in several climates.

Regarding the method adopted in coupled simulations, the pattern identified in all reviewed studies was a substitution of the initial weather data. Thus, in the indoor simulation, initial boundary weather data was substituted by data extracted from the outputs of the outdoor simulation. Apart from the pattern, the exact way of doing that varies according to the software employed, and also according to the study. Even in the most common combination of tools (ENVI-met and EnergyPlus), the level of sophistication can be different. An example of sophistication is given by Yang et al. (2012). In order to analyse the effects of different microclimatic factors on the energy balance of an individual building in a case study, in addition to the use of ENVI-met and EnergyPlus, the coupling platform Building Controls Virtual Test Bed (BCTVB) was employed to link the two software, exchanging data between them as they simulated.

Focusing on the combination of ENVI-met and EnergyPlus, two main ways of collecting data were found: averaging data extracted from site cells around the building (e.g. Peng & Elwan, 2014; Morakinyo et al., 2016) or averaging data from receptors[30], strategically positioned among the building facades (e.g. Yi & Peng, 2014; Pastore et al., 2017).

3.6 Conclusions

This chapter reviewed literature on green roofs. It began by presenting green roofs in general, further focusing on extensive green roofs. It also discussed the simulation tools currently adopted for simulations with green roofs, and the conclusions from the studies performed with them. The main conclusions are:

1. Green roofs are likely to provide benefits to the city, as well as to the building owner. Therefore, the decision of adopting a green roof can take other benefits into consideration, in addition to the aim for increasing aesthetics and thermal comfort.
2. Extensive green roofs represent an interesting solution for increasing the indoor thermal comfort in a passive way, suitable for housing projects, especially with poor building insulation.
3. A green roof balance is a function of a complex system, adding organic elements to the energy balance of the roof, which interact to a great extent with the microclimate. Concerning the study of green roofs, there are a few studies on the relationship of microclimate and indoor thermal comfort. Thus, there is a need for investigations about how the microclimate affects the impact of green roofs on indoor thermal comfort.
4. The configuration of the gardening layers plays a key role in a green roof's energy balance. Thus, there is a need to find out suitable LAI and substrate depth, in order to offer a climate-responsive green roof project.
5. There is a lack of Brazilian studies about green roofs and thermal comfort in peer-reviewed international journals, both for indoor thermal comfort and for outdoor microclimate. There is thus a need to conduct further research on these subjects, for different Brazilian contexts.

[30] ENVI-met receptors are selected points inside the model site area, where processes in the atmosphere and the soil are assessed in detail.

This study relies on a modelling approach, aiming to improve the understanding of the effect of green roofs on indoor thermal comfort, in the Subtropical Brazilian city of Porto Alegre. Besides, it investigates the impact of extensive green roofs on the microclimate, in different outdoor scenarios. Furthermore, the effect of the microclimate on the impact of extensive green roofs on indoor thermal comfort is explored, through coupled outdoor-indoor simulations.

4 Method

4.1 Research methods

This research is in the fields of buildings' thermal comfort and energy efficiency. Additionally, it is related to architecture, landscape design and urban microclimate. Groat & Wang (2013) state that the investigation on the performance of building components has constituted a significant and long-standing domain within architectural research. The subject "green roofs" is of interest in different fields of knowledge, so an overall understanding of it has a multidisciplinary character.

The nature of this investigation is applied research, as it seeks to take results of scientific research for utilising it directly in real-world situations. The approach employed is quantitative: it is based on simulations, dealing with the manipulation of phenomena possible to be measured by numbers. Groat & Wang (2013) explain the quantitative paradigm as involving a deductive process of inquiry that seeks cause-and-effect explanations. The quantitative approach assumes an objective reality where the researcher has an independent view of the studied subject.

This study is exploratory, as it intends to explore the research questions and to determine the nature of the problem, to have a better understanding of it. According to Groat & Wang (2013), in exploratory research, the variables can be controlled, and the results can be quantified. Also, in the exploratory research, it is possible for the researcher to change its direction according to new data and findings on the studied subject.

The method employed is the computer simulation. A simulation aims to replicate all the relevant variables in a given phenomenon, in a holistic manner. Simulation gives us knowledge about possible real-world conditions without going through the ethical barriers, physical danger, or financial expense of the actual conditions. It allows testing solutions since the early architectural design stages, with a low cost and without the need for interference in the building. Computer simulation, as a research method, keeps a high similarity with experimental research, enabling the researcher to establish a cause-effect association.

As research design in this study, simulation studies of the predictive kind were performed. The main characteristics of this investigation are summarised in Table 4.1.

Table 4.1: Main characteristics of the investigation

Phenomenon under study	The extensive green roofs thermal performance for housing projects in Porto Alegre, Brazil	
Variables	Independent	Leaf Area Index, substrate depth, building envelope (indoors); shading by trees (outdoors).
	Dependent	Operative temperature (indoors); dry-bulb air temperature, mean radiant temperature, air humidity, wind speed, wind direction, solar radiation (outdoors).
Parameters	Adaptive Thermal Comfort model of ASHRAE 55 (2013) and degree-hours (indoors); Differences in dependent variables.	
Unit of assignment	The twin-houses (indoors) and part of the site area (outdoors).	
Use of a control group	The Original roof, the Baseline roof and the Baseline green roof (indoors); the ENVI-met output data from receptors (outdoors).	
Focus on causality	Changes on independent variables modify the dependent variables.	

Operative temperature (T_{op}), according to the definition given by ASHRAE (2013), is the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. A simplified way of describing the T_{op} is as the average of T_{air} and T_{mrt} of an environment. In this work, T_{op} was calculated by EnergyPlus.

Together with T_{air}, RH and wind speed, the mean radiant temperature (T_{mrt}) is one of the variables of the environment influencing thermal comfort. A detailed explanation of T_{mrt} (indoors and outdoors) was given in Section 3.4.3. In this investigation, the T_{mrt} was calculated for the outdoors by ENVI-met. The calculation takes all radiation fluxes into account: direct irradiance, diffuse and diffusely reflected solar radiation, as well as the total long-wave radiation fluxes from the atmosphere, ground and urban surfaces, as explained by Ali-Toudert (2005). ENVI-met considers T_{mrt} for a standing person at street level. The calculation assumes that 50% of the long-wave radiation fluxes come from the upper hemisphere (sky and urban surfaces) and 50% from the ground.

Degree-hour is the sum of the differences between the hourly average indoor temperature and a standard temperature. It is often adopted for the estimation of energy required for heating or cooling in a specific environment until the standard temperature is achieved. In this study, the accounting of degree-hours is related to the thermal comfort limits of the ASHRAE Standard 55. Therefore, heating degree-hours are the sum of degrees below the lower operative temperature in the comfort range and cooling degree-hours account for the sum of degrees above the highest operative temperature.

Computer simulation models are classified as mathematical models, as they translate physical phenomena into mathematical equations to reproduce real-world relationships in the form of quantified values. Wetter (2011) points out that mathematical equations mostly do not offer the same advantages as physical experiments. The main reason is that, during this process of translating physical phenomena into mathematical equations, aspects regarding the real behaviour of the studied object carry a certain level of uncertainty. The process performed by computer simulations software to quantify thermal comfort and energy efficiency of buildings exemplifies a mathematical simulation model, that can be explained as follows:

- The construction of a virtual model adapts a physical system into a mathematical model;
- That mathematical model is transformed in a model compilation, resulting in a simulation software;
- In the simulation software, a computer model is constructed. That is when the model simulation starts, and the trajectory behaviour of the physical system is analysed. From that phase on, multiple changes in the original physical system can be tested.

Figure 4.1 outlines the process of simulating a physical system trajectory behaviour with a computer simulation method.

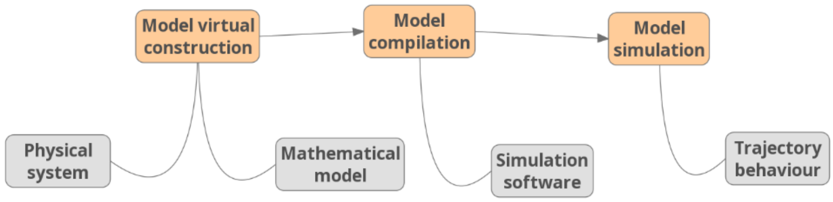

Figure 4.1: Process of simulation as a method. Based on Wetter (2011)

4.2 Research strategy

Modelling and simulations were performed in four different phases, as listed below:

1. Indoor thermal comfort;
2. Outdoor microclimate;
3. Outdoor microclimate with green strategies;
4. Indoor thermal comfort with green strategies.

The structure of the research into four phases is related to the objectives and the method employed, at each phase.

Phase 1 aimed to *explore the effect of a set of variables in a green roof composition*, in the climate of Porto Alegre. In Phase 1 *the Baseline roof and the Baseline green roof* were defined. Indoor simulations with a one-year cycle were made in that phase. To understand specific thermal behaviour in the warmest and coldest seasons, the simulations were also performed the Typical summer week and Typical winter week.

Phase 2 aimed to provide an understanding of the outdoor microclimate in the site area. The main contribution given at this phase was *the definition of the Baseline site*. The simulations performed in phase 2 allowed the assessment of variables outdoors where the Original site project and the Original roof were considered. Outputs generated at this phase were further employed in phases 3 and 4, substituting meteorological data from the weather file in the Baseline site model. Due to the software adopted (ENVI-met), simulations made in phase 2 were performed in a 24-hour cycle, as the Typical summer day and the Typical winter day.

Phase 3 had two objectives: to evaluate changes in the site area when integrating green scenarios and to assess the effect of green roofs on the local microclimate. After preliminary tests, five new scenarios were created for the summer, and five for the winter.[31] The scenarios were defined to compare the effect of green roofs with and without surrounding vegetation (grass on the ground and deciduous trees). A detailed description of the outdoor scenarios is provided in Section 4.5.1 (Creation of the green scenarios). Phase 3 addressed the outdoor microclimate, so the same software used in Phase 2 (ENVI-met) and the simulated periods (Typical summer and winter days) were adopted.

Phase 4 intended to estimate *changes in the indoor thermal comfort due to the microclimate (using green roofs).* Another contribution from this phase was the evaluation of the impact coupled simulations had on the study. In phase 4 the assessments were made indoors, with EnergyPlus. Coupled simulations were performed, adopting variables from ENVI-met outputs (extracted from Phases 2 and 3) as the initial boundary conditions. In phase 4 the simulation periods were the Typical summer day and the Typical winter day[32]. Figures 4.2 to 4.5 illustrate the evaluations made in Phases 1 to 4, respectively, in the format of schematic mind maps.

[31] As deciduous trees are suggested for the use in Porto Alegre climate, the density of leaves was different in the models for summer and winter. Apart from that, the scenarios were the same.

[32] Although EnergyPlus allows larger assessment periods, in Phase 4, the inputs boundary values came from ENVI-met outputs, one typical day simulated for summer and one for winter.

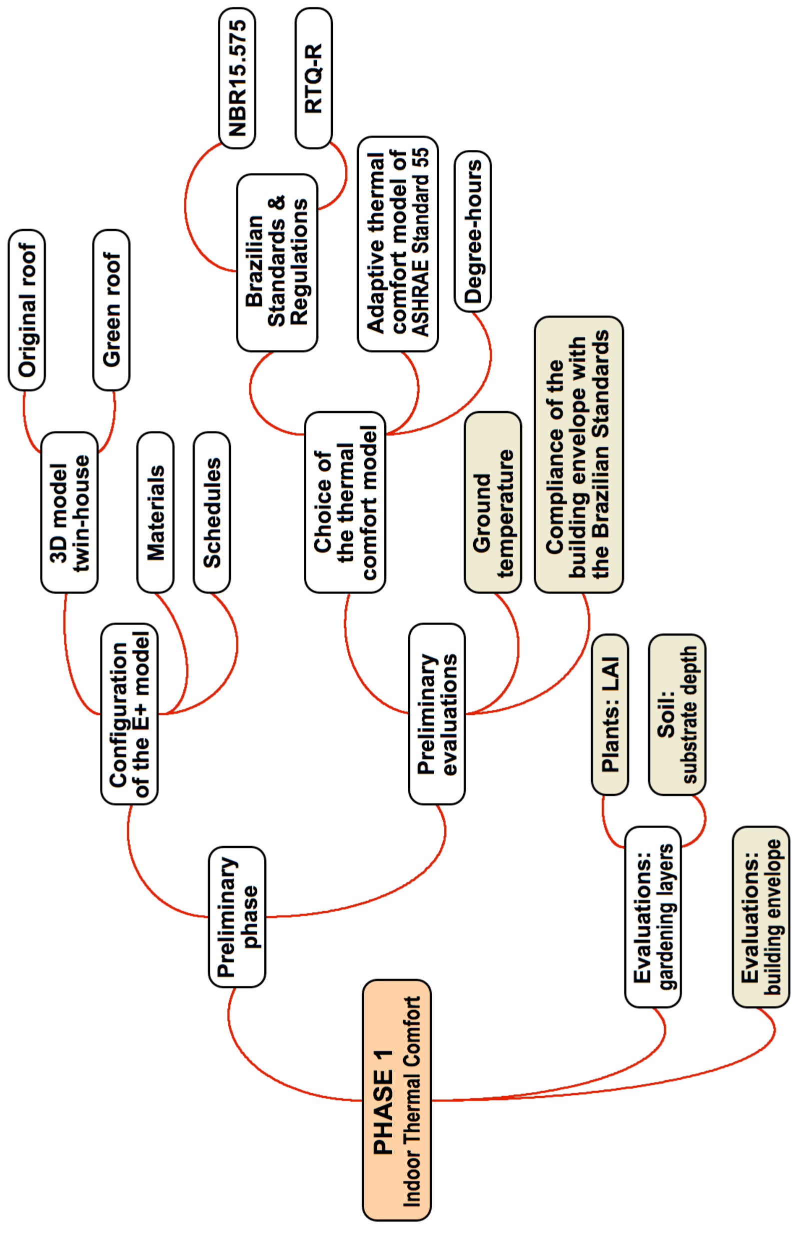

Figure 4.2: Mind map of the evaluations made in research Phase 1. The boxes with the background colour involved simulations.

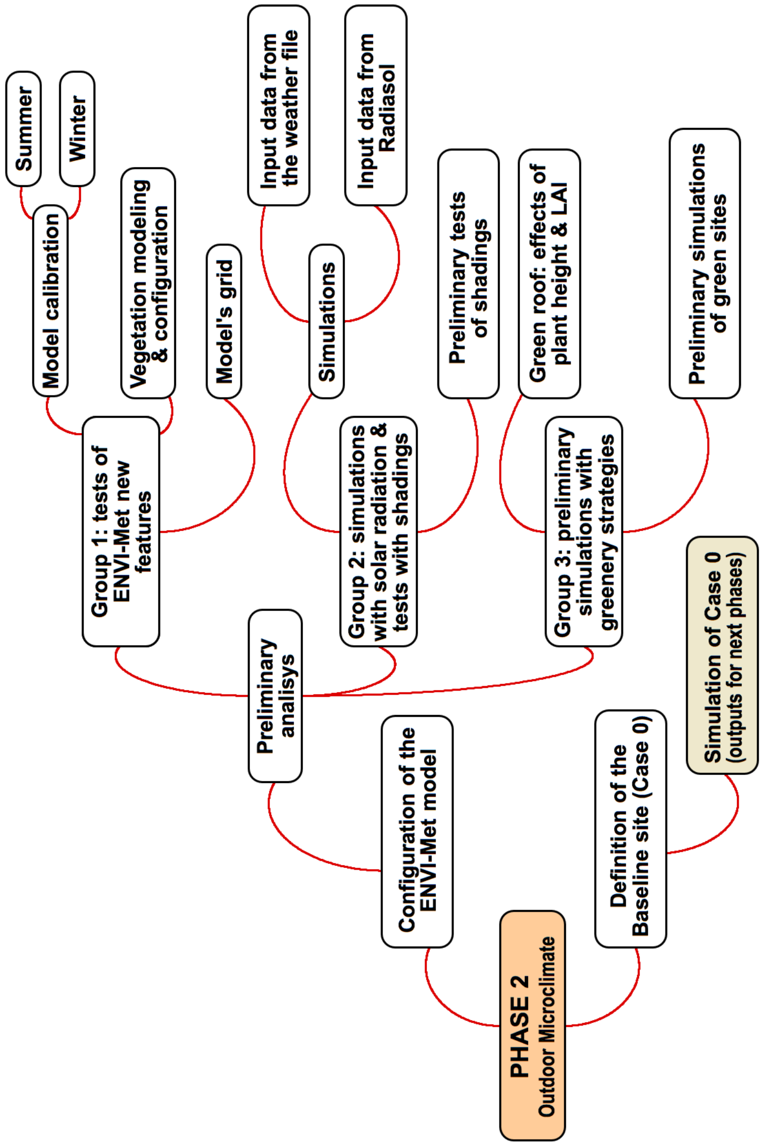

Figure 4.3: Mind map of the evaluations made in research Phase 2. The box with the background colour involved simulation.

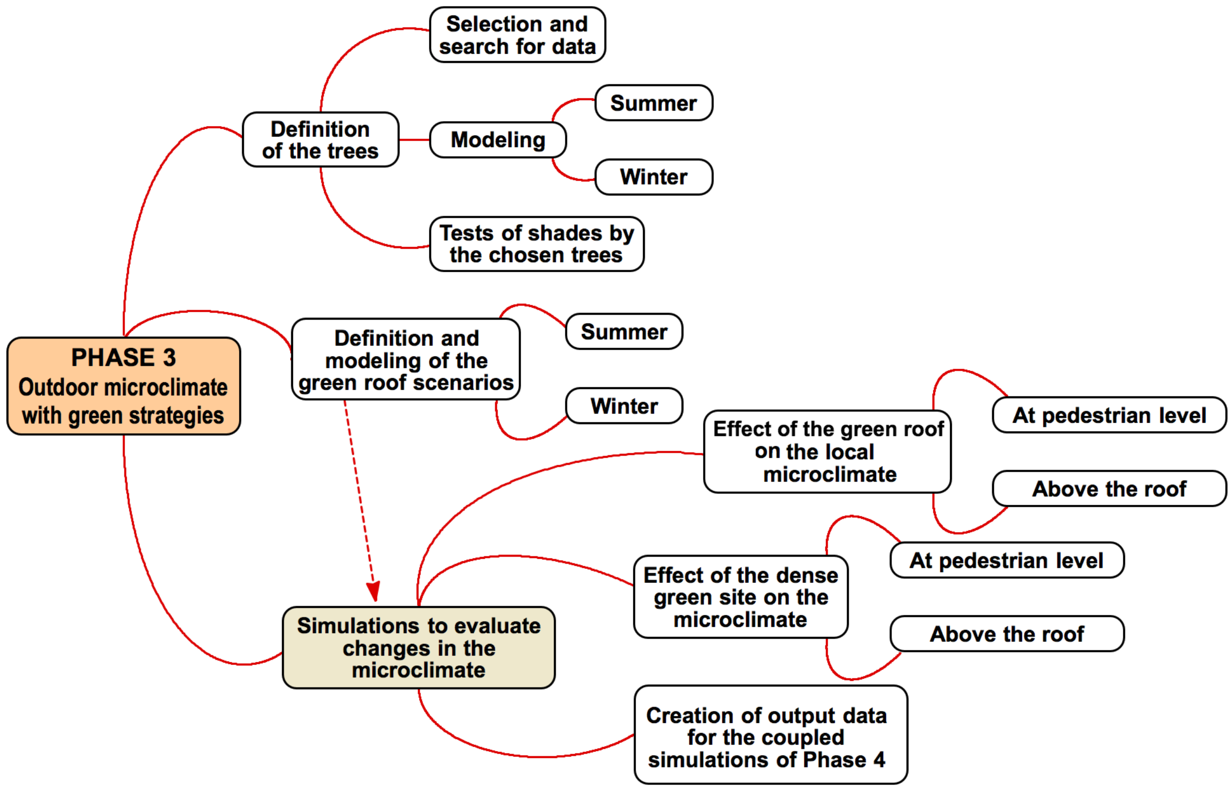

Figure 4.4: Mind map of the evaluations made in research Phase 3 The box with the background colour involved simulation.

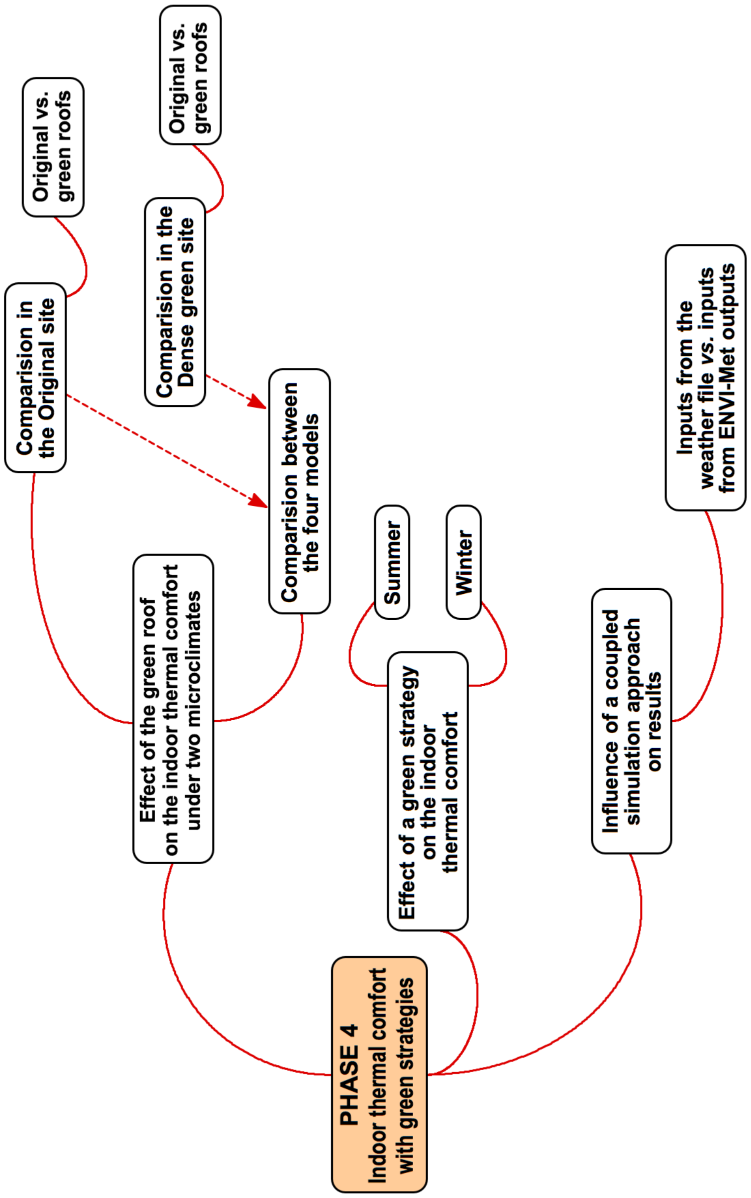

Figure 4.5: Mind map of the evaluations made in research Phase 4

Table 4.2 presents, for each research phase, the type of simulation software and the complementary software used.

Table 4.2. Types of simulation and complementary software employed in the four research phases

Simulation phase	Simulation software	Complementary software
1. Indoor simulations	EnergyPlus	SketchUp Make; Euclid; Excel
2. Outdoor simulations	ENVI-met	Leonardo; Excel
3. Outdoor simulations with green strategies	ENVI-met	Leonardo; Excel
4. Indoor simulations with green strategies	EnergyPlus	SketchUp Make; Euclid; Excel

4.3 Phase 1: Indoor thermal comfort

The first phase of the research had the objective of testing a set of features and defining the building and the green roof configuration for simulations in the next research phases, creating the Baseline roof and the Baseline green roof. In order to comply with this objective, at first, an understanding of the thermal response of the twin-houses for the climate of Porto Alegre was needed. Therefore, the twin-houses were modelled and simulated according to the original design, and changes in its design were tested.

Firstly, a correction for the ground temperature was made, followed by changes in the building envelope, to comply with the Brazilian Standards. Secondly, changes were made in the green roof composition (LAI and substrate depth), and results were compared. Thirdly, an evaluation of the impact of green roofs on the indoor thermal comfort, for different building envelopes, was made. Simulations were performed for a one-year cycle. Furthermore, simulations were performed for the Typical summer week and Typical winter week. The parameters assessed in Phase 1 were the indoor thermal comfort and the degree-hours. Figure 4.6 presents the flowchart of Phase 1.

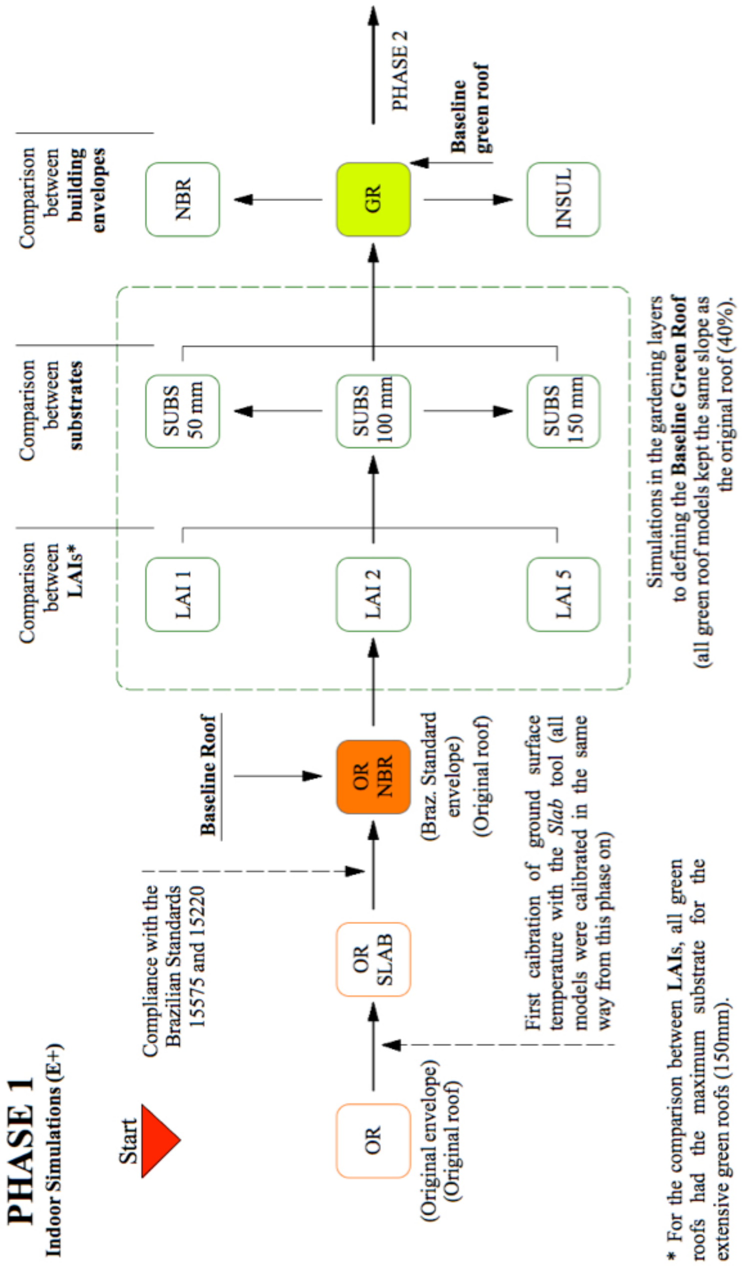

Figure 4.6: Flowchart of the simulations performed during Phase 1

The simulation cases at the building scale were modelled geometrically in the software SketchUp Make v.2018 with the plug-in Euclid v.9.3 and were simulated in the software EnergyPlus v.8.7. To evaluate the indoor thermal comfort, the ASHRAE Standard 55 for naturally ventilated buildings (ASHRAE, 2013) – was chosen.

The EnergyPlus model is divided into thermal zones – spaces with similar thermal behaviour and space-conditioning requirements. The twin-houses are composed of two dwellings with ten thermal zones at the ground floor (as illustrated in Figure 4.7) and six at the attic space (as illustrated in the architectural sections – Appendix A, Figures A.5, A.7 and A.8).

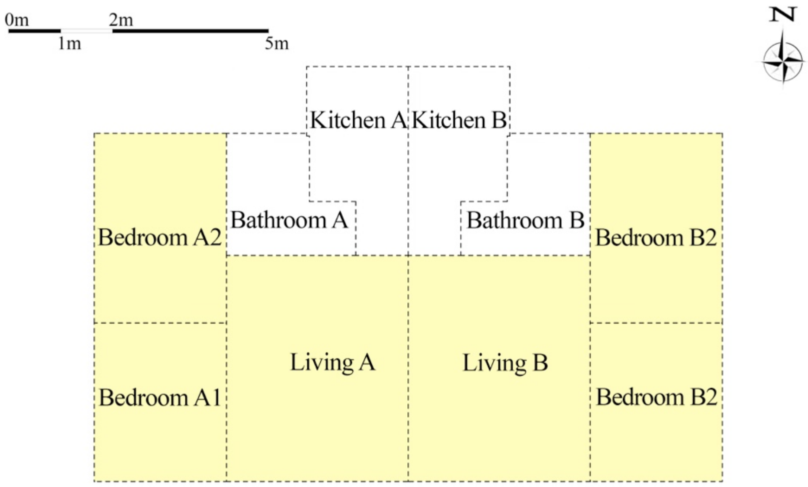

Figure 4.7: Thermal zones in the ground floor of the twin-houses. The rooms marked with yellow are the ones with a permanent use.

All thermal zones were configured and simulated. However, only the rooms with permanent use (living rooms and bedrooms) were analysed, which is consistent with the Brazilian regulation for energy efficiency in residential buildings – RTQ-R (INMETRO, 2012). In order to calculate the representative operative temperature (T_{op}) for the twin-house, a weighted average (by area) of the T_{op} in the thermal zones was calculated[33].

[33] The choice of the T_{op} was to comply with ASHRAE Standard 55.

4.3.1 Configuration of the EnergyPlus model

A standard EnergyPlus simulation uses time steps of 5–15 min (see Section 3.3.1). As recommended by the U.S. Department of Energy (2012), for an accurate calculation of green roof thermal fluxes a higher number of time steps is needed and therefore, all simulations performed with EnergyPlus had a time step of 1 minute (60 time-steps per hour). The following sections detail the configuration of the models simulated in EnergyPlus.

Weather file

The EnergyPlus Weather File (EPW file) used in the simulations was created with statistical meteorological data and solar radiation measured by the Brazilian National Institute of Meteorology (INMET), covering the period from 2001 to 2010. The type of weather file is a "Typical meteorological year" (TMY) that contains one year of hourly data representing weather conditions of a period with several years. In the creation of a TMY file, a data set is analysed and, from that time frame, 12 months that best represent typical conditions are chosen.

The weather file used in this investigation is the latest version of data in that format, for Porto Alegre. In 2015, the team of the Energy Efficiency of Buildings Laboratory, in the Federal University of Santa Catarina (Brazil) made corrections in the global solar radiation, that were underestimated (Scheller, Melo and Lamberts, 2015). The EPW file used by this investigation is the updated version, including those corrections.

Internal heat gains

In naturally ventilated buildings, internal gains occur due to occupancy, illumination and electric appliances. All internal gains used in the simulations were estimated according to the Brazilian regulation for energy efficiency in residential buildings –RTQ-R (INMETRO 2012) and are explained in the following sections.

According to RTQ-R (INMETRO, 2012), the minimum residential occupancy for simulations is of 2 persons per bedroom. Therefore, for the calculation of internal gains due to occupancy it was considered 4 persons per dwelling, resulting in 8 persons in a twin-house unit. The occupancy is determined according to two different schedules: one for weekdays, and another for weekends and holidays, as shown in Table 4.3.

Table 4.3: Detailed occupancy schedule, according to RTQ-R (INMET, 2012)

	Living room (%)		Bedroom (%)	
Hours (full-hour)	Weekdays	Weekends & holidays	Weekdays	Weekends & holidays
1:00h – 7:00h	0	0	100	100
8:00h – 9:00h	0	0	0	100
10:00h	0	0	0	50
11:00h	0	25	0	0
12:00h	0	75	0	0
13:00h	0	0	0	0
14:00h	25	75	0	0
15:00h – 17:00h	25	50	0	0
18:00h	25	25	0	0
19:00h	100	25	0	0
20:00h	50	50	0	0
21:00h	50	50	50	50
22:00h	0	0	100	100
23:00h – 24:00h	0	0	100	100
Total in hours	2h45min	3h45min	3h30min	5h

Table 4.4 shows values of the metabolic rates considered[34], according to activities performed.

Table 4.4: Daily estimated internal gains due to activities performed

Room	Activity	Produced heat (average person) (W)
Living room	Seated or watching TV	108
Bedroom	Sleeping or resting	81

The lighting power density was estimated according to the Standard RTQ-R (INMET, 2012). For the living room, it is 5.0 W/m^2; For the

[34] The metabolic rate used for the calculations in RTQ-R is estimated according to (ASHRAE, 2009), considering a skin area of an average person (1,80 m^2).

bedrooms, the value is 6.0 W/m^2 (per bedroom). The lighting gains are stipulated according to two different schedules: one for weekdays, and other for weekends and holidays, as detailed in Table 4.5.

Table 4.5: Detailed lighting schedule, according to RTQ-R

	Living room		Bedroom	
Hours	Weekdays (%)	Weekends & holidays (%)	Weekdays (%)	Weekends & holidays (%)
1:00h – 6:00h	0	0	0	0
7:00h	100	0	0	0
8:00h	0	0	0	0
9:00h	0	100	0	0
10:00h	0	0	0	0
11:00h – 12:00h	0	0	0	100
13:00h – 16:00h	0	0	0	0
17:00h – 20:00h	0	0	100	100
21:00h	100	100	100	100
19:00h	100	25	0	0
20:00h	50	50	0	0
21:00h	100	100	100	100
22:00h	100	100	0	0
23:00h – 24:00h	0	0	0	0

Internal gains due to electric appliances have been estimated only for the living room, as defined by RTQ-R (INMET, 2012)[35]. The estimated internal gains due to electric appliances are 1.5W/m^2. Table 4.6 shows the total internal gains due to occupancy, lighting and appliances in one year.

[35] Although attributing an internal load density due to appliances just for the living room is considered underestimated, it estimates a value (1.5W/m^2) for all hours of the year (8760). It has been decided to keep this calculation, consistent with the method described by the Brazilian Regulation (RTQ-R).

Table 4.6: Total internal gains due to occupancy, lighting and appliances (annual)

Internal heat gains (kWh)						
Source	Living room A	Bedroom A1	Bedroom A2	Living room B	Bedroom B1	Bedroom B2
Occupancy	256	251	251	256	251	251
Lighting	266	107	129	266	107	129
Appliances	186	-	-	186	-	-
Total	708	358	380	708	358	380
Total internal heat gain (kWh)						2982

Ventilation schedule

A schedule was created for window openings considering the occupied hours (following the occupancy schedule). This schedule was based on one of the users' behaviour scenarios created by Sorgato (2015)[36]. In this research, the scenario named "intermediary user" was chosen: it estimates that the occupants ventilate the house to provide thermal comfort through air movement. This scenario was considered as the one that reflects the most the reality of naturally ventilated houses. However, for security reasons, the doors were configured as closed at all hours.

The schedule for the window openings was created as follows: all of the zone's openable windows are opened when:

$T_{zone} > T_{outdoors}$ ***and*** $T_{zone} > T_{setpoint}$ (=23ºC),

and when the availability schedule allows ventilation (it only works in the hours the zone is occupied, according to Table 4.3).

The opening schedule of windows was configured as 0.0 (closed) or 1.0 (opened), and the opening factor depended on the type of window. Thus, the opening factor was as follows:

- 0.45 for the horizontal sliding windows (living room and bedrooms);
- 0.80 for the jalousie windows (kitchen and bathroom).

[36] Sorgato (2015) created scenarios of users in a house, in a classification according to their interactions with systems and openings. The classification varies from "passive" to "active" users.

Air Infiltration

A zone infiltration is the unintended air flow from the outdoor environment which enters a thermal zone. Infiltration is generally caused by cracks around windows and doors, and even in very small amounts through building elements. The infiltration model adopted by this research is the *Effective Air Leakage Area*. According to the EnergyPlus Reference Guide (Berkeley Lab, 2016), this model is appropriate for smaller, residential-type buildings. For each thermal zone, one infiltration schedule for windows and external doors was created, as suggested by the Reference Guide.

The calculation of the leakage area was made for each type of opening, according to the equation given by ASHRAE Fundamentals (ASHRAE, 2009), Chapter 17.6, as follows:

$$AL = A_{es} \text{ x } A_{ul} \quad \textbf{(4)}$$

Where:

AL is the Leakage area (cm^2), at the reference pressure difference of 4 Pa;

A_{es} is the building exposed surface area (m^2);

A_{ul} is the unit leakage area (cm^2/m^2), defined according to ASHRAE Fundamentals, Chapter 17, Table 3. The A_{ul} value adopted in this calculation was 5.6, which corresponds to a leaky construction.

In addition to the *Effective Air Leakage Area*, two other values of inputs are needed for the Infiltration schedule: the *Stack Coefficient* and the *Wind Coefficient*. Values for the “Basic Model Stack Coefficient” are listed in the ASHRAE Handbook of Fundamentals. The value adopted in this research was 0.000145, corresponding to a one-story house. Values for the “Basic Model Wind Coefficient” are listed in the ASHRAE Handbook of Fundamentals (ASHRAE, 2005), and depend on the type of shelter. The Wind Coefficient value adopted by this research was 0,000104, corresponding to a *shelter class 4 – a typical shelter for urban buildings on large lots.*

Air changes per hour

As a result of the ventilation and infiltration configuration, the averaged air changes per hour for the analysed thermal zones were calculated for the whole year (see Table 4.7). EnergyPlus calculated the values after the first simulation was run.

Table 4.7: Averaged air changes per hour, per thermal zone, one-year period

Air Changes per hour						
All year	Living room A	Bedroom A1	Bedroom A2	Living room B	Bedroom B1	Bedroom B2
Average	1.04	1.20	1.00	1.03	1.2	1.0

Regarding the operation of shading devices, one difference was made in this research, compared to the scenario created by Sorgato (2015) (which estimates that the shading devices will be opened when there is no occupancy). In this research, the shading devices are in use the whole summer by 50% regardless of occupancy, a situation considered by the author as a more realistic estimation.

Ground temperature

The outdoor ground temperature represents an important input for simulations, as discussed in Section 3.4.2. The Brazilian Standard RTQ-R (INMETRO, 2012) recommends the use of the pre-process *Slab* to calculate the ground temperature, before conducting building simulations. Slab estimates the average monthly temperature for the ground based on thermal fluxes between the monthly ground temperatures provided by the weather file and the soil surface temperatures of the thermal zones.

The guidelines for Slab described in RTQ-R were followed for all models simulated in this research. The Slab pre-process needs a preliminary simulation to achieve the surface temperatures of the concrete slab for all internal zones. After that, a weighted average (by area) of indoor air temperature was made, considering the six thermal zones with frequent occupancy (2 living rooms and 4 bedrooms). Then, the resulting value was informed in the pre-process Slab, and the final procedure was to substitute the monthly average ground temperature in the simulation files by the ones calculated by Slab. Therefore, for each model simulated, two files were created: the “Before Slab” and the “After Slab” models, being the last one adopted for the estimation of ground temperature values.

4.3.2 Preliminary evaluation of the indoor thermal comfort of the studied twin-house

The correct choice of tools to evaluate thermal comfort represented a key factor to an understanding of the different variables in the green roof models. Also, changes in the building envelope to comply with the Brazilian Standards were made, increasing the level of insulation. The next sections explain these two preliminary evaluations.

Choice of the thermal comfort model to evaluate the building envelope

Brazil has two Standards and one Regulation dealing with the evaluation of the building envelope: the NBR 15575 (ABNT, 2013), which complies with NBR 15220 (see Section 2.2), and the RTQ-R (INMETRO, 2012). An evaluation of the building envelope according to NBR 15575 and RTQ-R, as well as the Adaptive model of ASHRAE Standard 55 gave the following results:

- According to NBR 15575, the building was considered as "Minimum level" on the scale "Minimum, Intermediary and Superior";
- According to RTQ-R, the building was classified as "Level D" on a scale from A (best performance) to E (worst performance);
- According to the Adaptive model of ASHRAE Standard 55, the building had 50.3% hours in comfort, 39.7% of discomfort by cold and 10.1% of discomfort by warmth in a one-year period.

After testing, it was observed that the Brazilian Standard (NBR 15575) and Regulation (RTQ-R) did not present the appropriate level of sensitivity to small changes in the building envelope. Therefore, the assessment through the Adaptive model of ASHRAE Standard 55 was adopted, instead of the methods from the two Brazilian standards. In addition, heating and cooling degree-hours were used, giving a more detailed evaluation of the green roofs' thermal performance.[37]

[37] Two other methods assess thermal comfort indoors: ASHRAE 90.1 (ASHRAE, 2016) and Predicted Mean Vote (PMV), but they do not comply with naturally ventilated buildings.

Adaptive model of ASHRAE Standard 55

The Adaptive model of ASHRAE Standard 55 is extensively used worldwide to evaluate indoor thermal comfort in naturally ventilated spaces. The model "Determining Acceptable Thermal Conditions in Occupant-Controlled Naturally Conditioned Spaces" relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters (ASHRAE, 2013). The Adaptive model is based on a study conducted by Brager & de Dear (1998), considering an adaptation of the occupants in their activities, including their change of clothing. After compiling an extensive database of field studies developing and testing adaptive models, Brager & de Dear (1998) suggested a range of thermal comfort indoors for naturally ventilated buildings, as illustrated in Figure 4.8.

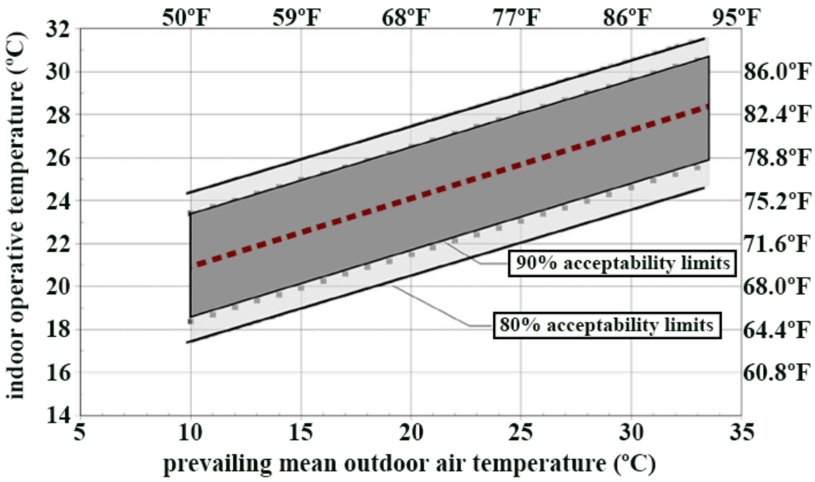

Figure 4.8: Acceptable operative temperature (T_{op}) ranges for naturally conditioned spaces (Based on ASHRAE, 2013)

Besides having no mechanical heating or cooling systems, the conditions for the use of the Adaptive model are: the representative occupants must have metabolic rates ranging from 1.0 to 1.3 met (corresponding to sedentary activities); the occupants are free to adapt their clothing to the thermal conditions within a range from 0.5 to 1.0

clo[38]; and the prevailing outdoor air temperature (T_{air})[39] must be greater than 10ºC and less than 33.5ºC. This investigation met all conditions for the use of the Adaptive model.

To calculate the acceptable limits for the operative temperature (T_{op}), the Adaptive model adopts Equation 5, corresponding to an ideal comfort T_{op}, also named "neutral temperature":

$$\text{Neutral temperature (ºC)} = 0.31\ T_{air} + 17.8 \qquad \textbf{(5)}$$

Two ranges are calculated according to the level of thermal acceptability: 90% and 80%. The range of 80% acceptability was considered suitable for this study, as it is not a highly-controlled environment. The comfort limits for T_{op} were calculated according to the ASHRAE Standard, as follows:

- Upper 80% acceptability limit (ºC) = (0.31 T_{air} + 17.8) + 3.5
- Lower 80% acceptability limit (ºC) = (0.31 T_{air} + 17.8) - 3.5

For this study, the range of comfort limits was calculated according to the respective periods evaluated: if one year, one week or one day. It is worth observing that the Adaptive model of ASHRAE Standard 55 was created based on a study from a global database of 21,000 cases, mainly in office buildings. It is extensively used in Brazil when evaluating indoor thermal comfort in naturally ventilated environments, but without being adapted to the local context. Therefore, a study of the adaptation of the Standard for Porto Alegre and residential buildings would increase the accuracy of the results. Also, it could imply a change of the neutral temperature, thus, modifying the comfort limit values for both summer and winter.

[38] Clo is the unit used to estimate the insulation effect of clothes. For the EnergyPlus simulations, the input value of clo adopted for the summer was 0.5 (representing trousers and short-sleeved shirt), and for the winter was 1.0 (representing trousers, long-sleeved shirt, and long-sleeved sweater). Typical clo values can be found in ASHRAE Handbook – Fundamentals (ASHRAE, 2017). 1 clo = 0.155m^2K/W.

[39] The T_{air}, in the context of the Adaptive thermal comfort of ASHRAE 55, is the prevalent outdoor T_{air}, calculated as an average, depending on the period assessed. The method to establish the prevalent outdoor T_{air} according to the period is detailed in the ASHRAE Standard 55 (2013), Section 5.4.

Adaptation of the building envelope

The Original envelope did not comply with the maximum U values prescribed by the Brazilian Standard NBR 15220 (as explained in Chapter 2). Thus, adjustments were made in the twin-house envelope, for compliance with NBR 15220 (see Section 4.3.4).

For the evaluations made in the next phase (Section 4.3.3), the Brazilian standard envelope was adopted as default to comply with Brazilian standards[40]. The compositions, thermal features and material properties of the three envelopes analysed in this research (the Original envelope, the Brazilian Standard envelope and the Insulated envelope) will be explained further, in Section 4.3.4.

4.3.3 Composition of the green roofs' plant and substrate layers

Within the plant and soil layers (gardening layers), the LAI of the plants and the substrate depth are the features identified in the literature as the ones with the most significant impact on a green roof thermal performance (Jaffal et al., 2012; Sailor et al., 2012; Kim et al., 2012; Zinzi & Agnoli, 2012; Ascione et al., 2013; Ferreira, 2014; Karteris et al., 2016; Silva et al., 2016).

Leaf Area Index

Values of LAI for green roofs vary depending on plant type but are typically in the range of 0.5–5.0 (Sailor, 2008). For this investigation, three LAI values were tested: 1 and 2 – corresponding to a wide range of plant combinations suitable for extensive green roofs, as previously explained in Chapter 2; and 5, as the maximum limit for green roofs found in the literature. As mentioned by Berardi (2016), Dias (2016), and Krebs et al. (2017), and previously tested in a reduced model in the preliminary phases of this research, the influence of plant height was negligible. For that reason, it did not take part in the evaluations in this phase.

[40] The only exception was the time-lag of external walls: it was not possible to achieve the required values with the technology employed (concrete walls with 100mm thickness). Any effort to meet the time-lag value for external walls ($\varphi \leq 4,3$ hours) would imply changing the walls, which was not an objective of this research.

Substrate depth

Three values of substrate depth were tested: 150mm (the upper limit considered as appropriate for an extensive green roof, according to (Gagliano et al., 2014; Scandinavian Green Roor Institute, 2018; ZinCo, 2018), 100mm and 50mm (the minimum substrate depth found in green roofs commercialized by Brazilian companies). Undoubtedly, the thickness of the substrate influences the weight on the roofing system. Although important, the topic is not relevant to the present work and, therefore, it is not discussed in this text.

4.3.4 Thermal properties of the building envelope

Due to the impact of the building envelope on the thermal exchanges between the building's internal and external environments, variations of building envelope were simulated. The objective was to understand how a green roof's thermal performance changes under different building envelopes, as claimed by (Jaffal et al., 2012; Zinzi & Agnoli, 2012; Dias, 2016). Three different envelopes were simulated by gradually increasing the level of insulation, namely: Original envelope, Brazilian standard envelope and Insulated envelope. The following sections detail the thermal features of the tested building envelopes and green roofs.

Building envelopes' compositions and thermal properties

The composition of each one of the tested buildings' envelopes is presented in Table 4.8. Figures 4.9, 4.10 and 4.11 illustrate the external walls of the three envelopes: Original, Brazilian Standard and Insulated, respectively. Figure 4.12 shows a Transversal section of the Baseline roof.

Table 4.8: Components of the Original building envelope and modifications made in the other two envelopes evaluated (Brazilian Standard and Insulated)

Components	**Original** building envelope
Roof	Original: metallic lattice structure, ceramic tiles + air space + 8mm PVC ceiling
External walls	100mm pre-fab concrete wall, painted ivory colour (outdoor face)
Windows	Aluminium framed and one-layer 3mm simple glass
External doors	Metallic (aluminium)
Floor	10mm ceramic tiles + 20mm cement plaster + 70mm concrete;
Components	**Brazilian Standard** envelope: changes from the Original building envelope
Roof	Addition of a 15mm expanded polystyrene board above the ceiling;
External walls	Addition of a 10mm fibre cement board in the inner face of the wall, with an air gap of 50mm;
Windows	No changes have been made;
External doors	No changes have been made;
Floor	No changes have been made;
Components	**Insulated** envelope: changes from the Original building envelope
Roof	Addition of 30mm expanded polystyrene board above the ceiling;
External walls	Addition of a 25mm mineral wool board + 0.3mm vapour barrier + 10mm fibre cement + 5mm cement plaster;
Windows	The windows have been changed for double-glazed windows with a low-emissivity (low-E) at the outer glass and 10mm air gap;
External doors	No changes have been made;
Floor	An addition of a 15mm expanded polystyrene (EPS) board and a 30mm mortar were installed above the 70mm concrete slab.

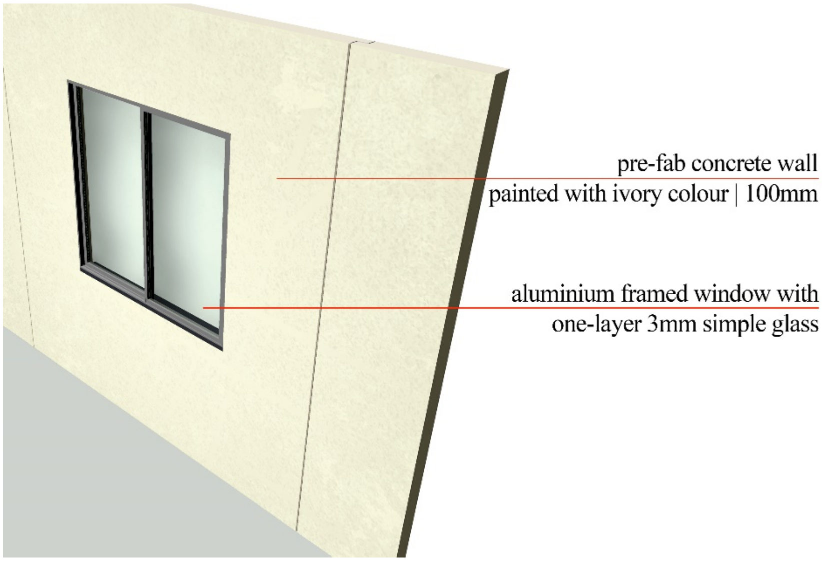

Figure 4.9: External walls of the Original building envelope

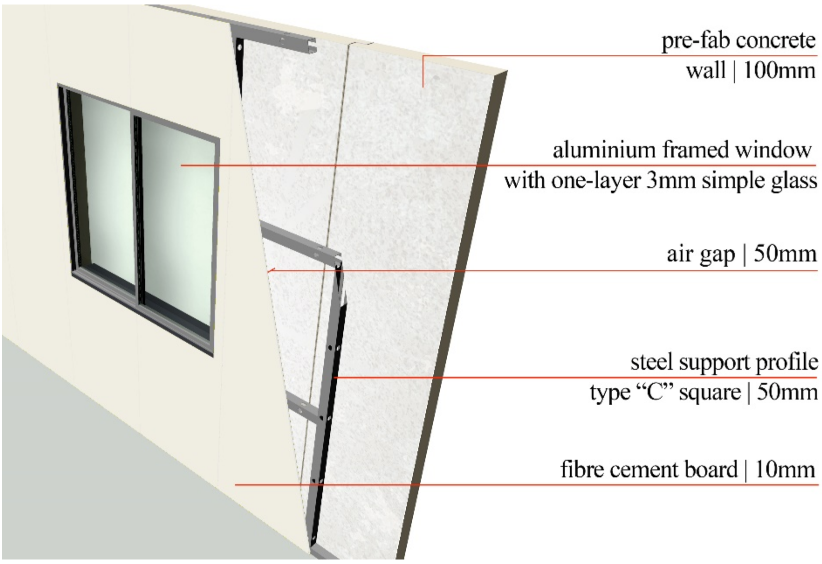

Figure 4.10: External walls of the Brazilian standard envelope

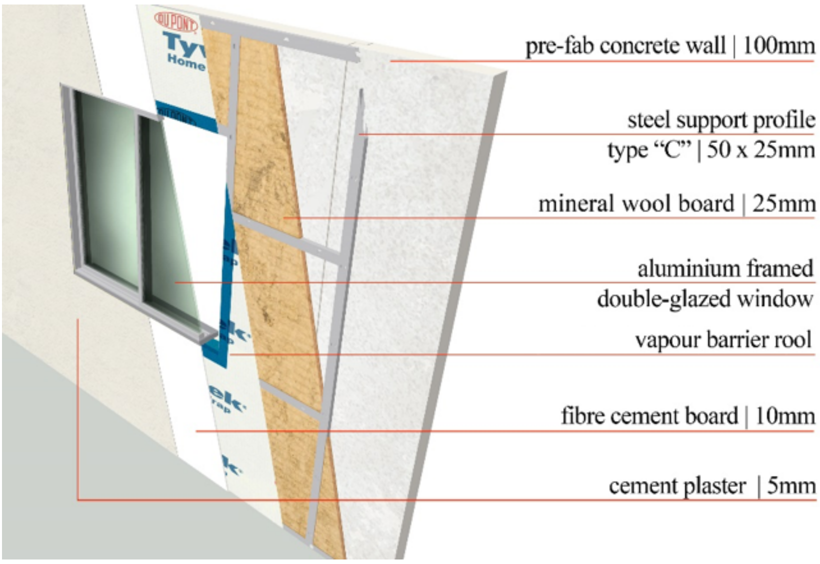

Figure 4.11: External walls of the Insulated envelope

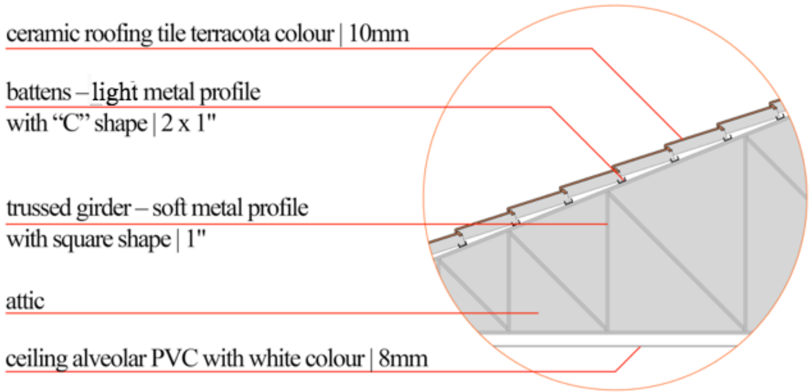

Figure 4.12: Transversal section of the Baseline roof

Table 4.9 presents thermal properties of the building envelope components. The values adopted for the Brazilian standard envelope are slightly lower than the maximum U values[41]. Table 4.10 shows the thermal properties of the building envelope materials.

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[41] The Brazilian Standard envelope is slightly better insulated than the minimum required.

Table 4.9: Thermal properties of the building envelope components – all envelopes: Thermal transmittance (U), Thermal capacity (C_T) and Solar absortance (α)

Envelopes / Components		U (W/m^2K)	C_T (kJ/m^2K)	α (dimension-less)
Original envelope	Roof	2.12	22.4	0.8
	External walls	4.40	215.0	0.3
Brazilian standard	Roof	1.18	22.7	0.8
	External walls	2.51	230.1	0.3
Insulated envelope	Roof	1.01	23.0	0.8
	External walls	1.25	240.1	0.3

Table 4.10: Properties of materials used on buildings' envelopes: Thickness (e), Thermal conductivity (λ), Density (ρ) and Specific heat (c)

Materials	e (mm)	λ (W/mK)	ρ (kg/m^3)	c (J/kgK)
Ceramic tiles*	10	1.05	2000	920
Expanded polystyrene board	15	0.04	35	1420
PVC white ceiling	08	0.21	1470	400
External concrete wall	100	1.75	2150	1000
Mineral wool board	25	0.045	96	750
Fibre cement board	10	0.95	1800	840
Metallic frames**	08	45	7800	500
Ceramic tiles[42]	10	0.9	1600	920
Cement plaster	05	1.15	1800	1000
Cement screed	03	1.15	1800	1000
Concrete slab	07	1.75	2150	1000

* Earth-red colour

** Used in windows, external doors and window shutters

[42] In all areas, the internal floor is ceramic; in the kitchen and bathroom, also the walls are ceramic.

Table 4.11 describes green roof's physical properties, highlighting the parameters that were tested: plants LAI of 1, 2 and 5, and a substrate thickness of 50mm, 100mm and 150mm.

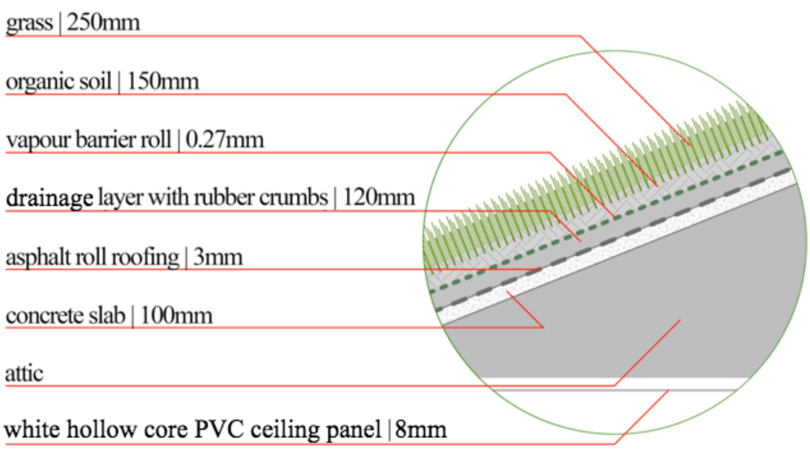
Table 4.11: Summary of green roof components in the EnergyPlus models

	Component	Unit	Fixed	Tested
PLANTS	LAI	m^2/m^2		1
				2
				5
	Height of plants	m	0.25	-
	Leaf reflectivity	-	0.20	
	Leaf emissivity	-	0.90	
	Minimum stomatal resistance	s/m	120.00	
SUBSTRATE[43]	Thickness	mm		50mm
				100mm
				150mm
	Conductivity of dry soil	W/mK	0.20	-
	Density of dry soil	kg/m^3	1020.00	
	Specific heat of dry soil	J/kgK	1100.00	
	Emissivity	-	0.90	
	Solar absorptance		0.75	
	Visible Absorptance		0.75	
	Saturation volumetric moisture content		0.30	
	Residual volumetric moisture content	-	0.01	
	Initial volumetric moisture content	-	0.15	

[43] The rain was taken into account in the simulations with data from the weather file. The values of dry-soil serve as the initial reference. For the soil composition, Table 4.12 adopted values from the Brazilian Standard NBR 15220.

Green roofs composition and thermal properties

From the best result obtained in each feature tested (as illustrated in the previous section), a combination was made to configure the green roof model for the next simulations performed (phases 2, 3 and 4). A transversal section of the selected roof is illustrated in Figure 4.13.



Figue 4.13: Section of the Baseline green roof (Drawing made by Carlos Krebs)

As mentioned in Section 3.4.2 (Subsection Substrate depth), the thermal properties of green roofs vary with the moisture content. Table 4.12 estimates the thermal properties of the Baseline green roof (having a substrate with 150mm thickness, plants with a LAI of 1 and 250mm height as a function of water content.

Table 4.12: Thermal properties of the Baseline green roof for different saturation levels of the soil

Saturation level (%)	Thermal transmittance U (W/m^2K)	Thermal capacity C_T (($kJ/(m^2K$)	Solar absorptance α (dimensionless)
0	0.68	439	0.8
100	0.78	669	0.8

4.4 Phase 2: Outdoor microclimate

The primary objective of Phase 2 was to understand the outdoor microclimate in the site area. In order to evaluate how the cluster of houses affects the microclimate around the twin-houses, they were located within the site area.

The software ENVI-met was the chosen modelling tool. As described in Section 3.4.3, ENVI-met is a three-dimensional microclimatic modelling system able to simultaneously calculating the meteorological conditions, surface energy fluxes, and soil and vegetative processes within the urban environment. Those characteristics enable a great variety of testing with vegetation, through a variety of urban configurations.

In Phase 2 a Typical summer day and a Typical winter day were created. The Typical summer and winter days were generated from averaged data of the Typical summer and winter weeks[44]. It should be noted that the Typical days employed in this work differs from the Typical *Design* Days stated in the Brazilian Standard NBR 15575 (ABNT, 2013). As in Phase 1, in Phase 2 data from the weather file was employed as the initial boundary conditions.

According to the statistical file of the last ten years measured (2001-2010), the Typical summer week occurred from November 29th to December 5th. and the Typical winter week occurred from May 15th to May 21th. The hourly averages made for the Typical days accounted for the following variables: T_{air}, RH, wind speed and solar radiation (global, direct and diffuse). For the wind direction, the monthly average for December (summer) and May (winter) were used.

In order to define the Baseline case (Case 0) to be simulated in phase 2, several preliminary assessments were needed. Sections 4.4.1 to 4.4.4 explain these preliminary studies and the creation of Case 0. All preliminary studies carried out in phase 2 are presented here, divided into 3 groups: 2 groups referring to ENVI-met simulations, and 1 group testing data to be used as inputs for the models. Figure 4.14 presents the flowchart of Phase 2, from the preliminary studies to the

[44] The Typical summer day and the Typical winter day averaged from their correspondent Typical weeks were considered more appropriate to this investigation studying naturally ventilated buildings, because they are more representative of the climate than the extreme days.

creation of Case 0. Detailed explanations of each preliminary assessment are given in the following sections.

As previously mentioned, the outputs generated in Phase 2 were further employed in phases 3 and 4, substituting meteorological data from the weather file in the Baseline site model.

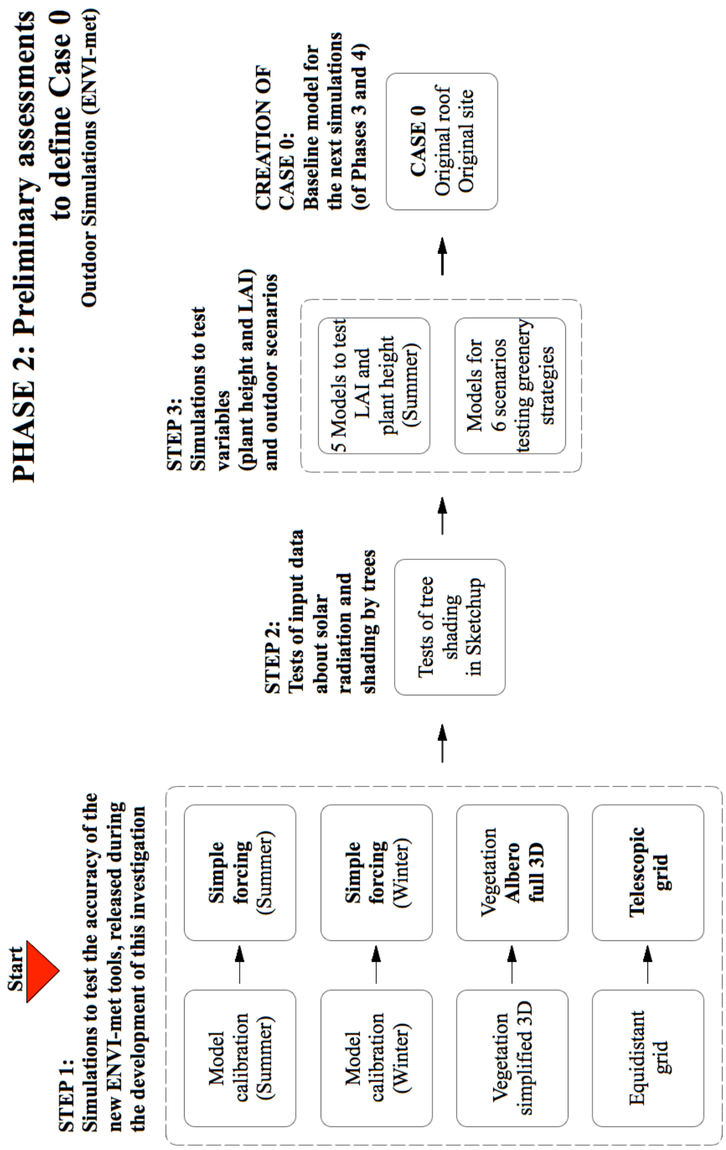


Figure 4.14: Flowchart of studies and simulations performed in Phase 2

4.4.1 Simulations to test the new features of ENVI-met V4.0

During the development of this research, all software had one or more updates released. In cases where a software update was launched with changes that would improve the way simulations are performed, the adoption of the new version was considered. Performing tests were needed, though, to compensate for the low number of published studies validating the new features. ENVI-met has presented new features with substantial improvements from version 3.1 to 4.0, modifying considerably the way simulations are made.

A selection was made of the new features that have a significant impact on the way ENVI-met simulations are made. Therefore, the following three new features were tested:

- *Simple forcing*, to calibrate the model;
- *Albero*, to create three-dimensional vegetation; and
- *Telescoping grid*, to define different cell heights within the same model.

Results were compared between "the current" and "the new" way of simulating, providing data for the decision about their suitability for the investigation.

Model calibration: initial T_{air} vs. Simple Forcing

As explained in Section 3.4.3, ENVI-met underestimates the T_{air} amplitude. Therefore, in places where there is a high thermal amplitude, calibration is needed to adjust the result to either the highest or lowest $T_{air,}$ depending on the purpose of the study. Three different methods of calibrations have been tested in the research.

The first method reproduced the most common calibration method found in the literature. Thus, simulations with a 48-hour schedule were run, using data from the second day. An averaged T_{air} of all cells within the site (excluding the buildings) was made for the Typical summer day with the first scenario (Case 0). Discarding the first 24 hours of simulated data, as suggested in other studies, results in a significant amount of waiting time, which motivated the testing with the other two methods.

Another solution to reach the higher or lower daily T_{air} is to adjust its initial temperature. Thus, the second calibration method tested the model with a 24-hour cycle. Simulations were performed gradually increasing the initial T_{air}, until the warmest T_{air} value during the day was reached in the model. While in the Typical summer day it was possible to achieve an acceptable similarity with data from the weather file, in the Typical winter day the amplitude was far too low[45]. The difficulty in achieving the daily T_{air} amplitude may be attributed to the lower solar radiation, in winter.

The third calibration method tested was performing simulations with the ENVI-met *Simple Forcing*. The tool enables the user to inform inflow boundaries (values of T_{air} and RH) at 2m height, hourly, for a period of up to 24 hours. In order to confirm the suitability of *Simple Forcing* to the study, simulations using the tool were made. Afterwards, the results were compared with the ones provided by the second calibration method tested (increase in the initial T_{air}). That was made for the Typical summer day for all six outdoor scenarios (from Case 0 to Case 5). The results were also compared with statistical data from the weather file. Figure 4.15 exemplifies one of the comparisons made, showing results from the Typical summer day of Case 0.

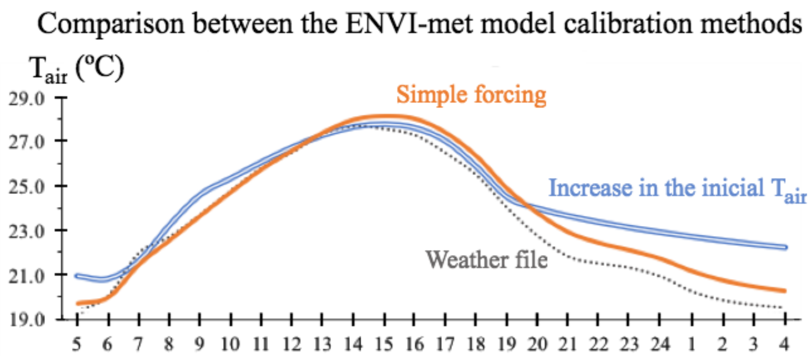


Figure 4.15: Results of T_{air} with two ways of model calibration, for Case 0: increase in the initial T_{air} and use of simple forcing, and T_{air} from the weather file, during a 24-hour period (Typical summer day).

From Figure 4.15 it can be observed how the curve produced in the model simulated with the *Simple Forcing* tool fairly well reproduced the curve of T_{air} values from the weather file. Consequently, the daily T_{air} amplitude was achieved (see Table 4.13). However, a certain level of increase in T_{air} was observed, when the forced values were compared

[45] As explained in Chapter 2, Porto Alegre has a high daily T_{air} amplitude, even in winter. That T_{air} amplitude was not possible to be reproduced by ENVI-met.

to T_{air} values from the weather file. While extremely relevant for both seasons, the daily T_{air} amplitude was a deciding factor in the winter.

Table 4.13: Maximum, minimum and daily T_{air} amplitude for Case 0 with two methods of weather input data calibration, and T_{air} from the weather file, in the Typical summer day

T_{air}	Data from the weather file (ºC)	Calibration by increasing the initial T_{air}	Calibration with Simple Forcing
Maximum	27.7	27.8	28.2
Minimum	19.3	20.8	19.7
Daily amplitude	8.3	7.0	8.4

Modelling of vegetation with Albero

In order to improve the reproduction of the complexity of vegetation, ENVI-met v.4.0 has released the application "*Albero*" (Figure 4.16).

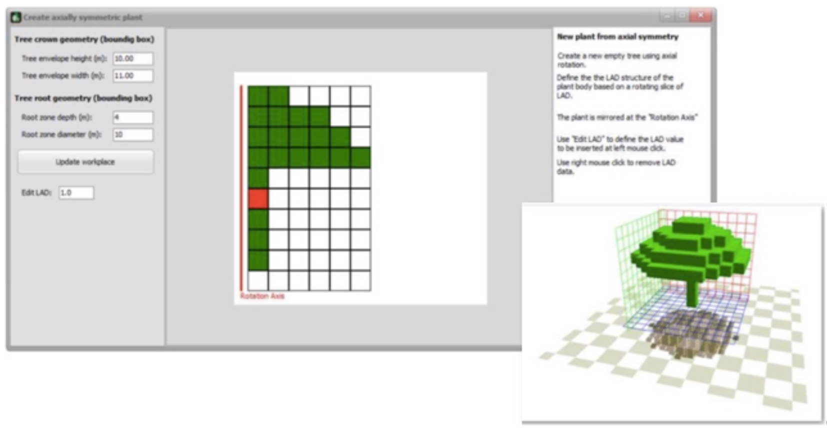


Figure 4.16: Example of a tree being created with Albero (Bruse et al., 2017)

Albero allows the user to construct three-dimensional models of vegetation, as it treats plants as individual organisms, simulating them with a higher level of detail. Physiological state (like water supply) can be informed, and three-dimensional visualisation of each vegetation unit is provided, while it is being created.

In order to evaluate the suitability of *Albero* in this investigation, tests were made with the outdoor scenarios. Thus, results from models where trees were constructed with *Albero* were compared with results from models where trees were created in the previous way. Results of T_{air} and RH have demonstrated negligible differences, therefore, confirming the suitability of *Albero* to generate plants in all ENVI-met models.

Telescopic grid feature

All ENVI-met models presented in this investigation were performed in V.4.0.3. A 3D raster grid composes the main model area in the software. The two biggest options for the model size available in the ENVI-met Science version are 100 x 100 x 40 or 250 x 250 x 30 grid cells. Hence, bigger models in x-axis and y-axis directions have a limitation of cells in the z-axis direction.

The creation of the green scenarios resulted in a necessity to organise the cell heights of different elements within the model. That was achieved with the use of the *Telescoping grid feature* (Figure 4.17). Figure 4.18 shows the elements organized with the use of the feature, as well as its respective heights in the model.

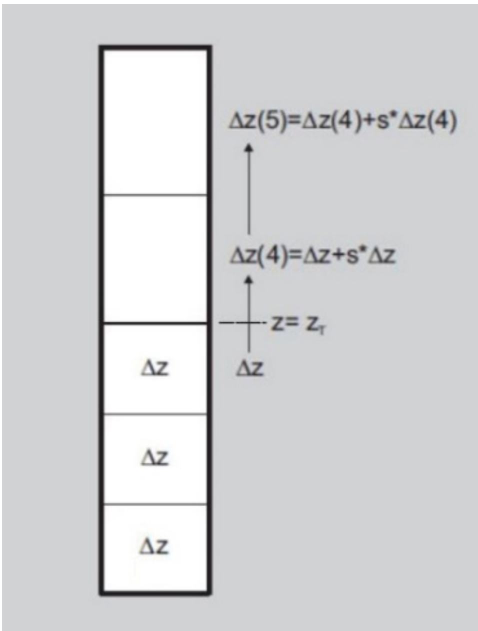


Figure 4.17: The telescoping grid model in ENVI-met 4.0.3, starting after $z=z_T$[46] (Bruse et al., 2017)

[46] Δz is the base cell height.

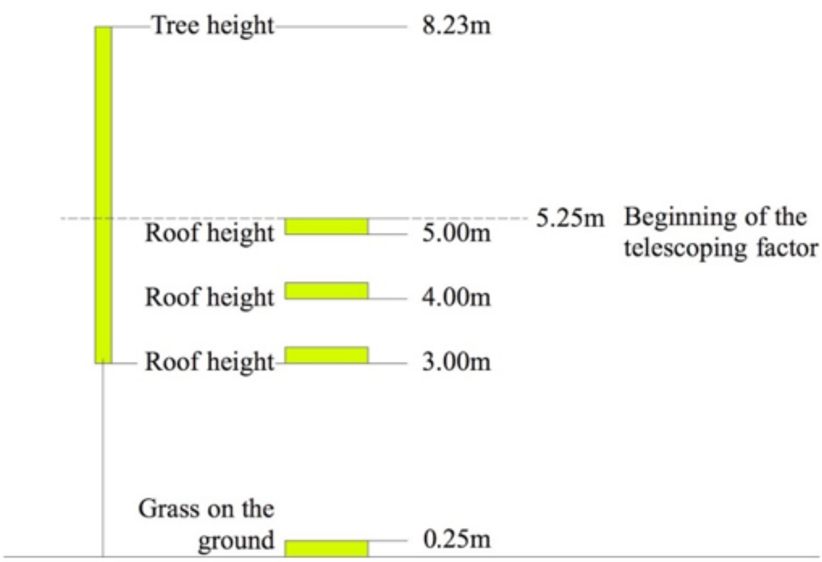


Figure 4.18: Schematic representation: element heights made compatible with modelling with the telescoping grid feature

Until v.3.1, nesting grids[47] could be added to give more stability to the calculations. However, from version 4.0 on, their use is not recommended (Bruse et al. 2017). As an alternative to the nesting grid cells, ten additional cells were added to the x-axis and 10 to the y-axis, 5 for each border. The grid configuration for all models was defined with the following number of grids:

- x-axis = 96
- y-axis = 99
- z-axis = 39

Resulting from the steps previously explained, and including the maximum number of houses within the size limits (respecting the site design), all models presented in the investigation have a site size of 96m x 99m x 43.7m height (see Figure 4.19). Two recommendations from ENVI-met (Bruse et al., 2017) regarding the models' heights were met:

- The resulting model height was bigger than twice the height of the highest building; and

[47] Nesting grids are boundaries empty cells, with the objective of increasing the model size in the horizontal plane, making the CFD simulations more stable.

- The model height was not less than 40 - 50 m.

Figure 4.19 exemplifies the site models, by showing the Baseline site model (Case 0).

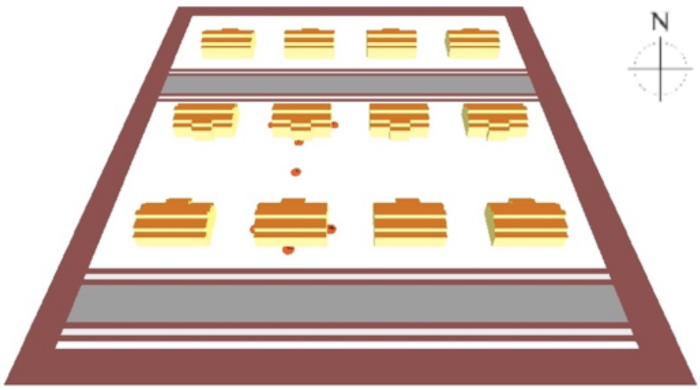


Figure 4.19: Definitive ENVI-met Baseline site model (Case 0)

4.4.2 Tests with shading

The solar radiation is a key aspect of the green roof's thermal performance. As seen in Section 3.2.2, the incidence of direct and diffuse solar radiation influence in a considerable amount the heat exchanges within the vegetation and the soil layers. Thus, an evaluation of the shading was considered highly relevant to the research.

As Porto Alegre has both cooling and heating needs, it was important to position the trees in a way they would provide the maximum shading in summer, and the maximum solar penetration in winter. That was possible due to the deciduous character of the trees, together with the knowledge about the solar path in both the Typical summer day and the Typical winter day. This study was performed with the software Sketchup Make v.2018 (Trimble, 2018), and served to define the outdoor vegetation layout in the site area.

The sun path is high in Porto Alegre, especially in the summer. The choice for the tree's location was made for the summer season, when the shades are beneficial to the thermal comfort. A day in the middle of the Typical summer week was specified for the study: December 2nd. After modelling the twin-houses, trees were constructed with the size of *T. chrysotricha*: 8m in total height (3m for the trunk and 5m for the crown) and 7m of crown diameter.

Tests were made by positioning the trees in different places within the model. Observations were made hourly. Figures 4.20 and 4.21 illustrate the shadows at 08:00h, 10:00h, 15:00h and 17:00h, respectively, with the position chosen for the trees. Thus, the hours were chosen to be illustrated due to their biggest shadows on the twin-house. The trees were located in front of the three facades with the highest solar gain in Porto Alegre: North, East and West. The tree trunks were located at 3m distance from the twin-houses at the left side and 4m distance at the right side, in compliance with the minimum distance suggested by the Technical Guideline of urban forestation (SVMA, 2015), and 7m distance from each other. Due to limitations of the site size, the two trees in the centre of the North façade have 6 meters between them.

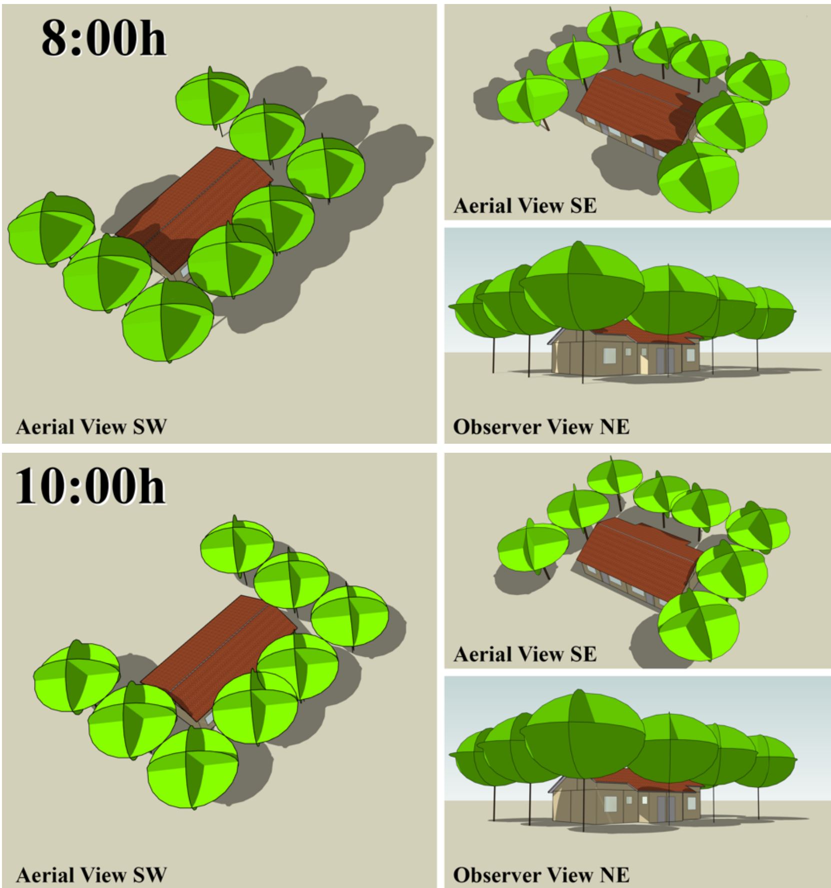


Figure 4.20: Shading by trees in its their final locations in the morning, at 08:00h and 10:00h, in the Typical summer day

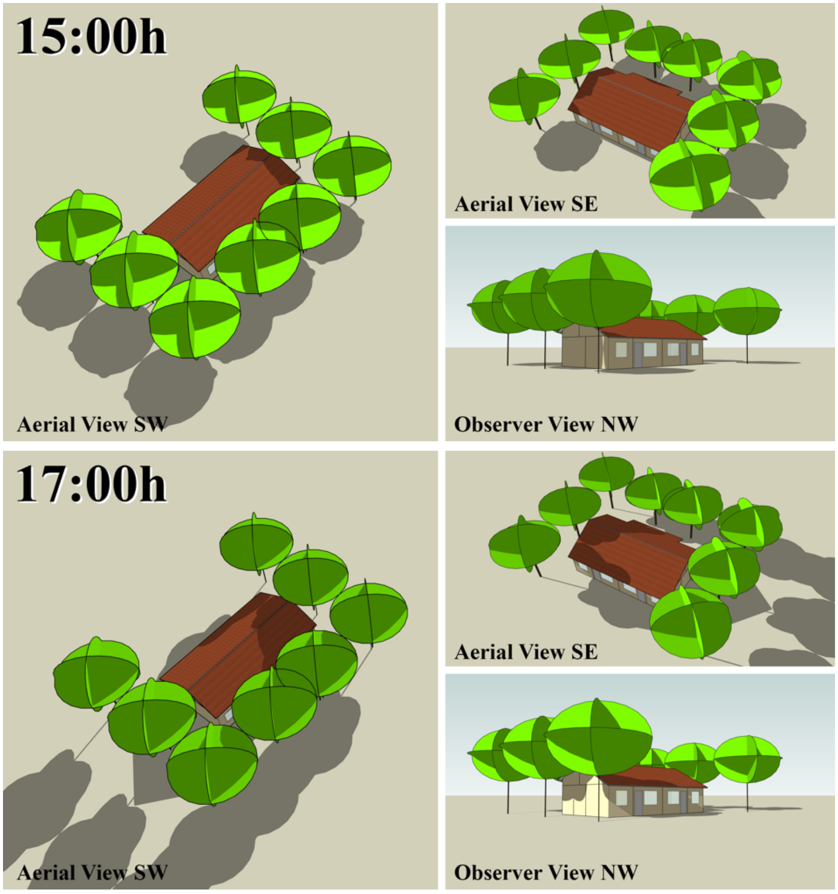


Figure 4.21: Shading by trees in its their final locations in the afternoon, at 15:00h and 17:00h, in the Typical summer day

4.4.3 Site modelling

In order to collect data from specific locations in the model, ENVI-met allows the position of receptors. Receptors are "virtual climate stations" that enable the state of the model to be followed in greater detail at specific points, as described by Bruse et al. (2017). They are manually located by the user in the model area, providing the output of climatic data at several heights, for specific grid points of the model.

In this investigation, the receptors have had two objectives. The first goal was to provide data for the coupled simulations with the indoor model in EnergyPlus (Phase 4). The second objective of the receptors was to collect data to analyse the potential influence of green roofs to the outdoor microclimate.

Creation of input data for the coupled simulations performed in Phase 4

To provide information for the coupled simulations, the procedure adopted by Pastore et al. (2017) and Peng & Elwan (2014) was reproduced[48]. Hence, four receptors were positioned in the model, alongside the twin-houses, each one located at 0.5m from each façade (Figure 4.22).

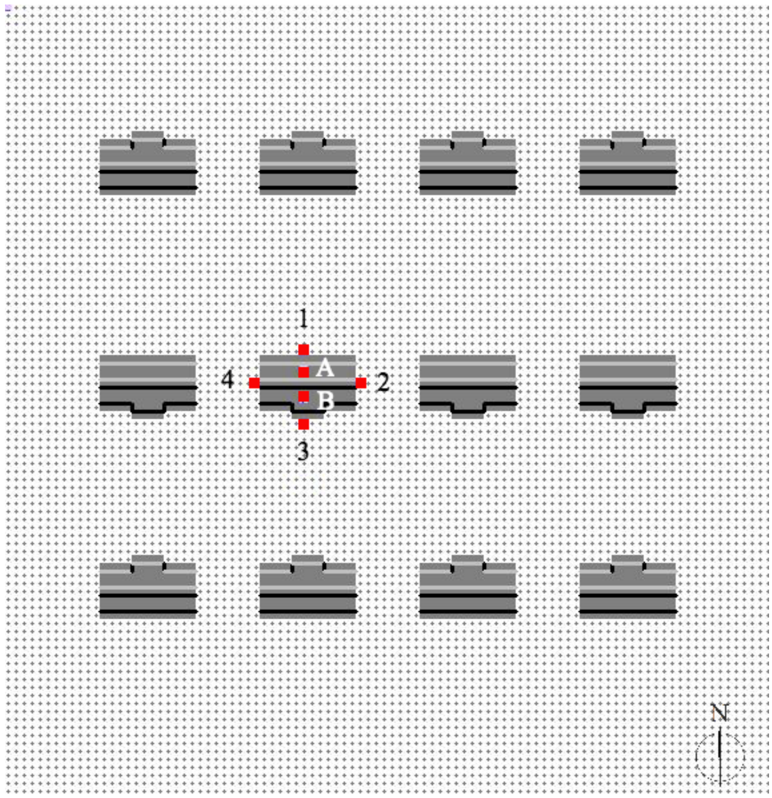


Figure 4.22: Location of the ENVI-met receptors in all models, in the site area with 96m in the x axis and 99 in the y axis

[48] An almost identical method for performing coupled simulations was adopted by Fahmy et al. (2017). The only difference was the reading of ENVI-met variable outputs: the averaging data from the receptors was substituted by the averaging of the site grid cells.

The receptors (1, 2, 3 and 4) have extracted exact values for air temperature (dry-bulb), relative humidity, wind speed, wind direction and solar radiation, for the direct use in the coupled simulations. As previously mentioned, ENVI-met receptors generate climate data at different heights. For the coupled simulations, data was collected at 2.38m height, representing a value approximately in the middle of the twin-houses façades.

Creation of input data to evaluate the effect of green roofs on the microclimate

To analyse the potential influence of green roofs on the outdoor microclimate, evaluations were made at pedestrian level and above the roof. The observation at pedestrian level was made at 1.38m height, and the same receptors used in the previous section were employed: receptors 1, 2, 3 and 4. Data from the receptors were averaged for the same variables as the ones analysed previously (wind speed, wind direction, T_{air} and RH). For the analysis made in this section, one more variable was included: the mean radiant temperature, as an indicator of changes in microclimate.

In order to evaluate the effect above the green roofs, two more receptors were added: A and B. The same variables extracted from Receptors 1 to 4 were extracted from receptors A and B, at 4.38m, 4.63m and 5.38m[49]. These heights represent an evaluation near the rooftop, one meter above it, and an intermediary height. As the readings took place above the part of the roof with 4m height, the defined extracted heights represented the following distance from the top of the vegetation layer: 0.13m, 0.38m and 1.13m, respectively.

Materials and initial boundary conditions

Table 4.14 presents the initial input data configured for simulations in the Typical summer and winter days. The models were run to an urban area. Table 4.15 informs the materials of Case 0 and their main characteristics. The Baseline site (Case 0) uses the same same materials as in the original project. For the other scenarios, changes were made for the ground and the roofing materials, as it will be explained in Section 4.5.

[49] The three heights above the roof were selected within the options given by ENVI-met.

Table 4.14: Initial input data configured in the ENVI-met simulations for summer and winter

Configuration data	Summer	Winter
Meteorological data		
Initial simulation hour (24-hour cycle)	5:00 a.m.	5:00 a.m.
Maximum temperature of the atmosphere (ºC)[50]	27.7	20.2
Minimum temperature of the atmosphere (ºC)	19.3	12.8
Diurnal temperature amplitude (ºC)	8.3	7.4
Wind speed at 10m above ground level (m/s)	2.1	1.1
Wind direction (º)	135	135
Solar data		
Solar adjustment factor	0.92	1.02
Fraction of Low clouds (x/8)	1	2
Fraction of Medium clouds (x/8)	1	2
Fraction of High clouds (x/8)	1	1
Soil data		
Soil temperature Upper layer (0.0 – 0.2m) (ºC)	20.5	22.0
Soil temperature Middle layer (0.2 – 0.5m) (ºC)	20.5	22.0
Soil temperature Deep layer (below 0.5m) (ºC)	19.5	21.0
Soil relative humidity in Upper layer (%)	50	50
Soil relative humidity in Middle layer (%)	60	60
Soil relative humidity in Deeper layer (%)	60	60

In ENVI-met the combination of clouds and the solar factor was used to reproduce, the quantity of direct and diffuse solar radiation, as informed by the weather file. Regarding initial boundaries, as previously explained, the Typical summer day was defined with averaged data from the Typical summer week: from November 29th to December 5th, identified from the statistical weather file. The same method was used to defining the Typical winter day: from May 15th to May 21st.

[50] Values of T_{air} and RH from weather file were informed as ENVI-met input hourly, in a 24-hour period.

Table 4.15: Characteristics of the materials in Case 0

Element	Material	Colour	Absorptance	Emissivity
Roofs	ceramic tiles	terracotta	0.8	0.9
External walls	concrete painted	ivory	0.3	0.9
External floors				
Tiles in the plot	ceramic	white	0.2	0.8
Sidewalk	smooth cement	grey	0.6	0.8
Paving	concrete blocks	grey	0.6	0.8

4.5 Phase 3: Outdoor microclimate with green strategies

This phase aimed to understand and to compare the effect of the green roofs and of the Dense green site on the local microclimate. Additionally, Phase 3 provided data for the indoor simulations to be performed in phase 4, when the coupled simulations were performed. Figure 4.23 presents the flowchart of Phase 3.

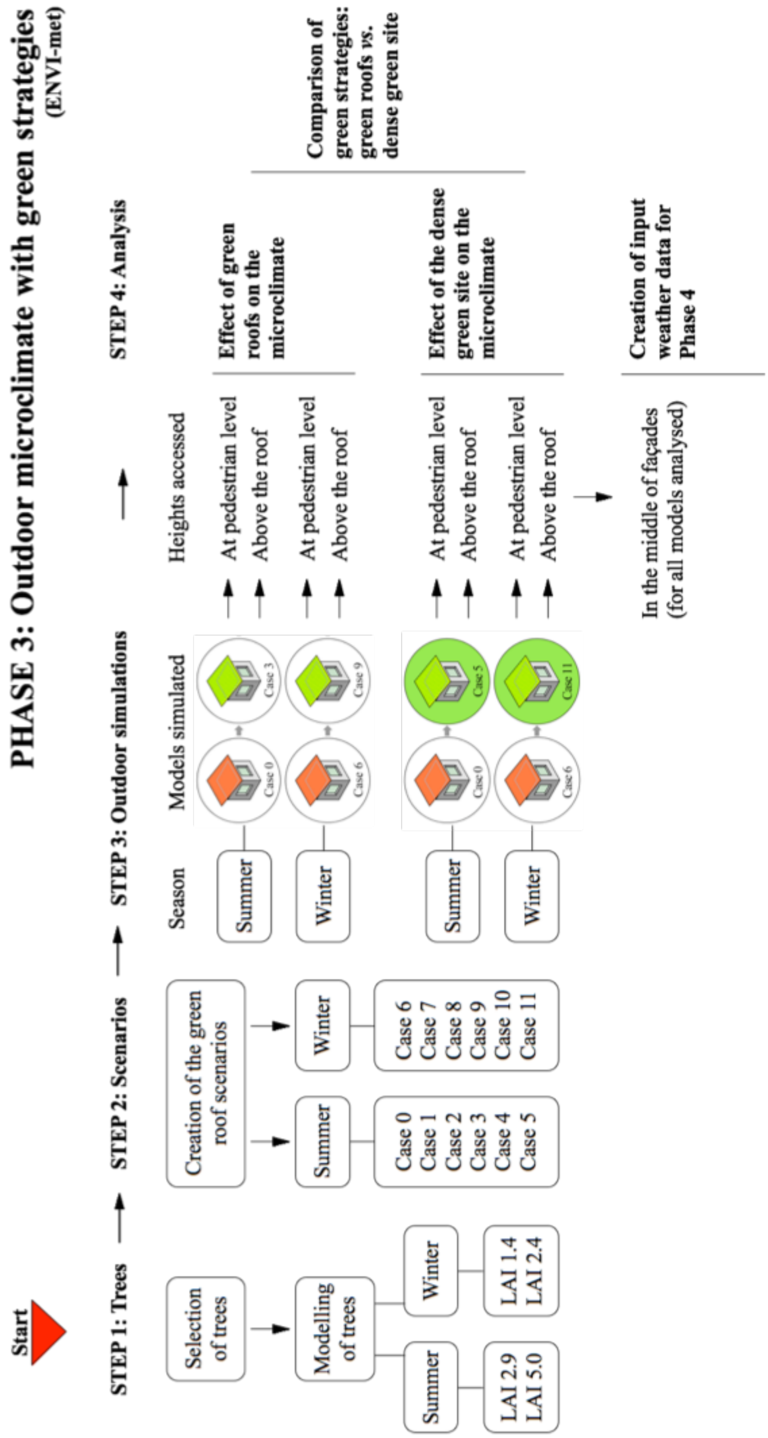


Figure 4.23: flowchart of Phase 3. The different cases are described in Table 4.18.

4.5.1 Selection of trees

The trees were fundamental elements in the creation of the outdoor scenarios. The aim was to specify species with characteristics as follows:

- *Commonly used* in Porto Alegre – representing a species with a high number of trees in the city, therefore, with a suitable response to the climate and good acceptance by the inhabitants;
- *Deciduous* – As explained in Chapter 2, the climate of Porto Alegre demands cooling and heating. A deciduous tree, by losing leaves in the winter, allows a good amount of solar radiation to pass through it;
- *Having documented properties* (through field measurements) about its characteristics: size, Leaf Area Index, periods and percentage of leaves lost in winter, and periods of blossom[51];
- *Suitable for the scale of the project*: having a height that would provide shade for the twin-houses, and have non-aggressive roots, so the trees could be close enough to the twin-houses to give the desired shading effect, without threatening the outdoor ground or the building structure.

Tree species having scientific studies published about their characteristics and their contribution to the urban microclimate were prioritised. In each study, the information provided was about measured shading, assessed cooling effect (such as the reduction on T_{air}, for instance), or both.

The first step taken was to select a group of tree species commonly found in Porto Alegre. After the analysis of trees with a good suitability to the study, two species from the same family (*Bignoniaceae*) were chosen: *T. chrysotricha* (Mart. ex A.DC.) *Standl*. (Figure 4.24) and *T. impertiginosa* (Mart. ex DC.) *Standl*. (Figure 4.25). The choice of these two trees was based on the fact that they are both deciduous, allowing penetration of sun during the winter. Furthermore, these two species, in addition to be commonly used, are also native from Porto Alegre. Both *T. chrysotricha* and *T. impertiginosa* are species suitable for the use of sidewalks, meaning they can be near the houses without damaging by their roots. The proximity to the houses is necessary to provide shading, as seen in the preliminary shading study (see Section 4.4.2.1). Some

[51] Knowing the periods of blossom allowed to avoid those periods in the simulations.

species, as *Caesalpinia peltophoroides* and *Bauhinia variegate*, while very common in Porto Alegre, are classified as semi-deciduous by the SMVA (2015). Thus, they were considered not eligible for this investigation. The two species chosen belong to the same family, are very similar in size, shape and other characteristics. Concerning the foliage density, *T. chrysotricha* is less dense (LAI of 2.9 in summer, according to Santana & Encinas (2011)), while *T. impertiginosa* has a higher density (LAI of 5 to 6, according to Callejas et al. (2014)). According to Duarte (2015), the LAI = 5 corresponds to a dense tree and LAI = 1 to a low-density tree. Thus, a value of LAI = 3 can be considered as medium density.

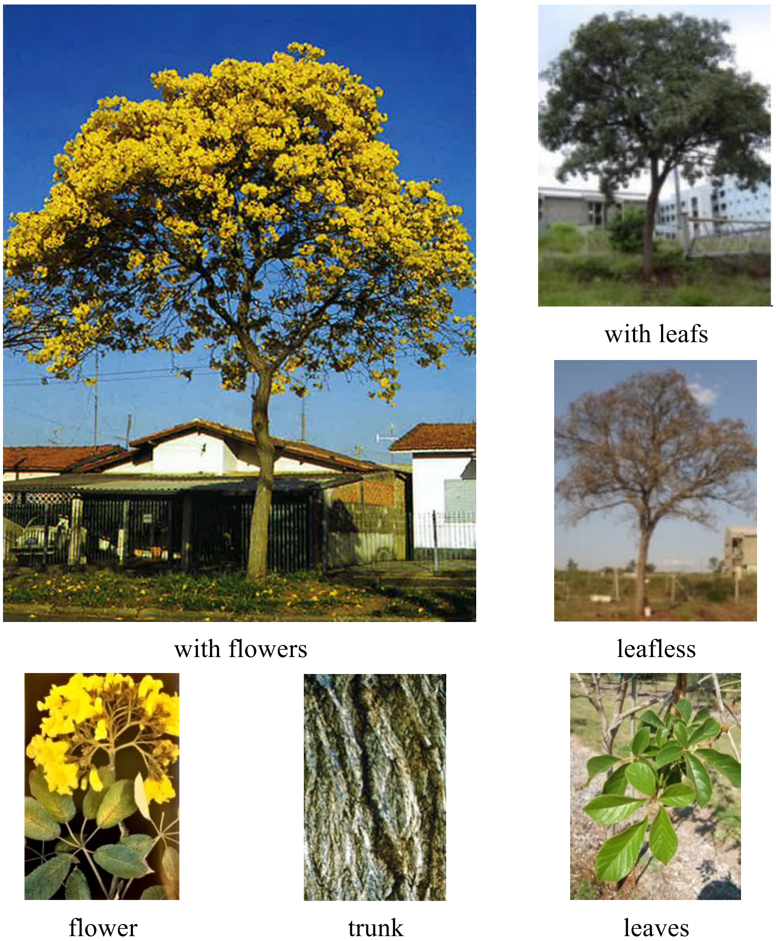


Figure 4.24: Tabebuia chrysotricha (Mart. ex A.DC.) Standl (Lorenzi, 2000; de Abreu, 2012; University of Florida, 2014)

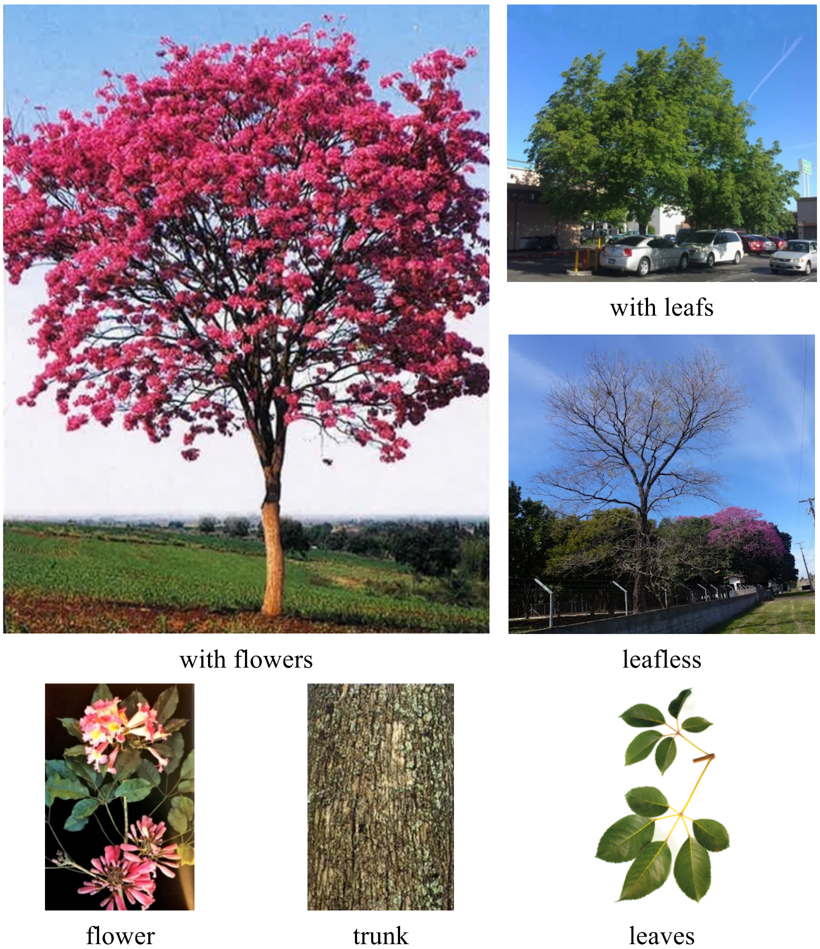


Figure 4.25: Tabebuia impertiginosa (Mart. ex DC.) Standl (Lorenzi, 2000; Arizona State University, 2017)

Data regarding the opacity of the crown in summer and winter, and about the attenuation of solar radiation (shade provided, in both seasons) are available in the literature for *T. chrysotricha*, in more than one study with field measurement made by de Abreu (2012). Measurements of the crown opacity of *T. impertiginosa* were not found in the literature. Information about the attenuation of solar incidence of *T. impertiginosa* is available, though, in studies like the one made by Bueno-Bartholomei (2003), for instance. As *T. chrysotricha* and *T. impertiginosa* belong to the same family and present a high similarity in size, shape and blossom cycle, data of opacity of *T. chrysotricha* were adopted for both trees, in summer and winter.

4.5.2 Modelling of trees

Table 4.16 summarises information about the two trees, showing field measured data and approximations made for the ENVI-met tree model. For the ENVI-met modelling, characteristics of *T. chrysotricha* were defined according to the field studies made by Santana & Encinas (2011) and by de Abreu (2012). *T. impertiginosa* had its characteristics set according to the study made by de Abreu (2012) and Callejas et al. (2014).

Table 4.16: Characteristics of *T. chrysotricha* and *T. impertiginosa* and corresponding values in the ENVI-met models, exemplified by their summer models

Characteristic	*T. chrysotricha*	*T. impertiginnosa*	ENVI-met models
Tree height	8.30m	8.30m	8.23m
Trunk height	3.10m	3.10m	3.00m
Crown height	5.20m	5.20m	5.23m
Crown diameter	7.10m	7.10m	7.00m
Crown density	Medium	Dense	Different trees were modelled (for the LAI values, see Table 4.18)
Leaf colour	Light green	Dark green	Albedo of T. chrysotricha = 0.4; Albedo of T. impertiginosa = 0.3
Seasonality opacity	Deciduous: 85.3% of opacity in summer; 41.3% of opacity in winter.	Deciduous (the same as T. chrysotricha)	Different averaged LAD for summer (1.0) and winter (0.5)

The classification made by Duarte (2015) served as the parameter to differentiate the density of trees. Thus, *T. chrysotricha* corresponds to a medium density tree (LAI 2.9, very close to 3, that is the value for a medium-density tree). By the same definition, *T. impertiginosa,* having the LAI 5, is considered as a dense tree.

For each vegetation species modelled in ENVI-met, a Leaf Area Density (LAD) profile was defined. LAD is defined by Lalic &

Mihailovic (2004) as the total one-sided leaf area (m^2) per unit layer of volume (m^3), for each horizontal layer of the tree crown. LAD profiles give information about each vegetation species (grass, bushes or trees) density and vertical leaf distribution.

By knowing the LAI value and the vegetation characteristics (size and profile), it is possible to calculate the LAD from the following equation, given by Lalic & Mihailovic (2004):

$$LAI = \sum_{i=1}^{n} LAD_i \, \mathrm{dz} \tag{6}$$

Where: n us the number of layers and dz is the layer thickness (m).

Regarding the deciduous character of the tree, de Abreu (2012) reported the percentage of the crown opacity found in her field measurements: 85.3% in the period with all leaves (summer) and 41.3% in the period partially without leaves (winter). As data of the LAI values were available for summer, a calculation[52] was made to reproduce the corresponding LAI value in winter. As the same opacity was defined for both trees, *T. impertiginosa* had its LAI calculated for winter in the same way it was calculated for *T. chrysotricha*. Results are shown in Table 4.17.

Table 4.17: Crown opacity and LAI of T. chrysotricha and T. impertiginosa, summer and winter.

Crown opacity	Both trees	
Summer	85.3%	
Winter	41.3%	
LAI	*T. chrysotricha*	*T. impertiginosa*
Summer	5.0	2.4
Winter	2.9	1.4

Since v.4.0, vegetation can be modelled in ENVI-met with *Albero*, as explained in Section 4.4.1. Figure 4.26 exemplifies *Albero* with the the model made for the *T. chrysotricha*. The averaged LAD for the models was 1.0 for the summer and 0.5 for the winter.

[52] If 85.3% of leafs corresponded to a LAI of 2.9, according to the field measurements made by de Abreu (2012), then 41.3% of leafs corresponds to a LAI of 1.4, approximately.

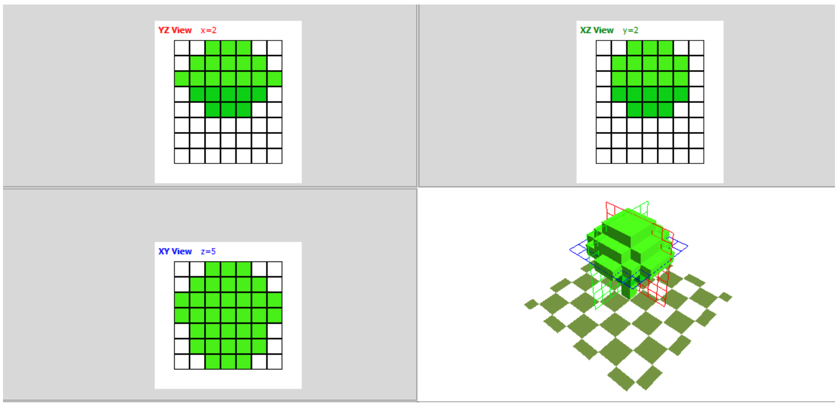


Figure 4.26: T. chrysotricha modelled with the Albero ENVI-met tool

4.5.3 Creation of the green scenarios

In this phase, five new outdoor scenarios were created, adding vegetation to the site. Table 4.18 shows the 12 ENVI-met models simulated: 6 for the summer season and 6 for the winter season.

Table 4.18: ENVI-met models simulated in phase 3, including the Baseline model from phase 2 (Case 0)

Summer season			
Roof type	Site*	Trees	Model name
Original	Original	no trees	Case 0
	Green	LAI = 2.9	Case 1
	Dense green	LAI = 5.0	Case 2
Green	Original	no trees	Case 3
	Green	LAI = 2.9	Case 4
	Dense green	LAI = 5.0	Case 5
Winter season			
Roof type	Site	Trees	Model name
Original	Original	no trees	Case 6
	Green	LAI = 1.4	Case 7
	Dense green	LAI = 2.4	Case 8
Green	Original	no trees	Case 9
	Green	LAI = 1.4	Case 10
	Dense green	LAI = 2.4	Case 11

*Except from the Original site, all sites have grass on the ground.

Figure 4.27 illustrate one of these scenarios: the Dense green site.

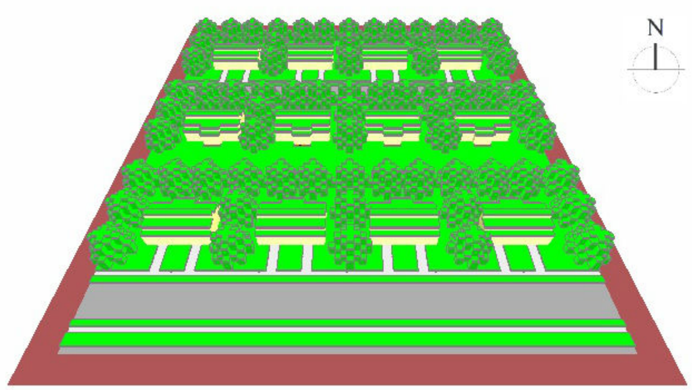


Figure 4.27: Site with the dense green scenario (dense trees, grass on the ground and green roofs): Case5, (summer) and Case 11 (winter)

4.5.4 Simulations of the outdoor climate with the green strategies

This phase aimed to evaluate and compare the effect of substituting the original roofs by green roofs in two distinct scenarios: in the Original site and in the Dense green site. Evaluations were made for the Typical summer and Typical winter days, and took place at pedestrian level (at 1.38m height), and above the roofs (at 4.38m and 5.38m height, representing 0.13m and 1.13m above the vegetation, respectively). Additionally, data was collected at 2.38m height, representing a value approximately in the middle of the twin-house façades[53], to create the climatic data for the inputs in the coupled simulations in Phase 4.

Four receptors were positioned in the model alongside the twin-house, one located at 0.5m distance from each façade (see Section 4.4.3). Averaged data were calculated for T_{air}, T_{mrt}, RH, wind speed and wind direction[54].In the analysis made in the Original site, the models simulated were: Case 0 and Case 3 for the summer; Case 6 and Case 11 for the winter. In the analysis made in the Dense green site, the models

[53] This is the height from where data was extracted from the receptors and further used as inputs in EnergyPlus, for the coupled simulations.

[54] An analysis of the incident solar radiation (direct and diffuse) was also made, but with another objective: to validate its values in the ENVI-met models, in order to be consistent with data from the weather file.

simulated were: Case 0 and Case 5 for the summer; Case 6 and Case 11 for the winter.

4.6 Phase 4: Indoor thermal comfort using coupled simulations

The last phase of the investigation aimed to evaluate the influence of microclimate and green roofs on indoor thermal comfort. That main objective was divided into three groups of assessments:

- Effect of green roofs on indoor thermal comfort in the Dense green site *vs*. in the Baseline site;
- Effect of the Dense green site on the indoor thermal comfort; and
- Influence of coupled simulations on the results.

As in Phase 1, all simulations in Phase 4 were performed with EnergyPlus. Two aspects were different in Phase 4 when compared to Phase 1:

- The input data: in all simulations performed in Phase 4 input weather data came from the outputs generated from the ENVI-met simulations. The exception was when models served as a baseline for results comparing the effect of coupled simulation. In that case, they were simulated with input data directly from the weather file.
- The simulation time: in Phase 1 all simulations were performed for three periods: one-year, Typical summer week and Typical winter week. In phase 4, as in Phases 2 and 3, two days were simulated for each case: the Typical summer day and the Typical winter day. The Typical days were created with data averaged from the Typical weeks.

All cases were constructed with the building envelope as defined in Phase 1: the Brazilian standard envelope. The variations were in the input data (which changed according to the outdoor scenario), and in the roof: from the Original roof to the Green roof. For all green roof models simulated in Phase 4, the Baseline green roof defined in Phase 1 was adopted: a green roof with LAI 1, 250mm of plant height and 150mm of substrate depth. Figure 4.28 presents the flowchart of Phase 4.

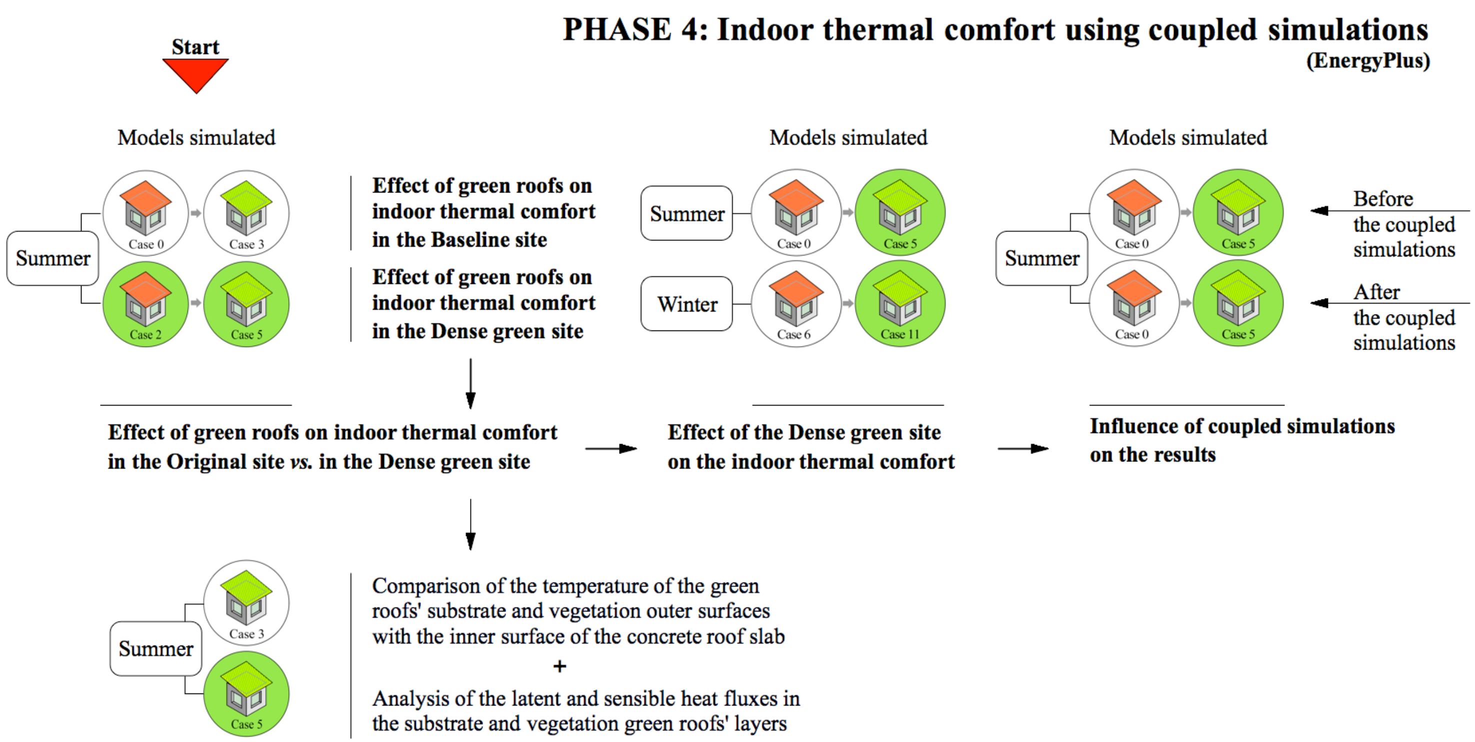


Figure 4.28: flowchart of models simulated in Phase 4 and the respective evaluations made. The cases are described in Table 4.18

The parameters to evaluate indoor thermal comfort in Phase 4 were the same as in Phase 1: the percentage of time (in hours) in comfort and discomfort according to the ASHRAE Standard 55, and the assessment of heating and cooling degree-hours. As in Phase 1, calculations considered the spaces with high occupancy (living rooms and bedrooms), and the variable employed was the T_{op}. All configuration schedules (as occupancy, lighting equipment and window openings) were the same as for the models in Phase 1.

To carry out the coupled simulations, the variables extracted from receptors 1 to 4 of the outdoor simulation (performed with ENVI-met) were averaged. For the creation of the Typical summer day and the Typical winter day in EnergyPlus, the variables collected from the ENVI-met receptors were (for the 24-hour cycle): maximum T_{air}, daily T_{air} amplitude, wind speed and wind direction. Additionally, the RH at the maximum T_{air} was also extracted, in order to calculate the dew-point at the maximum T_{air}.

In EnergyPlus, the trees were modelled as shading surfaces detached from the twin-houses (called "detached shading surfaces"), located in the same places where the trees were in ENVI-met.[55] The transparency to direct solar radiation was configured for the Typical summer day (15%) and the Typical winter day (59%). Figure 4.29 illustrates the representation of trees with detached shading surfaces in EnergyPlus.

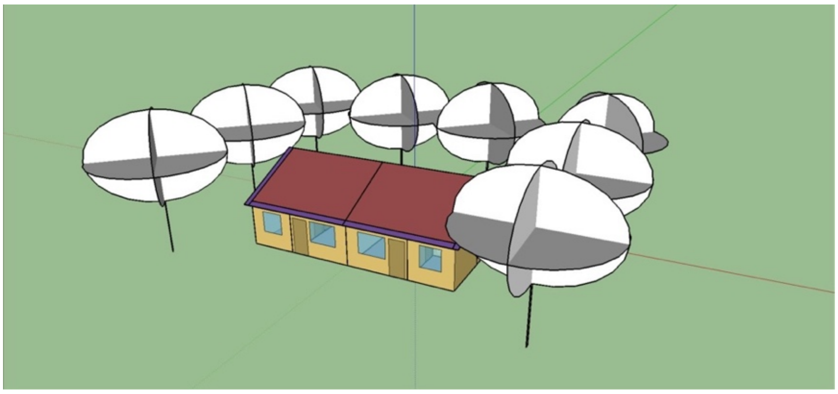


Figure 4.29: Modelling of T. impertiginosa in EnergyPlus with detached shading surfaces

[55] The axes of trees were located at 4m distance from the houses in the East and North façades and at 3m distance, in the West façade.

4.6.1 Effect of green roofs on indoor thermal comfort in the Dense green site *vs*. in the Baseline site

This analysis aimed to understand how a significant change in the local microclimate affects the contribution of a green roof on the indoor thermal comfort. The evaluations were made for the Original site and the Dense green site. Four cases were compared: Cases 0 and 3, representing the Original roof and the Green roof, in the Original site; and Cases 2 and 5 representing the same roofs, but in the Dense green site. As the interest was on the cooling effect[56], only the summer season was selected for this analysis.

In order to increase the understanding of the results, for the green roof models in the two scenarios (Case 3 and Case 5), the temperature of the outer surfaces of the soil and vegetation were compared to the inner surface temperature of their respective concrete roof slabs. To study this in more detail, the sensible and latent heat fluxes of the green roofs in Case 3 and Case 5 were observed.

4.6.2 Effect of the Dense green site on the indoor thermal comfort

This evaluation aimed to estimate the effect of the Dense green site as a whole, including green roofs (see Section 4.5.3, Table 4.18), on the indoor thermal comfort. The analysis was made for both the summer and the winter seasons. The two extreme cases were compared:

- The Original roof in the Original site (Case 0 in summer and 6 in winter); and
- The Green roof in the Dense green site (Case 5 in summer, and Case 11 in winter).

4.6.3 Influence of coupled simulations on the results

This stage aimed to quantify the impact of performing a coupled outdoor-indoor simulation on indoor thermal comfort. As the differences in results of indoor thermal comfort with and without the coupled simulations were, in general, higher in the summer than in the

[56] Phase 4 was conceived after the analysis of results from Phase 3, which showed that the biggest effect of the green scenarios on the local microclimate was in the summer season.

winter, the Typical summer day was chosen for this evaluation. The same two extreme cases compared in Section 4.6.1 (Case 0 and Case 5) were also adopted for this analysis. The assessment focused on the difference in results between two different methods of indoor simulations with green roofs:

1. Without considering the site, representing the most common type of simulations with green roofs found in the literature. In this method, that is the same as used in the simulations performed in Phase 1, the input meteorological data came from the weather file. In this step, simulations were performed only in EnergyPlus;
2. Performing a coupled outdoor-indoor simulation: the input meteorological data from the weather file was substituted by output data from the outdoor simulations (performed with ENVI-met).

In the end, a comparison of results from the two methods was made, allowing to quantify differences between Case 0 and Case 5 before and after the coupled simulations were performed. The intent of these evaluations was to know how a coupled simulation impacts the results of indoor thermal comfort depending on the scenario: with and without vegetation.

5 Impact of green roofs on indoor thermal comfort

This chapter presents results and discussions about the first phase of the simulations, using EnergyPlus to evaluate the indoor thermal comfort. From this set of analyses, the configuration of the building envelope, the Baseline roof and the Baseline green roof were defined for the further phases.

Before showing the results of the green roof simulations, firstly, a brief analysis is made about the increase in accuracy for the ground temperature. That was achieved through the calculation with the tool “Slab”, in EnergyPlus. Secondly, a discussion is made about the importance of the building’s envelope to comply with the Brazilian Standards NBR 15575 (ABNT, 2013) and NBR 15220 (ABNT, 2005).

It is important to highlight that the green roofs are compared to the Baseline roof as a system[57]. The comparison between components is made only between the green roof models, where one variable is changed at the time.

The analysis of green roofs starts with a parametric study of the density of the vegetation layer, followed by the thickness of the substrate layer. At last, an analysis is made about the influence of the building envelope insulation on the impact of green roofs on the indoor thermal comfort.

5.1 Preliminary evaluations of the indoor thermal comfort

5.1.1 Effect of the ground temperature

In a preliminary phase of the investigation, simulations were performed to analyse the influence of the ground temperature on the indoor thermal

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[57] This investigation is not a parametric study between building materials or components but between roofing systems. The concrete roof slab and the drainage layer are parts of the green roof systems.

comfort. As the first step of the model's configuration, the ground temperature was corrected by using the tool "Slab", as suggested by the Brazilian Standard RTQ-R (INMETRO, 2012). As previously explained in Chapter 4, this caution was taken in all models simulated, resulting in a "Before Slab" and "After Slab" file, for each model. In order to assess the differences in thermal comfort due to that change, the first model was taken as an example: the twin-houses with the *Original roof and the Original envelope*. Figure 5.1 shows the results of thermal comfort within a one-year period in the model with ground temperatures from the weather file, and in the model with the tool *Slab* performed.

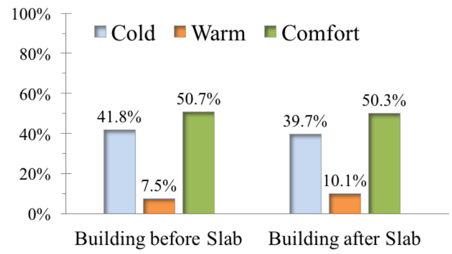
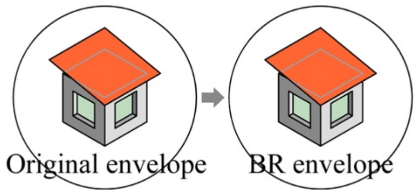


Figure 5.1: Percentage of hours below, within and above the comfort zone according to ASHRAE 55 Adaptive Thermal Comfort model, for the Original roof and envelope with the ground temperature before and after using the Slab tool, one-year period

Results showed a negligible change in the percentage of time in comfort, while the discomfort by cold was reduced and the discomfort by warmth was increased. Results comply with INMETRO (2012), Oliveira et al. (2012) and Silva et al. (2015) who studied the influence the ground temperature has on the indoor thermal comfort and about the importance of using the *Slab* tool to perform a correct estimation of the ground temperature below the building.

5.1.2 Compliance of the building envelope with Brazilian Standards



As explained in Section 1.1, since the creation of the Brazilian Standard NBR 15575 (ABNT, 2013) several requirements regarding building performance must be met. To establish a Baseline twin-house to be compared with all further models, the twin-houses with the Original envelope and the Original roof (reddish ceramic tiles) were adapted to comply with thermal requirements of the Brazilian Standards, as detailed in Section 4.3.2. Figure 5.2 shows the results of thermal comfort within a one-year period, for the Original envelope and the Brazilian standard envelope.

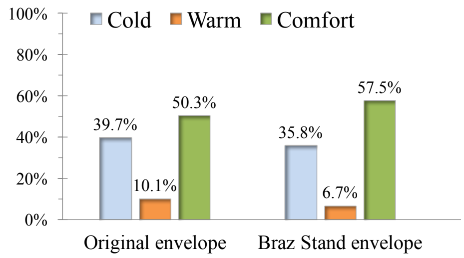


Figure 5.2: Percentage of hours below, within and above the comfort zone according to ASHRAE Standard 55, for the Original roof with the Original e and with the Brazilian standard envelopes, one-year period

As expected, the increase in the envelope insulation increased the time of thermal comfort indoors. With the changes made, the percentage of time in comfort increased by 7.2%. The decrease in the rate of hours in discomfort was registered for both cold and warmth. Table 5.1 expresses the cooling and heating degree-hours over one year of the Original roof with the Original envelope, and with the Brazilian standard envelope. The degree-hours were calculated according to the ASHRAE Standard 55 comfort limits, as explained in Section 4.3.2.

Table 5.1: Heating and cooling degree-hours for the Original roof with the Original envelope and with the Brazilian standard envelope, one-year period

Data / Building envelope	Original	Brazilian Standard
Heating degree-hours	9069.0	6207.3
Difference (degree-hours)		-2861.7
Reduction (%)		31.6
Cooling degree-hours	2023.4	823.8
Difference (degree-hours)		-1199.6
Reduction (%)		59.3

The main decrease was observed in the cooling needs. Figures 5.3 and 5.4 illustrate the operative temperature (T_{op}) of the Original and the Brazilian standard envelopes compared to the outdoor T_{air}, during the Typical summer and the Typical winter weeks, respectively. During the Typical summer week, both envelopes resulted in an indoor T_{op} that was, in general, warmer than the outdoor T_{air}.

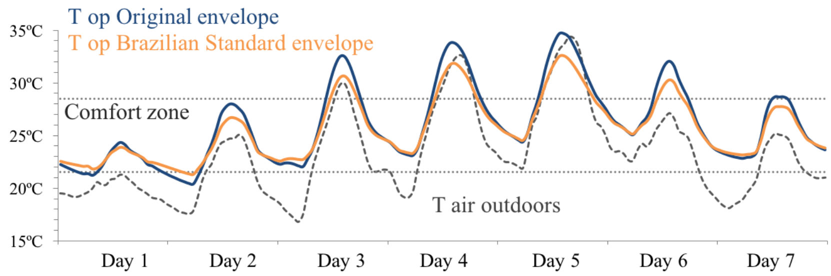


Figure 5.3: Indoor T_{op} for the Original roof, Original envelope and Brazilian standard envelope, compared to outdoor T_{air} in the Typical summer week

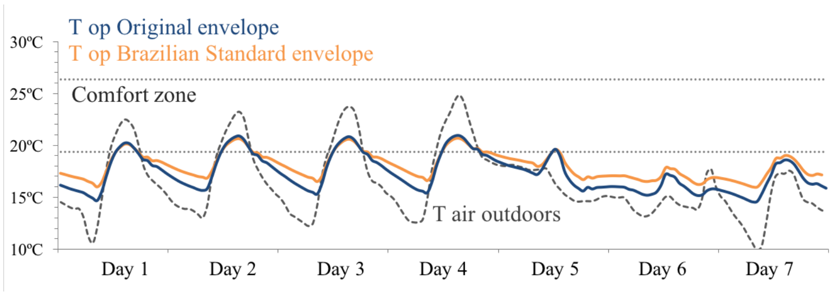


Figure 5.4: Indoor T_{op} for the Original roof, Original envelope and Brazilian standard envelope, compared to outdoor T_{air} in the Typical winter week

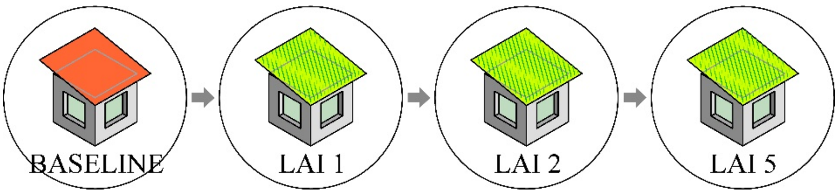
During the Typical winter week, it was observed a small increase in T_{air} with the Brazilian standard envelope. Still, discomfort by cold occurs mostly of the time. As expected, with the increase in the building insulation, the Brazilian standard envelope has decreased the thermal amplitude indoors for both Typical summer and Typical winter weeks.

5.1.3 Concluding remarks

Unlike Oliveira et at. (2012), who argued that the main differences between data of soil temperature were observed during winter, in this work significant differences were found both in winter and summer. It is worth mentioning that, while in this research simulations were performed for one entire year, Oliveira et al. (2012) conducted their simulations for typical days in winter and summer. Therefore, for an accurate estimation of the soil temperature, simulations within a one-year period are recommended, even when smaller periods will be further analysed.

A comparison between results in thermal comfort before and after the envelope compliance with the Brazilian Standards show how important their requirements are for an increase in thermal comfort for buildings in general, but especially for social housing. However, in order to achieve a substantial reduction in the hours of discomfort by cold, only the change made in the building envelope is not sufficient.

5.2 Impact of Leaf Area Index (LAI)



This section presents results and discussion about the Leaf Area Index (LAI). Initially, three LAI values were tested: 1[58], 2 and 5. From LAI 1 to 2 a wide range of grass and plants used in extensive green roofs are covered. Then, an increase in LAI to 5 was made to test the upper limit for extensive green roofs, as found in the literature (Sailor et al., 2012; Berardi et al., 2014). All tested green roofs had a substrate of 150mm, as it is considered by commercial green roof companies and by some authors as the upper limit of substrate depth for green roofs of the extensive type (see Section 3.13).

5.2.1 Effect of LAI over the whole year

The annual assessment showed a better response of all green roofs to the climate, in comparison with the Baseline roof. The green roof with LAI = 1 had the best performance in the climate of Porto Alegre. Figure 5.5 shows the percentage of time in comfort, in discomfort by cold or by warmth, indoors, during a one-year period.

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[58] According to Kolokotsa et al. (2013), the LAI 1 is the most common in extensive green roofs.

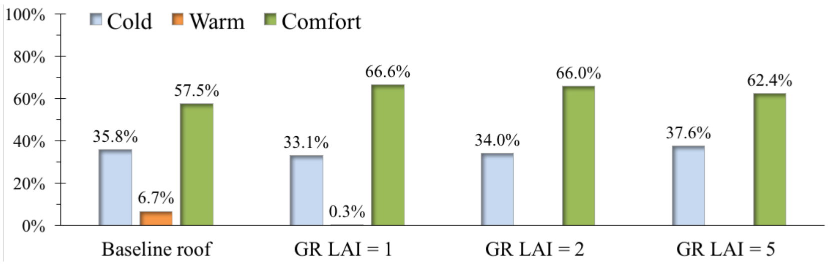


Figure 5.5: Percentage of hours below, above and within the comfort zone according to ASHRAE Standard 55, for green roofs with LAI =1, LAI =2, LAI = 5 and the Baseline (Original) roof, one-year period

The thermal comfort decreased with increasing LAI. The substitution of the Baseline roof by the green roof with the best performance (LAI 1) raised the time in comfort by 9.1%. The reduction was more in warmth (6.4%) than in cold (2.7%).

The use of green roofs resulted in a reduction of both heating and cooling needs. Table 5.2 expresses the calculated heating and cooling degree-hours for all models simulated in this section. The most significant decrease was achieved in cooling needs: from 98.8% to 100% reduction in degree-hours, confirming the efficiency of the extensive green roofs' cooling effect.

Table 5.2: Heating and cooling degree-hours (DH) for the Baseline roof and the Green roofs with LAI = 1, LAI = 2 and LAI = 5, one-year period

Data	Baseline roof	Green roofs		
		LAI 1	LAI 2	LAI 5
Heating degree-hours	6207.3	3767.3	3841.3	4709.6
Difference (degree-hours)		-2440.0	-2366.0	-1497.7
Reduction (%)		39.3	38.1	24.1
Cooling degree-hours	823.8	9.5	0.0	0.0
Difference (degree-hours)		-814.3	-823.8	-823.8
Reduction (%)		98.8	100.0	100.0

Although also contributing to reducing the discomfort by cold, the main discomfort reduced with the green roofs over the whole year was by warmth. This result agrees with Gargari et al. (2016).

5.2.2 Effect of LAI in the Typical summer week

Figure 5.6 illustrates the indoor T_{op} of the green roofs with different LAI and the Baseline roof, compared to the outdoor T_{air}, during the Typical summer week. The range of comfort was from 21.5ºC to 28.5ºC. Contrary to what happened in the one-year assessment, the green roof with the best performance during the Typical summer week was the one with LAI 5.

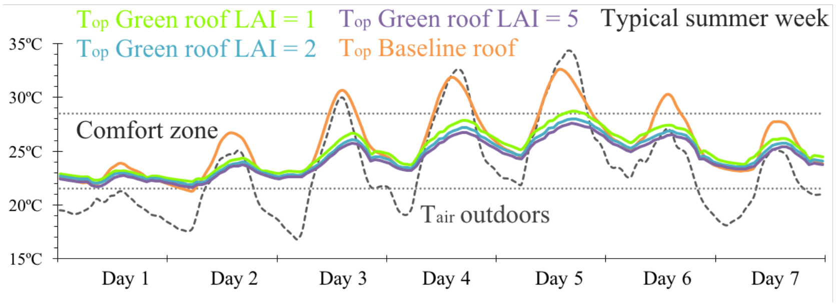


Figure 5.6: Indoor T_{op} for LAI = 1, LAI = 2, LAI = 5 and Baseline roof, compared to outdoor T_{air} in the Typical summer week

A considerable reduction in thermal amplitude in the Typical summer week was observed for all green roofs. That reduction was beneficial for the indoor thermal comfort: while reducing the warmest temperatures indoors, it took the houses within the comfort zone in the majority of hours. The increase in LAI resulted in a proportional decrease in the daily maximum T_{op} and T_{air} amplitude. While the outdoor T_{air} had up to 13.5 ºC of diurnal amplitude and the Baseline roof had until 8.6ºC (from 31.9ºC to 23.3ºC), the maximum thermal amplitude observed in the green roof models was in LAI 1, of º 4.1ºC. In the green roofs with LAI 2 and LAI 5, the maximum daily thermal amplitude of were 3.7ºC and 3.5ºC, respectively.

The Baseline roof followed the warmest outdoor T_{air} peak values and sometimes even exceeded them, as observed in Figure 5.6. The green roofs, on the other hand, presented an exceptional performance during the Typical summer week: they all increased the percentage of time in comfort, compared to the Baseline roof. The Baseline roof achieved 78.6% of hours in comfort, whereas the green roof with LAI 1 achieved 97.6% (a difference of 19%, compared to the Baseline), and LAI 2 and LAI 5 reached 100% (a difference of 21.4%).

The decrease in the daily maximum T_{op} with increasing LAI can be explained by the fact that the increase in LAI rises the shading from plants to the substrate's external surface, therefore decreasing heat gains by solar radiation (Emilsson, 2008; Jaffal et al., 2012; Sailor et al., 2012). In addition to that, the higher LAI indicates a higher vegetal density, so higher transpiration of plants. Together, these two factors (decrease of absorbed short-wave radiation and increase in latent heat losses) lead to a higher cooling effect, as explained by Sailor et al. (2012) and by Jaffal et al. (2012).

5.2.3 Effect of LAI in the Typical winter week

In general, the extensive green roof was proven insufficient to increase indoor thermal comfort in the Typical winter week in Porto Alegre. Figure 5.7 illustrates the percentage of time in comfort and discomfort by cold with the Baseline roof and with the three green roofs, in the Typical winter week. In the Typical winter week, the green roofs had a majority of hours below the comfort limit established by the ASHRAE Standard 55. The green roof can be part of a strategy for increasing the indoor thermal comfort in the cold season in Porto Alegre, but cannot be the only strategy. For the Typical winter week, the range of comfort was from 19.4ºC to 26.4ºC.

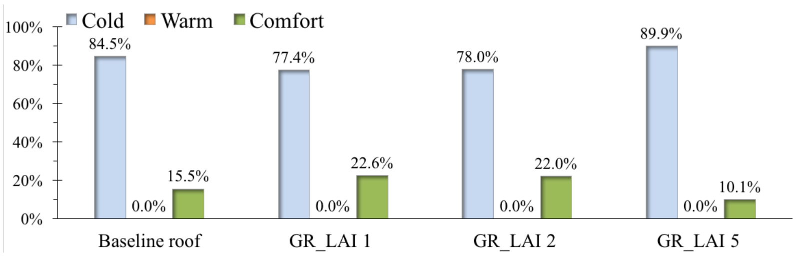


Figure 5.7: Percentage of hours below and within the comfort zone according to ASHRAE Standard 55, for LAI =1, LAI =2, LAI = 5 and Baseline roof, Typical winter week

Although by a small difference, the model with LAI 1 registered the best performance: it decreased the percentage of discomfort by 7.1% compared to the Baseline roof. Figure 5.8 illustrates the indoor T_{op} of the green roofs with different LAI and the Baseline roof, compared to the outdoor T_{air}, during the Typical winter week.

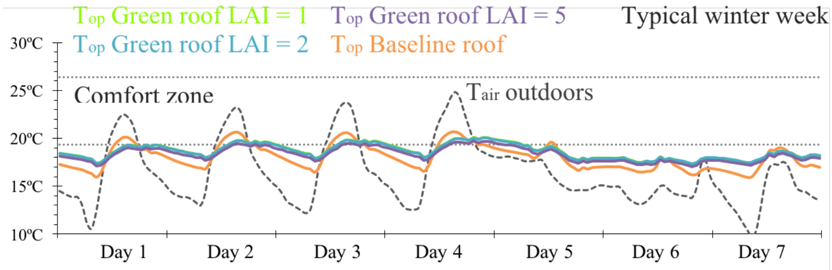


Figure 5.8: Indoor T_{op} for LAI = 1, LAI = 2, LAI = 5 and Baseline roof, compared to outdoor T_{air} in the Typical winter week

The minimum T_{air} increased with all green roofs, compared to the Baseline roof. Also, the green roof models registered a T_{op} closer to the comfort zone than the Baseline roof. As the thermal behaviour of the three green roofs was so similar during the Typical winter week, a calculation of the heating degree-hours (as shown in Table 5.3) allowed a better quantification of the differences between them. In the Typical winter week, there was a significant reduction in heating degree-hours with the green roof, compared to the Baseline roof. The roof with LAI 1 had the most significant decrease (47.1%).

Table 5.3: Heating degree-hours (DH) for the Baseline roof and the Green roofs with LAI = 1, LAI = 2 and LAI = 5, Typical winter week

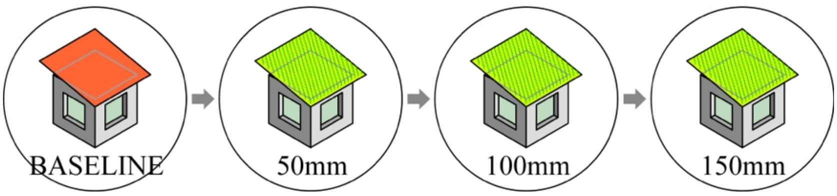
	Baseline roof	Green roofs		
		LAI 1	LAI 2	LAI 5
Heating degree-hours	249.1	131.7	135.6	176.2
Difference (degree-hours)		-117.4	-113.5	-72.9
Reduction (%)		47.1	45.6	29.3

The reason why the green roof with LAI 1 is better for the Typical winter week is that it allows a higher penetration through the leaves, reaching the soil layer and warming it up. This solar heat gain will then be transferred through the soil layer to the roof structure by conduction, and, from there it will be released to the indoors by longwave radiation, contributing to the increase in the T_{air} (and T_{op}).

5.2.4 Concluding remarks

Results found in this section are consistent with previous findings of the influence of LAI to the thermal comfort by both simulation studies (e.g. Sailor et al., 2012; Berardi et al., 2014; Ferreira 2014), and by field measurements (e.g. Emilsson 2008). According to Sailor (2008) and Jaffal et al. (2012), increasing the LAI reduces the indoor T_{air} and the cooling demand in summer, but it also raises the heating demand in winter. It is worth underlining that this is a rule for climates with defined warm and cold seasons, like in Porto Alegre. As for the twin-houses the majority of discomfort was by cold, the model with the most suitable green roof configuration was the one with the LAI 1. Therefore, this value was adopted for all green roof compositions in the following research phases.

5.3 Impact of substrate depth



This section presents results of simulations performed with three substrate depths: 50mm, 100mm and 50mm.[59]

5.3.1 Effect of the substrate depth over the whole year

Figure 5.9 shows that the differences in the percentage of time in comfort, according to ASHRAE Standard 55, were practically inexistent between the different substrate depths. Similar to the LAI assessment, the substitution of the Baseline roof system for the green roof systems presented a general increase in thermal comfort, during the one-year evaluation, for all substrate thickness.

[59] Although it can be found that the value of 30mm is the lowest soil depth value for extensive green roofs, the most common values found for extensive green roofs substrates supplied by commercial green roof companies in Brazil are in the range of 50mm to 150mm.

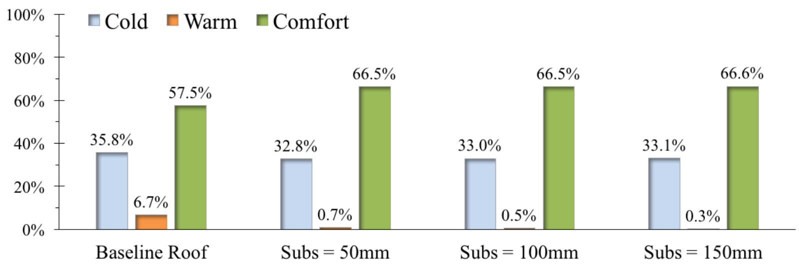


Figure 5.9: Percentage of hours below, within and above the comfort zone according to ASHRAE Standard 55, for 50mm, 100mm and 150mm of substrate depth, one-year period

Although small in magnitude, there was a clear tendency of decreasing both heating and cooling degree-hours with increasing soil depth, as shown in Table 5.4. As expected, due to the higher thermal mass and better thermal insulation, the green roof model with the 150mm depth had the most significant decrease both in heating and cooling needs.

Table 5.4: Heating and cooling degree-hours for 50mm, 100mm and 150mm of substrate depth, and Baseline roof, one-year period

Data	Baseline roof	Substrate depth		
		50mm	100mm	150mm
Heating degree-hours	**6207.3**	3943.8	3831.3	3767.3
Difference (degree-hours)		-2263.5	-2376.0	-2440.0
Reduction (%)		**36.5**	**38.3**	**39.3**
Cooling degree-hours	**823.8**	27.8	16.0	9.5
Difference (degree-hours)		-795.96	-807.76	-814.26
Reduction (%)		**96.6**	**98.1**	**98.8**

Results are consistent with the ones found by Ferreira (2014), who also found that, due to the addition of insulation and thermal mass to the roof, increasing the soil depth results in lower cooling and heating needs.

5.3.2 Effect of soil depth in the Typical summer week

Figure 5.10 illustrates the indoor T_{op} of the green roofs with different substrate depths and the Baseline roof, compared to the outdoor T_{air}, during the Typical summer week.

The three soil depths improved the indoor thermal comfort to a great extent, when compared to the Baseline roof. As in the one-year analysis, in the Typical summer week, the differences between the soil depths were almost inexistent. Table 5.5 shows the reduction in degree-hours with the different substrate depths, for the Typical summer week.

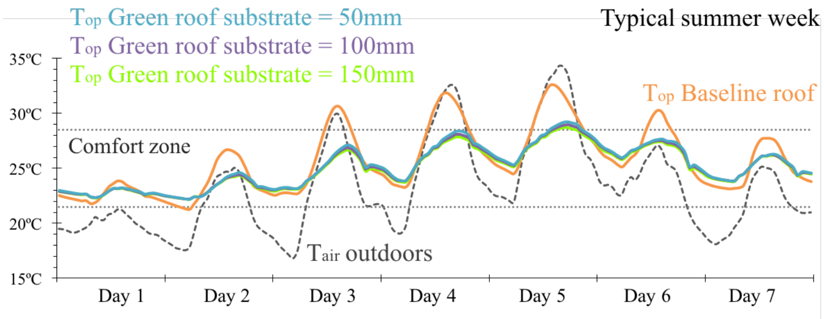


Figure 5.10: Indoor T_{op} for 50mm, 100mm and 150mm of substrate depth and Baseline roof, compared to outdoor T_{air} in the Typical summer week

Table 5.5: Cooling degree-hours for 50mm, 100mm and 150mm of substrate depth, and Baseline roof, Typical summer week

Data	Baseline roof	Substrate depth		
		50mm	100mm	150mm
Cooling degree-hours	62.7	3.6	1.8	0.7
Difference (degree-hours)		-59.1	-60.1	-62.0
Reduction (%)		94.3	97.1	98.9

5.3.3 Effect of the soil depth in the Typical winter week

Figure 5.11 shows the indoor T_{op} of the green roofs with different substrate depths and the Baseline roof, compared to the outdoor T_{air}, during the Typical winter week. As in the Typical summer week, in the Typical winter week the differences between the three green roofs are minimal. Table 5.6 quantifies the heating degree-hours for the Typical winter week.

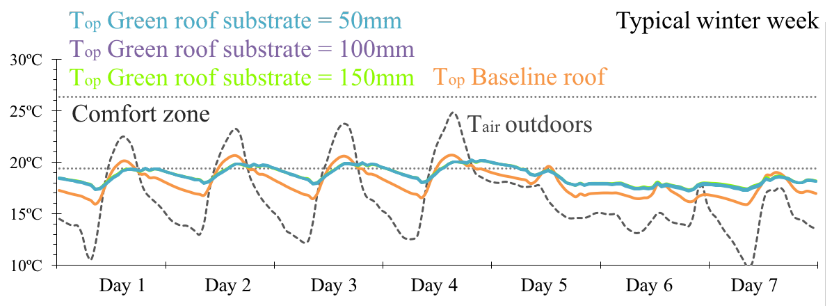


Figure 5.11: Indoor T_{op} for 50mm, 100mm and 150mm of substrate depth and Baseline roof, compared to outdoor T_{air} in the Typical winter week

Table 5.6: Heating degree-hours for 50mm, 100mm and 150mm of substrate depth, and Baseline roof, Typical winter week

Data	Baseline roof	Substrate depth		
		50mm	100mm	150mm
Heating degree-hours	249.1	141.8	135.1	131.7
Difference (degree-hours)		-107.3	-114.0	-117.4
Reduction (%)		43.1	45.8	47.1

5.3.4 Concluding remarks

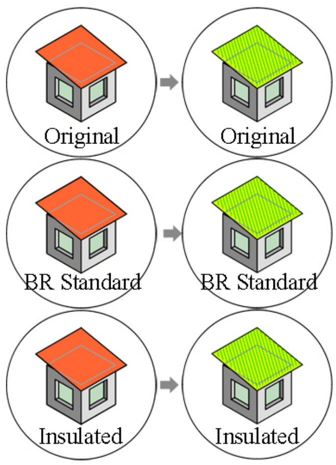
The findings from this section showed that the thicker the substrate, the better. Results agree with Silva (2016), who claim that while a higher LAI is a key factor to maximise energy savings in the cooling season, the highest soil depth is the solution to reduce energy use also in the heating season. However, in practice, it is not possible to have too thick roofs (as in intensive green roofs) without significant implications in weight. Therefore, compositions that increase the level of insulation in other ways as in other layers of the green roof system, or in compositions of a substrate that increase the insulation level, might represent an alternative that is suitable to low-weight extensive green roofs. That would represent a viable option for projects as the one studied by this investigation, as well as for retrofit projects.

Different from the LAI cases, where the lowest value (LAI 1) was the best option for the winter, and the highest value (LAI 5) was the best value for the summer, the same soil depth was better for both seasons: 150mm. The most significant effect was the decrease of heating needs. During the one-year assessment, the 150mm substrate resulted in 2440.0 less heating degree-hours and 814.26 less cooling degree-hours. That result agrees with findings from other studies showing that increasing the soil depth of green roofs result in a reduction of both heating and cooling needs (Sailor et al., 2012; Ferreira, 2014; Dias, 2016).

While the LAI influences the solar heat gain to the roof, the soil depth is related to the insulation and thermal mass, affecting both heat gains and heat losses through the green roof, as explained by Sailor et al. (2012). The added mass serves to even out the diurnal fluctuation of heat flux through the roof, by smoothing out the night and daytime peak temperatures of the surface adjacent to the conditioned space (Sailor et al., 2012).

At the end of this analysis, the Baseline green roof was defined for the next simulations phases. The Baseline green roof combined the variables with the best performance within the gardening layers, thus, having plants with LAI 1 and 150mm of substrate depth. The Baseline green roof kept the same slope as the Original roof (40% sloped) and, except for the roof, the same building envelope (the Brazilian Standard envelope).

5.4 Evaluation of the effect of the building envelope insulation



This section evaluates the impact of the green roof on indoor thermal comfort using different building envelopes. Three envelopes were simulated, gradually increasing the level of insulation (the envelopes' compositions are detailed in Section 4.3.4):

- the Original building envelope (U value of 4.40 W/m^{2}K and 2.13 W/m^{2}K for external walls and roof, respectively);
- the Brazilian standard envelope (U value of 2.45 W/m^{2}K and 1.18 W/m^{2}K for external walls and roof, respectively); and
- the Insulated envelope (U value of 1.25 W/m^{2}K and 0.82 W/m^{2}K for external walls and roof, respectively).

5.4.1 Effect of the building envelope insulation over the whole year

For each building envelope, a comparison was made between the green roof model and the corresponding reference roof (Original roof). Thus, it was possible to evaluate absolute and relative improvements. Figures 5.12, 5.13 and 5.14 demonstrate the performance of the two roofs, for the three building envelopes: Original envelope, Brazilian standard envelope and Insulated envelope. The evaluation was made according to the ASHRAE Standard 55, for a one-year period (8760 hours).

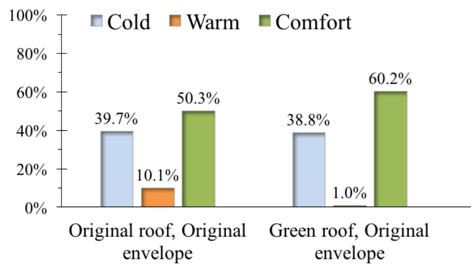


Figure 5.12: Percentage of hours below, within and above the comfort zone according to ASHRAE Standard 55, Original roof and green roof, Original envelope, one-year period

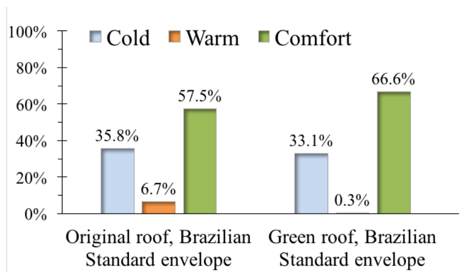


Figure 5.13: Percentage of hours below, within and above the comfort zone according to ASHRAE Standard 55, Original roof and green roof, Brazilian standard envelope, one-year period

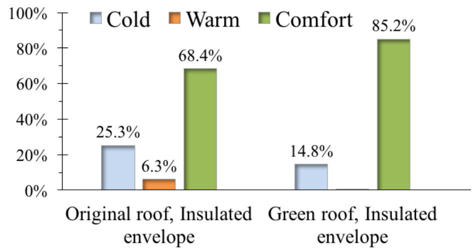


Figure 5.14: Percentage of hours below, within and above the comfort zone according to ASHRAE Standard 55, Original roof and Green roof, Insulated envelope, one-year period

As expected, the thermal comfort increased proportionally with the increase in the envelope´s insulation. Table 5.7 summarises the differences in heating and cooling needs in degree-hours (DH). Each green roof model (GR) is compared to its reference roof model (OR), according to the envelope type.

Table 5.7: Heating and cooling degree-hours (DH) for the Original, the Brazilian Standard and the Insulated roofs, Original, Baseline and Green roofs, all year

Envelope	Original		Braz. Standard		Insulated	
Roof	OR	GR	OR	GR	OR	GR
Heating DH	9069.0	6731.7	6207.3	3767.3	3090.4	925.0
Reduction (DH)		2337.3		**2440.0**		2165.4
Reduction (%)		25.8		39.3		**70.1**
Cooling DH	2023.4	45.1	823.8	9.5	777.8	0.4
Reduction (DH)		**1978.2**		814.2		777.5
Reduction (%)		97.8		98.8		**100.0**

Analysis of the heating needs

Between the three building envelopes, the Insulated was, as expected, the one with the lowest heating needs. In absolute values, the Brazilian standard envelope had the most significant reduction in heating needs with the green roof, followed by the Original roof. Results are consistent with other studies where authors argue that the roofs (and envelopes) with lower insulation are the ones benefiting the most with their substitution by green roofs. In relative values, the Insulated envelope had the most significant reduction in heating needs.

Results indicate that, regarding the level of insulation, there is a limit to the contribution given by green roofs for reducing the heating needs. If the building envelope is too poorly insulated, the green roof contributes to the thermal comfort indoors, but to a lower extent. In that case, the heat losses through the rest of the building envelope reduces the time of thermal comfort indoors, and the contribution of the green roof is small.

Analysis of the cooling needs

The assessment of the relative improvement showed a high similarity between all envelopes: the green roof has almost eliminated the cooling needs. Similar to the heating needs, the Insulated envelope presented the lowest cooling needs in the one-year assessment. A pattern was observed, analysing the absolute values reduced: the lower the envelope insulation, the higher the reduction in cooling needs.

The roof is the part of the building that is most exposed to solar radiation. In single-store buildings, the area of the roof represents a significant portion of the building envelope. Porto Alegre has a high intensity of solar radiation and a high solar elevation in summer. The contribution of the roof to the thermal fluxes through the building envelope is significant, similar or even higher than the one provided by the external walls and windows. Concerning the cooling needs, the shading effect, the evapotranspiration and the extra insulation provided by the green roof were more relevant to buildings with the lower insulation level.

5.4.2 Effect of the building envelope insulation in the Typical summer week

Figure 5.15 illustrates the T_{op} of the Green roof and the Original roof for the Original, the Brazilian Standard and the Insulated envelopes, compared to the outdoor T_{air}, for the Typical summer week.

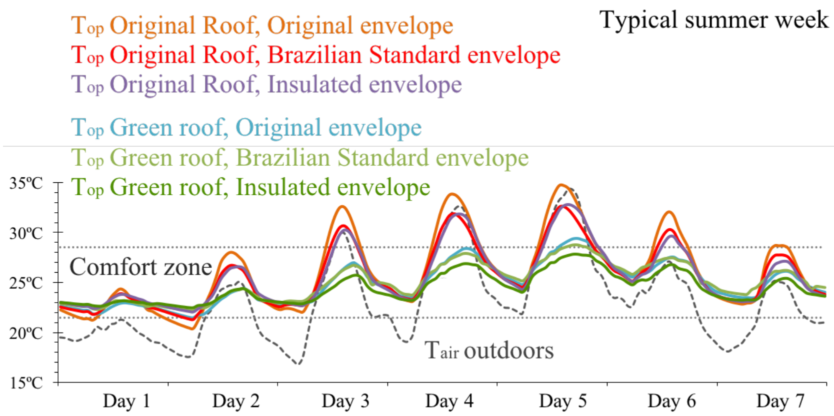


Figure 5.15: Indoor T_{op} for the Green roof and the Original roof, with the Original, the Brazilian Standard and the Insulated envelopes, and compared to the outdoor $T_{air,}$ in the Typical summer week

The increase of the percentage of hours in comfort according to the ASHRAE Standard 55 was proportional to the increase in the envelope insulation, both for the Original and the Green roof models. The model with the best cooling effect was the Green roof in the Insulated envelope: it had 100% of hours within the ASHRAE Standard 55 comfort zone, and the lowest thermal amplitude. As expected, the Original roof with the Original envelope, being the one with the poorest insulation among all models, presented the worst performance: 67.9% of the hours within the comfort zone limits, and the largest thermal amplitude; it was the model with the larger discomfort by warmth (25% of the hours). Except for the Original roof with the Original envelope, all combinations of roofs with envelopes eliminated the existent discomfort by cold outdoors (at night and first hours in the morning).

All green roofs presented a reduction in T_{op}, compared to their respective baseline (Original) roofs. Also, the green roofs decreased the thermal amplitude. The biggest increase in the indoor thermal comfort due to the substitution of the original by a green roof was in the Original building envelope: 26.8% increase of hours in comfort, compared to 19% for the Brazilian Standard and 17.9% for the Insulated envelope.

Except for the Green roof in the Original envelope, that had 1.8% of hours below the comfort limits, all green roofs kept the indoor temperature in the ASHRAE Standard 55 comfort zone. The Green roof in the Original roof was the only green roof model presenting discomfort by cold, and it was negligible (0.6% of hours). Among the green roofs, the discomfort by warmth was 0% in the Insulated envelope, against 2.4% in the Brazilian Standard and 4.8% in the Original envelope.

5.4.3 Effect of the building envelope insulation in the Typical winter week

The differences were very small in the results for the Typical winter week, which made it difficult to visualize it in only one graph. Thus, the two extreme cases were selected to demonstrate the performance of the green roofs, illustrated in two graphs: one with the lowest insulation (Figure 5.16) and one with the highest insulation (Figure 5.17).

Figure 5.16 shows the T_{op} for the Original roof and the Green roof with the Original envelope, compared to the outdoor T_{air}, for the Typical winter week. Neither the Original roof nor the Green roof were enough to put the indoor temperature within the ASHRAE Standard 55 comfort zone. For both roofs, the discomfort was exclusively by cold. With the Original envelope, the Green roof had in 9.5% of hours within the comfort limits of ASHRAE Standard 55, against 14.5% with the Original roof.

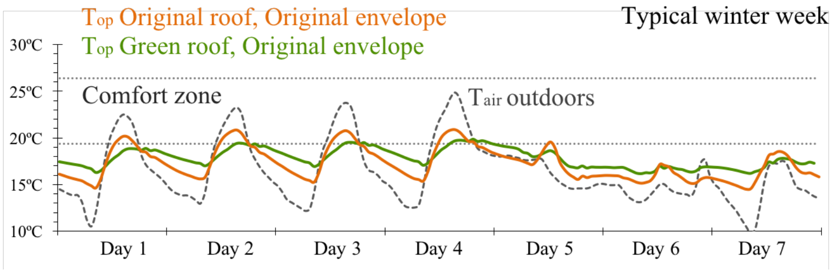


Figure 5.16: Indoor T_{op} for the Green roof and the Original roof, with the Original envelope, compared to outdoor T_{air} in the Typical winter week

Figure 5.17 illustrates the T_{op} for the Original roof and the Green roof with the Insulated envelope, compared to the outdoor T_{air}, for the Typical winter week. Both roofs performed considerably better in the Insulated envelope: the Green roof had a considerable increase in the hours within the comfort limits of ASHRAE Standard 55: 84.5%, against 47.6% for the Original roof.

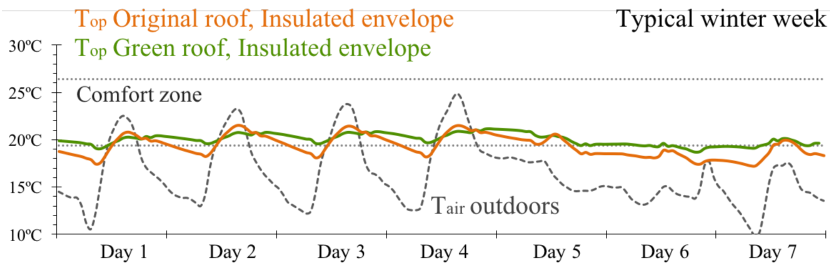


Figure 5.17: Indoor T_{op} for the Green roof and the Original roof, with the Insulated envelope, compared to outdoor T_{air} in the Typical winter week

5.4.4 Concluding remarks

As described in Chapter 3, several authors state that non-insulated buildings benefit most from the green roof. These authors suggest green roofs to renovations of old buildings, constructed before the higher insulation levels required by recent building regulations[60] (Gagliano et al., 2014; Rakotondramiarana et al., 2015; Dimitrijević et al., 2016; Gargari et al., 2016; Silva et al., 2016). Their studies, though, were made for the European context, where the level of the buildings' insulation is higher than for the ones usually built in Brazil, including the one tested by this research.

In the extreme seasons, a comparison of the differences between the green roofs in the two extremes envelopes (Original envelope *versus* Insulated envelope) shows a similar increase in the percentage of hours in comfort. In the Typical summer week, the Green roof in the Original envelope kept 95.2% of hours within the comfort limits, against 100% for the Insulated envelope. In the Typical winter week, the Green roof in the Original envelope had 9.5% of hours within the comfort limits, against 14.5% in the Insulated envelope. These results indicate that the green roofs had a better thermal performance with the more insulated envelope, both for reducing the discomfort by warmth in the summer, and by cold in the winter.

One difference should be pointed out: the *relative improvement* changed according to the building envelope, in the summer and winter seasons. In the Typical summer week, the substitution of the Original

[60] The level of building insulation in Europe became higher after the implementation of the 2010 Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive.

roof by the Green roof in the Original envelope led to an increase in hours in comfort by 26.7%. That was more than the same substitution, made with the Insulated envelope (17.8%). In the Typical winter week, the substitution of the Original roof by the Green roof in the Original envelope *decreased* the hours within the comfort limits by 5.4%. In the Insulated envelope, the same substitution increased those hours by 36.9%.

A conclusion is that, for the summer season, the change of the Original by the Green roof was more beneficial in the Original envelope, confirming what has been found in other studies. Conversely, for the winter season the heat losses in the poorly insulated building were not compensated by the Green roof system. Therefore, for the climate of Porto Alegre, the Original building envelope requires an additional insulation due to the heating needs in the winter.

6 Effect of green strategies on the outdoor microclimate

This chapter answers the research question on how green roofs affect the microclimate. Firstly, this is done through a substitution of all the original roofs by green roofs, in the Original site. Secondly, trees and grass on the ground are also added to the scenario. As explained in Section 4.5.3, in total, 12 cases were studied: 6 for the summer and 6 for the winter (see Table 4.18).

The evaluations focused on understanding what happens immediately adjacent to the twin-house, and also served to further evaluate results indoors (through the coupled simulations, discussed in Chapter 7). Input weather data in ENVI-met was informed hourly, with data from the weather file (by adopting the *Simple forcing* feature, as explained in Section 4.4.1). Four receptors were positioned in the model alongside the twin-house, located at 0.5m distance from each façade (see Section 4.4.3). Averaged data were calculated for T_{air}, T_{mrt}, RH, wind speed and wind direction[61] at different heights: at pedestrian level, at the middle of façades and above the roofs, as described in Section 4.4.3.

At the end of the chapter, a comparison between the two extremes is made: green roofs in the Original site *versus* in the Dense green site. A green site was also studied, having trees with a medium density. The decision for discussing only the extreme cases was due to the more significant results).

For the analysis made in this chapter, evaluations made at pedestrian level (1.38m height) and above the roof (at 4.38m and 5.38m, as explained in Section 4.4.3) were adopted. Besides, assessments made at the middle of façades (at 2.38m height) were used to extract weather input data for the coupled simulations further performed, as discussed in Chapter 7.

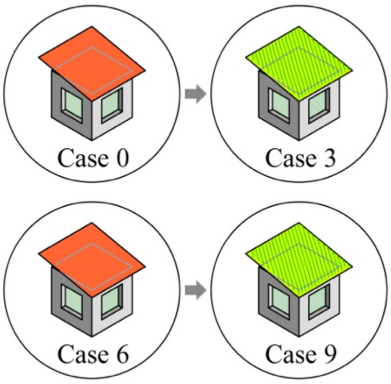
[61] An analysis of the incident solar radiation (direct and diffuse) was also made, to validate its values in the ENVI-met models, in order to be consistent with data from the weather file.

In order to provide a first overview of the changes in microclimate variables, Table 6.1 summarizes the meteorological data from the ENVI-met simulations. Data was averaged from receptors at 2.38m heigh (approximately the middle of façades), at the maximum daily T_{air} (at 3:00 p.m.). The abbreviations "OR" and "GR" mean, respectively, Original roof and Green roof.

Table 6.1: Meteorological data from the microclimate simulations with ENVI-met at the maximum daily $T_{air,}$ averaged from receptors at 2.38m height

OR (Original roofs) GR (Green roofs)		Max. T_{air} (ºC)	RH at max. T_{air} (%)	Wind speed (m/s)	Wind direction (º)
Cases	Scenarios	Typical summer day			
0	Original site, OR	28.0	51.9	0.73	135.2
1	Green site, OR	27.5	60.7	0.54	135.6
2	Dense green site, OR	26.8	62.8	0.52	135.9
3	Original site, GR	27.7	53.3	0.78	135.8
4	Green site, GR	27.2	60.6	0.48	135.9
5	Dense green site, GR	26.7	62.5	0.47	136.1
Cases	Scenarios	Typical winter day			
6	Original site, OR	20.0	73.3	0.44	136.0
7	Green site, OR	20.0	80.2	0.37	135.9
8	Dense green site, OR	20.0	80.2	0.36	136.0
9	Original site, GR	19.8	74.3	0.45	136.0
10	Green site, GR	19.8	80.2	0.37	136.0
11	Dense green site, GR	19.8	80.2	0.36	136.1

6.1 Effect of green roofs on the microclimate



The objective of this evaluation was to estimate the effect green roofs alone had on the microclimate. Simulations in ENVI-met were performed for the Original site, for the Original roofs and the Green roofs. T_{air}, RH and T_{mrt} were analysed with data averaged from four receptors, during a 24-hour cycle, for summer and winter.

6.1.1 Typical summer day – effect of the green roofs at pedestrian level

Figure 6.1 shows T_{air} for Original roofs in the Original site (Case 0) and Green roofs at the Original site (Case 3), at pedestrian level, compared to T_{air} from the weather file, for the Typical summer day.

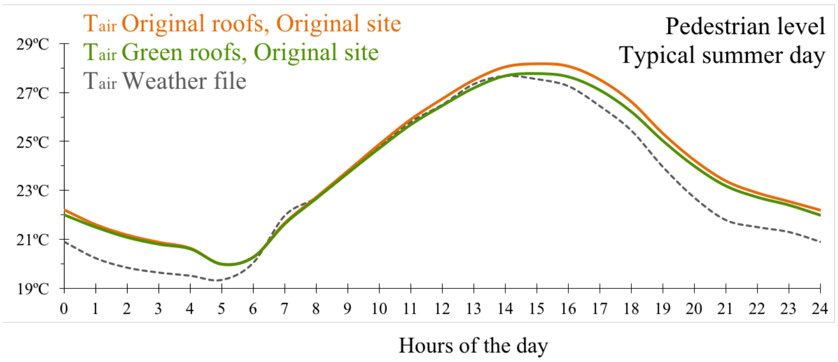


Figure 6.1: T_{air} for Original roofs in the Original site (Case 0) and Green roofs in the Original site (Case 3), at pedestrian level, compared to T_{air} from the weather file, in the Typical summer day

A small cooling effect at pedestrian level was observed. At the warmest hour of the day (at 15:00h), the model with the original roofs (Case 0) registered 28.2ºC and the model with the green roofs (Case 3) registered 27.8ºC. The diurnal amplitude was also slightly decreased: from 8.2ºC, in Case 0, to 7.8ºC, in Case 3.

Interestingly, in both models, higher T_{air} values were observed, compared to the T_{air} values from the weather file. The higher T_{air} values in the models might be caused by the model configuration regarding materials and building geometry. The surfaces of the model are heated (ground, façades and roofs) during the hours with the incidence of solar radiation, and this heat is released to the atmosphere through convection and long-wave radiation (with some delay). That effect starts to be evident from the beginning of the afternoon, heating the T_{air} at the receptors, at pedestrian level.

Results about the cooling effect of extensive green roofs at pedestrian level agree with previous studies, where decreases in T_{air} were registered in a range from 0.2ºC to 1.0ºC. Those studies used either both measurements and simulations (Alcazar et al., 2016), or only simulations (Peng & Jim, 2013; Rosseti et al., 2015; Berardi, 2016).

Unsurprisingly, the relative humidity increased proportionally to the decrease in T_{air}. At the maximum T_{air}, the RH was 51% in the case with original roofs and 53% in the case with green roofs. As expected[62], the use of green roofs did not result in a reduction in T_{mrt} at pedestrian level.

6.1.2 Typical summer day – effect above the green roofs

A very small and local cooling effect was observed above the green roofs, both vertically and horizontally. The differences were more significant near the roof, thus, at 4.38m height. Table 6.2 quantifies the T_{air} registered above the Original roof and the Green roof at two heights (at 4.38m and at 5.38m), at the warmest hour of the day (at 15:00h), for the Typical summer day.

[62] The direct solar radiation increases the surface temperatures of building façades and streets, which in turn warm up the ambient air. Thus, the warming by long-wave radiation occurring at pedestrian level, in addition to the incident short-wave radiation, will not be influenced by the green roofs. That explanation is corroborated by Alcazar et al. (2016).

Table 6.2: T_{air} above the Original roof and the Green roof in the Original site, at 15:00h, in the Typical summer day

	0.13m above plants			1.13m above plants		
Variable	Case 0	Case 3	≠	Case 0	Case 3	≠
T_{air} (ºC)	27.6	27.4	-0.2	27.4	27.3	-0.1

Figure 6.2 shows T_{air} for the Original roofs and the Green roofs in the Original site (Cases 0 and 3, respectively), 0.13m above the plants, compared to T_{air} from the weather file, for the Typical summer day. The model with green roofs presented a very small reduction in T_{air} during the majority of hours.

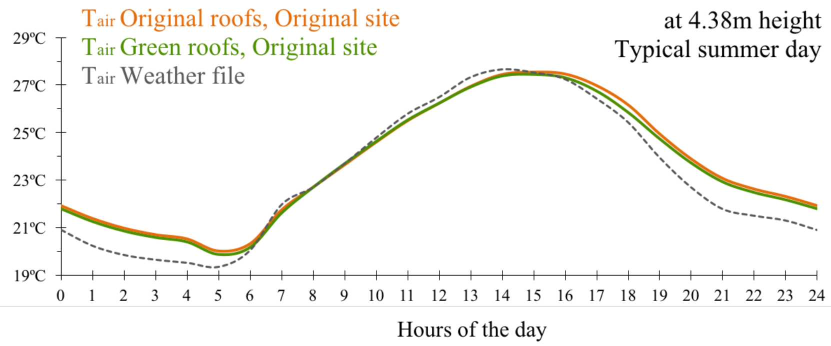


Figure 6.2: T_{air} for the Original roofs in the Original site (Case 0) and the Green roofs in the Original site (Case 3) at 0.13m above the plants (at 4.38m height), compared to T_{air} from the weather file, in the Typical summer day

6.1.3 Typical winter day – effect of the green roofs at pedestrian level

Figure 6.3 shows T_{air} for the Original roofs and the Green roofs in the Original site, at pedestrian level, compared to T_{air} from the weather file, in the Typical winter day. At the hour with the maximum T_{air} (at 15:00h), a reduction of 0.2ºC was registered: from 20.1ºC in the model with the Original roof, it dropped to 19.9ºC in the model with the Green roof.

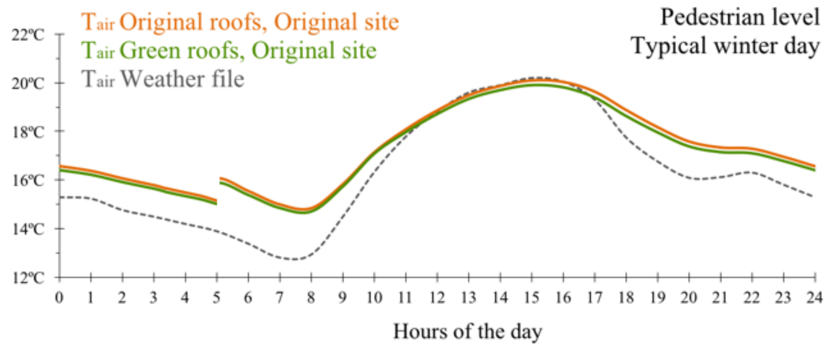


Figure 6.3: T_{air} for Original roofs in the Original site (Case 6) and Green roofs in the Original site (Case 9), at pedestrian level, compared to T_{air} from the weather file, in the Typical winter day

As for the summer season, a limitation of ENVI-met in reproducing the T_{air} amplitude was observed. The models reached the maximum T_{air}, but not the minimum.

6.1.4 Typical winter day – effect above the green roofs

Table 6.3 shows the values of maximum T_{air} at two heights above the roof, in the Typical winter day.

Table 6.3: T_{air} above the Original roof and the Green roof in the Original site, at 15:00h, in the Typical winter day

	at 4.38m (0.13m above plants)			at 5.38m (1.13m above plants)		
	Case 6	Case 9	≠	Case 6	Case 9	≠
T_{air} (ºC)	19.8	19.7	-0.1	19.6	19.6	0

The cooling effect of green roofs on the microclimate was nearly zero. It was registered only at 0.13m distance from the plants (at 4.38m height).

6.1.5 Concluding remarks

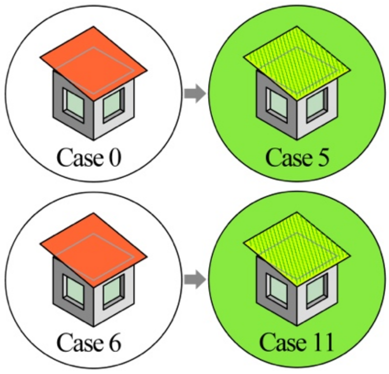
Findings from this section *partially* agree with Rosseti et al. (2015), who claim green roofs can be a passive strategy to increase thermal comfort in urban environments, at pedestrian level. Although having an influence, results about the effect of green roofs as the only green strategy presented small values, reaching up to 0.4ºC of reduction in the Typical summer day and up to 0.2ºC, in the Typical winter day. Those values were similar to results from Berardi (2016), which found up to 0.4ºC reduction with the substitution of conventional by green roofs in Toronto. Also, results agree with findings from Rosseti et al. (2015), Alcazar et al. (2016) and Peng & Jim (2016), but with smaller values (these authors found reduction in T_{air} from 0.4ºC, up to 1ºC reduction with the use of green roofs).

The cooling effect of green roofs in the site was higher in the summer than in the winter season. The almost inexistent reduction of T_{air} with the green roofs in the Typical winter day indicates it would not have a negative impact on the site, in winter. That meaning, as a green strategy for Porto Alegre, the extensive green roofs present a potential of slightly cooling the microclimate in summer (as seen in Sections 6.1.1 and 6.1.2), without having a negative impact in the winter, as other green strategies might have (by excessively cooling and humidifying the air in winter, for instance).

Regarding the vertical impact of the green roofs on the outdoor T_{air}, the biggest reductions in T_{air} were, in this study, at pedestrian level. Results differed from previous findings that state that the effect of green roofs at the roof level is more expressive than at pedestrian level, (e.g. Berardi (2016)), The explanation for that is due to a limitation in the ENVI-met model, regarding the configuration of green roofs. Although other studies have validated the use of ENVI-met for simulating green roofs with acceptable results (e.g. Rosseti et al., 2015; Alcazar et al., 2016; Berardi, 2016), a limitation of the software should be pointed out. At present state, it does not take into account the heat exchange in the soil layer as part of the roofing composition, thus, as part of the green roof. It means that only the plants are considered in the calculations of green roofs made by ENVI-met.

The addition of the surrounding area to the simulation opens a possibility for new studies, reproducing the method adopted in this research and adding a new parameter: the scenario at the neighbourhood scale. By inserting the model in specific locations in the city, the consolidated environment would influence results. That step could result in an adjustment of the boundary input weather data from the weather file in the Baseline case and could create different scenarios in the mesoscale.

6.2 Effect of the dense green site on the microclimate



This evaluation aimed to investigate the effect of a green strategy applied to the site area including green roofs, dense trees and grass on the ground (named Dense green site). Simulations also provided data to Phase 4 (coupled simulations). In order to compare results, the same method as employed in Section 6.1 was adopted.

6.2.1 Typical summer day – effect of the Dense green site at pedestrian level

Figure 6.4 shows T_{air} for the Original roof in the Original site (Case 0, the baseline case) and for the Green roof in the Dense green site (Case 5), at pedestrian level, compared to T_{air} from the weather file, for the Typical summer day.

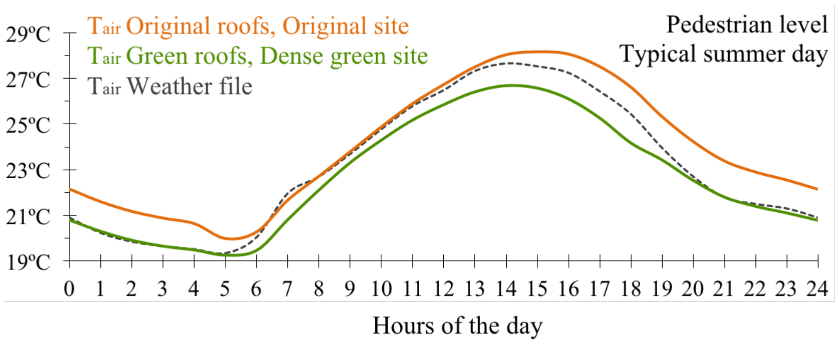


Figure 6.4: T_{air} for Original roofs in the Original site (Case 0) and Green roofs in the Dense green site (Case 5), at pedestrian level, compared to T_{air} from the weather file, in the Typical summer day

Reductions in T_{air} in Case 5 occurred in all hours of the 24-hour cycle, being more expressive in the warmest hours from 13:00h to 16:00h. At the maximum T_{air} for Case 0 (28.2ºC, at 15:00), Case 5 resulted in 26.6ºC, a decrease of 1.6ºC. The diurnal amplitude was also reduced: from 8.2ºC in Case 0, it dropped to 7.4ºC in Case 5.

Differently from the scenario analysed in Section 6.1 (Green roofs in the Original site, Case 3), Case 5 presented a substantial reduction of T_{mrt} at pedestrian level. The average T_{mrt} decreased from 58.4ºC in Case 0 to 33.2ºC in Case 5, at 15:00. At the same hour, the RH increased 12%: from 51.4 (Case 0) to 63.4 (Case 5). Figure 6.5 illustrates the cooling effect regarding location, in a plan view, showing the T_{mrt} for Cases 0 and 5 at 1.38m height at 15:00h for the Typical summer day.

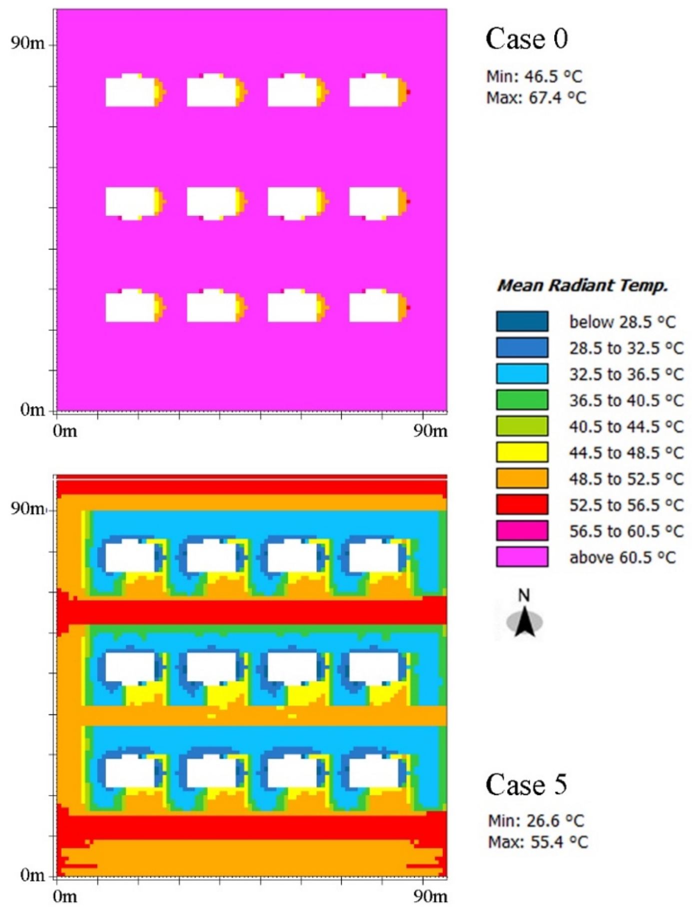


Figure 6.5: T_{mrt} for the Original roofs in the Original site (Case 0) vs. the Green roofs in the Dense green site (Case 5) at 15:00h, at pedestrian level, in the Typical summer day

Trees play a key role in providing a considerably more comfortable environment around the buildings. Thus, results about the cooling effect (reduction on T_{air}) of the Dense green site at pedestrian level agree with previous studies conducted in Brazil (de Abreu & Labaki, 2010; Labaki et al., 2011; de Abreu, 2012; de Abreu-Harbich et al., 2015; Duarte et al., 2015; Shinzato et al., 2017).

Results are consistent with previous studies that claimed T_{mrt} is the variable most affected by the shading of trees, e.g. Duarte et al. (2015), who simulated different scenarios in São Paulo, Brazil (Subtropical climate), validating results with measurements. In their study with dense trees (LAI 4.6) for the summer season a reduction of 13ºC in T_{mrt} was registered at pedestrian level, at the warmest hour of the day (at 15:00h).

Other variables were also modified with the addition of the green strategy to the site. A reduction of the wind speed was observed, as a direct effect of the trees near the houses: it dropped from 0.65m/s in Case 0 to 0.40m/s in Case 5. This change in the wind speed has implications on the ventilation indoors, by reducing it.

6.2.2 Typical summer day – effect of the Dense green site above roof level

In Case 5 a cooling effect occurred at pedestrian level and immediately above the roofs. Differently from Case 3, where the Green roof was the only green strategy (see Section 6.1), in Case 5, due to the presence of trees, the cooling effect also occurred in areas adjacent to the roofs. Table 6.4 quantifies the T_{air} for Cases 0 and 5 registered at the warmest hour of the day (at 15:00h), for the two heights analysed: at 4.38 and 5.38m.

Table 6.4: T_{air} above the Original roof in the Original site (Case 0) and the Green roof in the Dense green site (Case 5), at 15:00h, in the Typical summer day

	at 4.38m (0.13m above plants)			at 5.38m (1.13m above plants)		
	Case 0	Case 5	≠	Case 0	Case 5	≠
T_{air} (ºC)	27.6	26.6	-1.0	27.4	26.6	-0.8

Case 5 presented a reduction in T_{air} during the whole day, especially in the periods of afternoon and night, as observed in Figure 6.6.

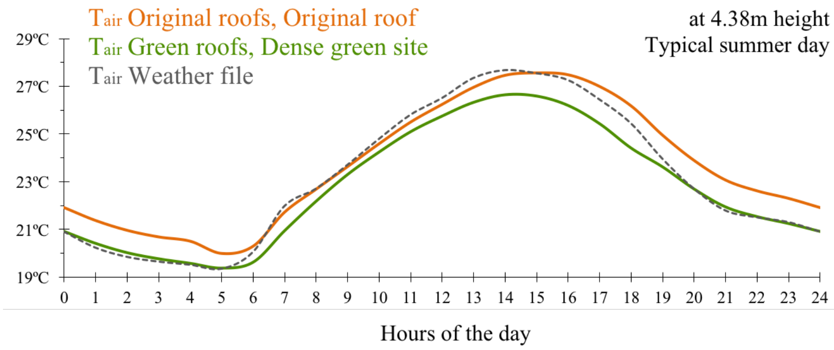


Figure 6.6: T_{air} for Original roofs in the Original site (Case 0) and Green roofs in the Dense green site (Case 5), at 0.13m above the plants, compared to T_{air} from the weather file, in the Typical summer day

6.2.3 Typical winter day – effect of the Dense green site at pedestrian level

Figure 6.7 shows T_{air} for the Original roofs in the Original site (Case 6) and for the Green roofs in the Dense green site (Case 11), at pedestrian level, compared to T_{air} from the weather file, for the Typical winter day.

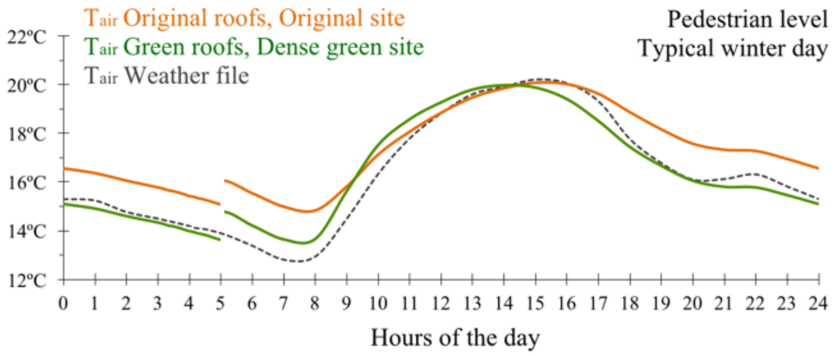


Figure 6.7: T_{air} for Original roofs in the Original site (Case 6) and Green roofs in the Dense green site (Case 11), at pedestrian level, compared to T_{air} from the weather file, in the Typical winter day

A small cooling effect was registered at the warmest hour of the day (at 15:00h): a maximum of 0.2ºC reduction in T_{air} from Case 6 (20.1ºC) to Case 11 (19.9ºC). However, differently from summer, in winter the thermal amplitude increased for the Green roofs in the Dense green site. The minimum T_{air} was lower in Case 11 than in Case 6, which made the thermal amplitude 6.3ºC for Case 11 and 5.3ºC for Case 6. In both cases, the thermal amplitude from the weather file (7.4ºC) was larger than the ENVI-met outputs, as also observed in Section 6.1.

Figure 6.8 illustrates the spatial distribution of the cooling effect, in plan view, showing the T_{mrt} for Cases 6 and 11 at pedestrian level. The map was extracted at 15:00h, for the Typical winter day. While in Case 6 the average T_{mrt} was 42.0 ºC, in Case 11 it was 24.3ºC, a reduction of 17.7ºC.

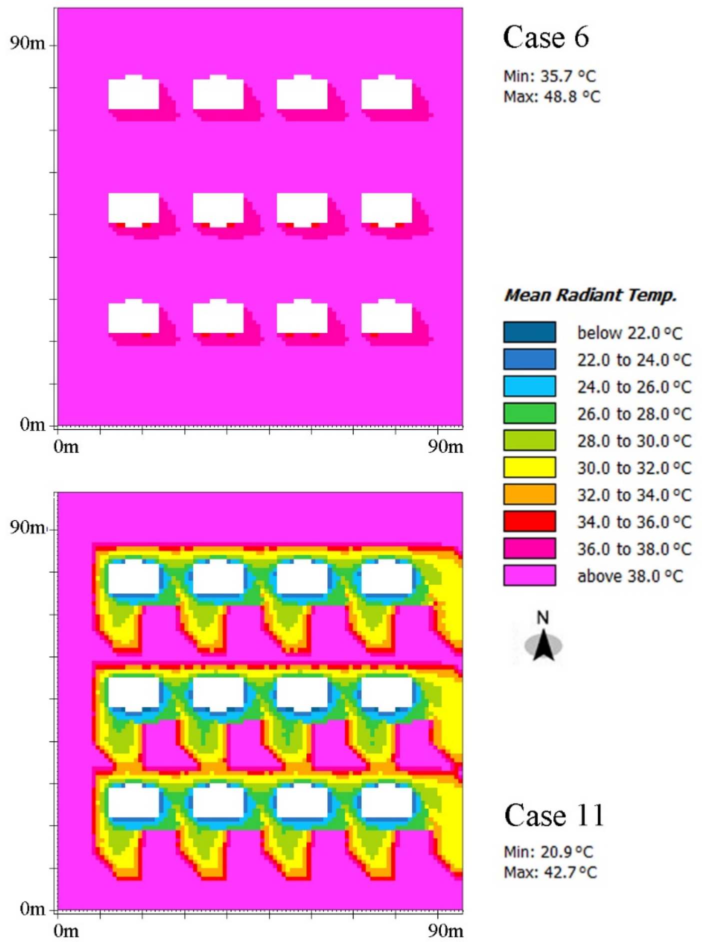


Figure 6.8: T_{mrt} of the Original roofs in the Original site (Case 6) vs. the Green roofs in the Dense green site (Case 11) at 15:00h, at pedestrian level, for the Typical winter day

The combination of weaker solar radiation and lower LAI of trees in winter (the trees are deciduous, as explained in Section 4.5.1), led to a lower cooling effect in winter than in summer. In winter, there is a mixture of shade from trees and solar access in the area as shown in Figure 6.8.

6.2.4 Typical winter day – effect of the Dense green site above roof level

Above the roof level, the cooling effect of the Dense green site in the Typical winter day was registered only at 0.13m and 0.38m distance from the plants. At the warmest hour of the day (at 15:00h), the biggest difference in T_{air} from the baseline case (Original roof in the Original site) was -0.2ºC. Table 6.5 shows T_{air} above the roofs, for Case 6 and Case 11, for the Typical winter day.

Table 6.5: T_{air} above the Original roof in the Original site (Case 6) and the Green roof in the Dense green site (Case 11), at 15:00h, Typical winter day

	at 4.38m (0.13m above plants)			at 5.38m (1.13m above plants)		
	Case 6	Case 11	≠	Case 6	Case 11	≠
T_{air} (ºC)	19.8	19.6	-0.2	19.6	19.6	0

6.2.5 Concluding remarks

The evaluations made in this section indicate that the Dense green site, while contributing to a decrease in T_{air} and T_{mrt} both in summer and in winter, had more significant results in summer. Therefore, for Porto Alegre, the slight cooling effect in winter is compensated for by a bigger and favourable cooling effect in summer. Regarding the vertical effect, the effect of trees made the differences more expressive at pedestrian level than above the roof level. In summer, T_{air} was reduced by 1.6ºC at pedestrian level with the substitution of Case 0 for Case 5, against 1.0ºC reduced at 0.13m above the roof level. Additionally, the horizontal cooling effect of the Dense green site was observed (see Figures 6.5 and 6.8). As an effect of the Dense green site on vicinity areas, a spatial reduction of Tmrt was observed, mainly in summer.

6.3 Comparison between green strategies: green roofs alone *vs.* Dense green site

The comparison between the two green strategies (green roofs alone, and Dense green site) indicate that green roofs, as the only green strategy, would not give a big contribution to cooling the air at the site, in Porto Alegre. However, as expected, the Dense green site had a bigger cooling effect than the green roofs alone, both for summer and winter, especially at pedestrian level.

In the Typical summer day, at pedestrian level, the reduction in maximum T_{air} between Case 5 and Case 0 (the baseline), was four times the one reached between Case 3 and Case 0 (1.6ºC and 0.4ºC reduction, respectively). The same pattern was observed above the roofs. At 0.13m above plants, Case 5 was reduced 1ºC in maximum T_{air}, while Case 3 was reduced 0.2ºC. At the same hour and height, the T_{mrt} in a plan view showed a difference in the spatial distribution, between the two green strategies. The influence of green roofs alone was minor, while the Dense green site reduced Tmrt around buildings.

The comparative analysis was also made in winter, showing a repetition of the same pattern (reduction in T_{air} and increase in RH) both at pedestrian level and above the roofs. However, in winter, the cooling effect was much smaller than in summer. The less intense solar radiation and the lower LAI of trees in winter made the differences between the green strategies and the baseline case less significant in winter than in summer.

6.3.1 Concluding remarks

Results corroborate the statement made by Alcazar et al. (2016), that green roofs have a moderate effect on the surrounding microclimate, but a bigger effect is achieved when they are combined with vegetation. When results in summer and winter were compared, the summer was the season with the most significant cooling effect, whereas the cooling in winter was negligible. That is a point in favour of the use of green roofs in Porto Alegre, indicating it would not have an adverse impact in winter by decreasing T_{air}, outdoors. As the analysis was made for the Typical summer and winter days, and not for the extreme days, the cooling effect can be even higher than the ones found in this study, during hot summer days.

Trade-offs should be considered when a green roof composition is defined. An example of that is the decision about the LAI of plants: the green roofs had the configuration with the best thermal contribution for the *indoor thermal comfort* in Porto Alegre, during the whole year: LAI 1. If the focus was only on the outdoors, a design with a higher LAI would be more beneficial for a cooling effect in summer, as previously tested by Krebs et al. (2017).

Findings indicate an interesting field to be further explored in research: parametric studies assessing the limits of green strategies (especially including green roofs), until when they provide positive effects that overcome adverse effects, in Brazilian climates. That will be especially useful for the climatic zones 1, 2 and 3, representing the coldest climates in the country (Subtropical climate).

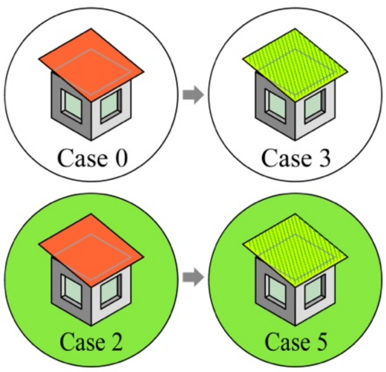
7 Indoor thermal comfort using coupled simulations

This chapter responds to the research question on how the microclimate influences the impact of green roofs on indoor thermal comfort. The chapter presents results and discussion on the research Phase 4 (Coupled simulations), and is divided into three sections:

- The effect of green roofs on indoor thermal comfort in the Dense green site *vs* in the Original site;
- The effect of the Dense green site on the indoor thermal comfort; and
- The influence of coupled simulations on the results.

The parameters employed for quantifying results were the percentage of time in comfort and discomfort, according to the ASHRAE Standard 55, and degree-hours. In Sections 7.2.1 and 7.2.3, one parameter was added in order to make a more detailed comparison: the averaged T_{op} of the building's thermal zones.

7.1 Effect of green roofs on indoor thermal comfort in the Dense green site *vs*. in the Baseline site



The evaluation in this section aimed to understand how a significant change in the local microclimate affects the contribution of a green roof on the indoor thermal comfort. As observed in Chapter 6, the highest impact of the green strategies on the microclimate occurred in the summer season. Therefore, that season was chosen for this evaluation. The evaluations were made for the Original site and the Dense green site. Four cases were compared: Cases 0 and 3, representing the Original roof and the Green roof, in the Original site; and Cases 2 and 5 representing the same roofs, but in the Dense green site.

7.1.1 Comparison between the Original roof and the Green roof, in the Original site

For the Original site, the substitution of the Original roof (Case 0) by the Green roof (Case 3) resulted in a decrease of the indoor T_{op} repeating, as expected, the same pattern as presented in Chapter 5. Figure 7.1 illustrates the percentage of time in comfort and discomfort, according to the Adaptive model of ASHRAE Standard 55 for the two cases, in the Typical summer day. The range of thermal comfort was from 21.5ºC to 28.5ºC.

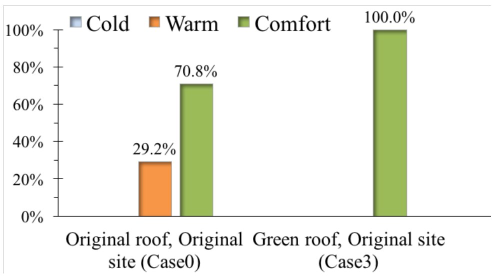


Figure 7.1: Percentage of hours below, within and above the comfort zone according to ASHRAE Standard 55, Original roof and Green roof, in the Original site, (Cases 0 and 3), Typical summer day

Figure 7.2 illustrates the indoor T_{op} of the Original roof and the Green roof in the Original site, during the Typical summer day. The outdoor T_{air} was below the comfort limits from midnight until around 8:30h in the morning. Conversely, neither the Original, nor the Green roof presented discomfort by cold at night. The Original roof, while having a good indoor T_{op} during most of the day, was above the comfort limits from 11:30h to 16:30h. The Green roof, on the other hand, was 100% of the time within the comfort limits.

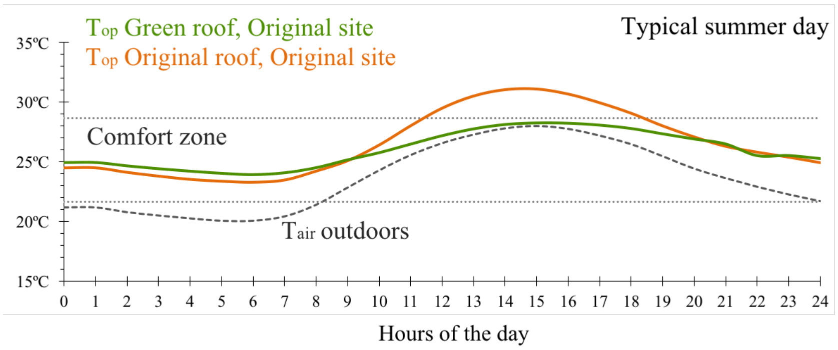


Figure 7.2: Indoor T_{op} for the Original roof and the Green roof, in the Original site (Case 0 and Case 3), compared to outdoor T_{air} in the Typical summer day

7.1.2 Comparison between the Original roof and the Green roof in the Dense green site

Figure 7.3 illustrates the percentage of time within and outside the comfort zone, according to the Adaptive model of ASHRAE Standard 55, for the two cases.

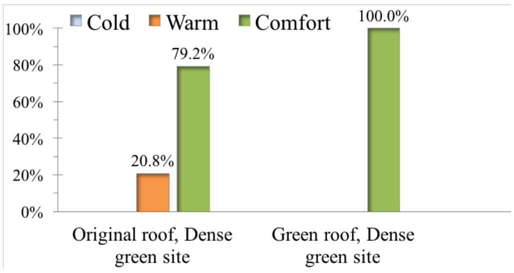


Figure 7.3: Percentage of hours below, within and above the comfort zone according to ASHRAE Standard 55, Original roof and Green roof in the Dense green site (Cases 2 and 5, respectively), Typical summer day

For the Dense green site, substitution of the Original roof (Case 2) by the Green roof (Case 5) resulted in a significant decrease of the indoor T_{op}. Consequently, the discomfort by warmth was eliminated, setting all hours within the comfort zone, in the Typical summer day.

Figure 7.4 illustrates the indoor T_{op} of the Original roof and the Green roof in the Dense green site, for the Typical summer day. For both cases, there was a visible drop in the T_{op} during the day if compared to the same roofs in the Original site (see Figure 7.2). For the Original roof, that drop resulted in fewer hours above the comfort limit. A comparison between Figures 7.2 and 7.4 shows that the difference between the Original and the Green roof is higher in the Dense green site than it was in the Original site. Moreover, a comparison between the two figures shows a reduction in the T_{air} amplitude, when the roofs are in the Dense green site.

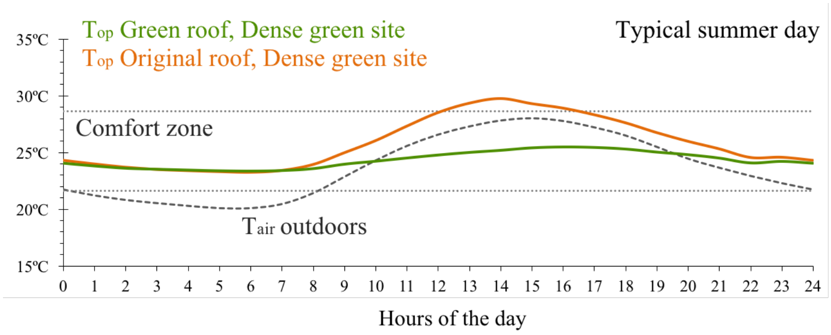


Figure 7.4: Indoor T_{op} for the Original roof and the Green roof, in the Dense green site (Cases 2 and 5, respectively), compared to outdoor T_{air}, in the Typical summer day

7.1.3 Comparison between the Original and Green roofs in the Original and Dense green sites

A comparison between the Green roof and the Original roof in the Original site (Case 3 and Case 0, respectively), and the same roofs in the Dense green site (Case 2 and Case 5, respectively), allowed to estimate the effect of the *site* on the impact of the green roofs on indoor thermal comfort.

Table 7.1 shows values of T_{op} for the Original roof and the Green roof, for the Original and the Dense green sites.

Table 7.1: Comparison between the T_{op} for the Original roof and the Green roof, in the Original site and in the Dense green site, Typical summer day

Site	Original site			Dense green site		
Roof	Original	Green	≠	Original	Green	≠
Model	Case 0	Case 3		Case 2	Case 5	
Average T_{op} (ºC)	26.6	26.0	-0.6	25.8	24.4	-1.4
Max. T_{op} (ºC)	31.1	28.3	-2.8	29.8	25.5	-4.3
Min. T_{op} (ºC)	23.3	23.9	0.6	23.2	23.4	0.2
Amplitude (ºC)	7.8	4.3	-3.4	6.5	2.1	-4.4

A direct influence of the microclimate on the indoors was observed. For both cases, the maximum daily T_{op} and diurnal amplitude were smaller in the Dense green site than in the Original site. That happened due to the cooling of T_{air} outdoors, thus, decreasing the T_{op} indoors.

A comparison between the two sites showed that, in summer, the green roof led to a higher degree of cooling when in the Dense green site. Results indicate that the partial shading by trees during some hours of the day have reduced the thermal fluxes through the green roof in summer, by reducing the heat gain through the roof. Besides, the Dense green site had an overall reduction in the outdoor T_{air}, which both reduces the thermal transmission through the roof and directly affects the indoor T_{op}, due to the natural ventilation in the twin-houses.

Figure 7.5 illustrates the soil and vegetation surface temperatures for Case 3 and Case 5, together with the inner surface temperature of the correspondent concrete slabs. The effect of shading on the surface temperatures was observed in soil and plants: they were lower in the partially shaded green roof (Case 5), especially when the solar radiation was more intense (from 11:00h to 13:00h). That resulted in the lower temperature in the inner surface of the concrete slab of Case 5.

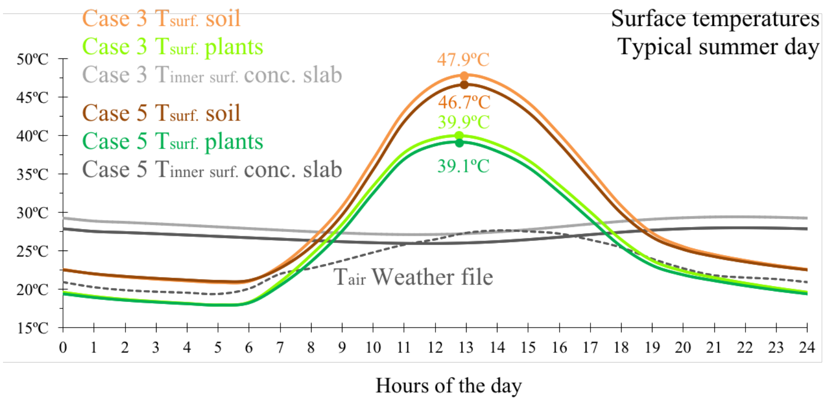


Figure 7.5: Surface temperatures of plants and soil, and inner surface of the concrete slab for the Green roof in the Original site (Case 3) and in the Dense green site (Case 5), compared to T_{air} from the weather file in the Typical summer day

Figure 7.6 shows the latent and sensible heat fluxes in the vegetation layer for the Green roof in the Original site and in the Dense green site (Cases 3 and 5, respectively). As expected, during the day, the green roof exposed to direct solar radiation during all hours (Case 3) loses more latent heat, through the transpiration of plants.

Additionally, the Green roof in the Original site is surrounded by a lower relative humidity of the air, which increases the transpiration rates of plants. That heat loss, however, is not sufficient to compensate the higher heat gain from the direct solar radiation (if compared to Case 5, where the roof is partially shaded during some hours of the day).

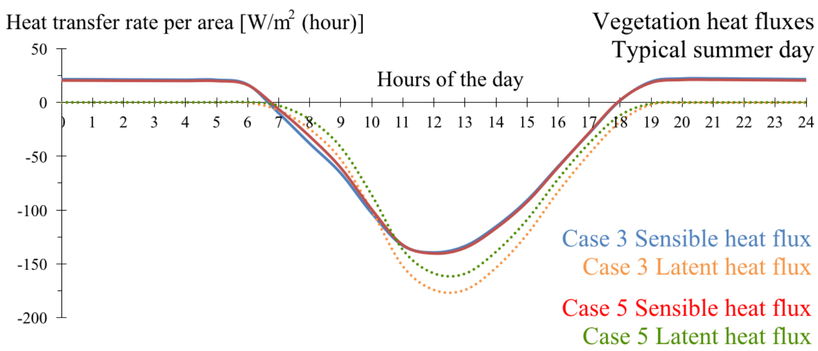


Figure 7.6: Sensible and latent heat fluxes in the vegetation layer, for the Original roof and the Green roof in the Dense green site (case 3 and Case 5, respectively), Typical summer day

Figure 7.7 shows the latent and sensible heat fluxes in the soil layer for the Green roof in the Original site and in the Dense green site (Cases 3 and 5, respectively). In the soil layer, due to its higher thermal mass, differences between the latent and the sensible heat fluxes and the amplitude are lower than in the vegetation layer (see Figure 7.6). As in the vegetation layer, also in the soil layer the Green roof in the Dense green site has a lower latent heat flux than the Green roof in the Original site. In the soil layer, that happened during all hours.

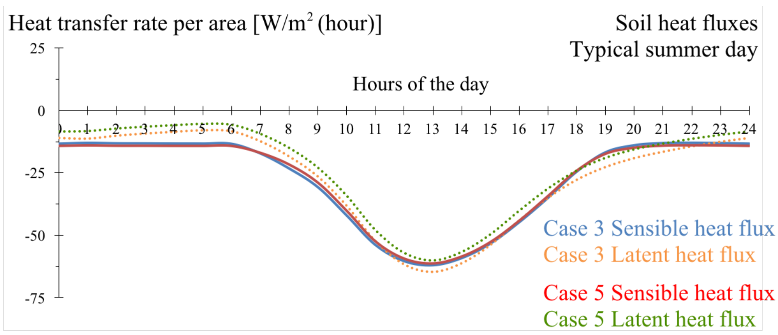


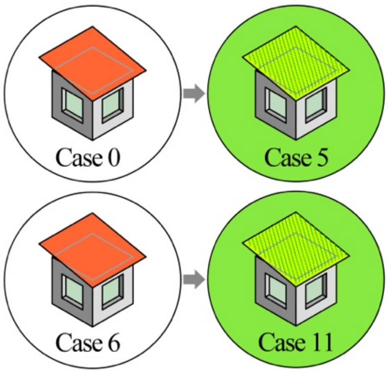
Figure 7.7: Sensible and latent heat fluxes in the soil layer, for the Original roof and the Green roof in the Dense green site (case 3 and Case 5, respectively), Typical summer day

With the green roof partially shaded in the Dense green site, the exposed surface of the soil was reduced, thus reducing the evapotranspiration rate from it. The decrease in the water loss kept the moisture higher in the substrate, increasing the thermal capacity of the soil in Case 5, compared to Case 3. Since the thermal conductivity also increased, the sensible heat flux was similar for both cases. The hypothesis is that, although the increase in humidity in the soil also increased the conductivity, it was compensated by the increase in the thermal capacity happening in Case 5. That and the lower solar gain (due to the partial shading from trees), made the total heat gain lower in Case 5.

7.1.4 Concluding remarks

The analysis made in this section indicated the importance of considering the microclimate, when evaluating the effect of a green roof on the indoor thermal comfort. Moreover, it showed that a significant change in the microclimate directly impacts the effect of a green roof on the indoor thermal comfort. The combination of shading and reduction of outdoor T_{air} caused by trees in the Dense green site (see Section 6.2) resulted in a lower T_{op} and diurnal amplitude indoors, for both the Original and the Green roof. The effect of the change in microclimate, though, made *the difference* between the Original and the Green roof more significant in the Dense green site. The partial shading had a higher cooling effect on the soil and vegetation of the Green roof, than on the ceramic surface of the Original roof. In the Green roof, the surface temperature of both the soil and plants were lower than for the ceramic, thus, less heat was transferred to the indoors.

7.2 Effect of the Dense green site on the indoor thermal comfort



This evaluation aimed to estimate the effect of the Dense green site as a whole, including green roofs (see Section 4.5.3, Table 4.18), on the indoor thermal comfort. The analysis was made for the summer and the winter seasons. The two extreme cases were compared:

- The Original roof in the Original site (Case 0 in summer and 6 in winter); and
- The Green roof in the Dense green site (Case 5 in summer, and Case 11 in winter).

As results of the summer season were already presented in Section 7.1 (Cases 0 and 5), this section presents graphs and tables from the winter season. As can be seen in Section 4.5.1, the deciduous trees do not lose all the leaves in the winter. Therefore, the addition of dense trees, even deciduous, creates a physical barrier for solar gain by the twin-houses, which is not beneficial for Porto Alegre's heating needs in the winter.

Figure 7.8 illustrates the indoor T_{op} for Case 6 and Case 11, compared to the outdoor T_{air}, for the Typical winter day. The range of comfort for the Typical winter day was from 19.4ºC to 26.4ºC. The outdoor T_{air} was below the comfort zone in all hours, except in the warmest hours of the day (from 14:00h to 16:30h, approximately). Both roofs were below the comfort zone limits during all hours and their thermal amplitude much smaller than for the outdoor T_{air}. For both cases, the temperature indoors was higher than the outdoor T_{air} during the hours with the more intense solar radiation. The Original roof in the

Original site (Case 6) was slightly warmer than the Green roof in the Dense green site (Case 11).

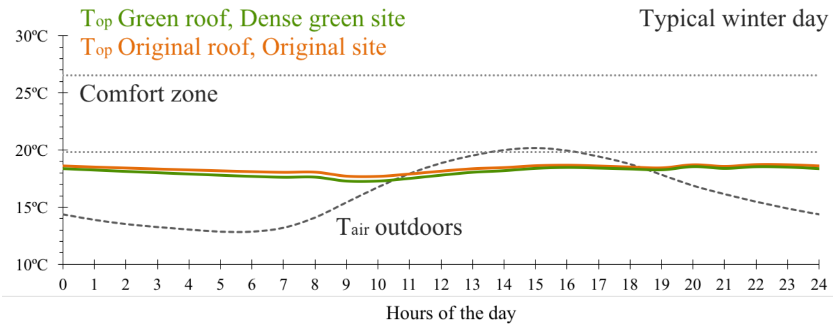


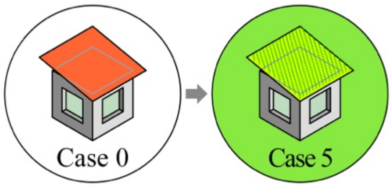
Figure 7.8: Indoor T_{op} for the Original roof in the Original site (Case 6) and the Green roof in the Dense green site (Case 11), compared to the outdoor T_{air}, in the Typical winter day

7.2.1 Concluding remarks

In the Typical winter day, the addition of grass on the ground and, mainly, the addition of trees, resulted in a slight increase in discomfort by cold, indoors. Thus, the Dense green site was beneficial for the indoor thermal comfort in the summer, but not in the winter. The evaluation made for a one-year period (see Section 5.2.1, for the LAI of 1, or Section 5.3.1, for the substrate of 150mm) showed that the Green roof, when not in the Dense green site, was beneficial for both seasons [63]. The difference in results due to the changes in the microclimate shows the importance of considering the microclimate generated by the urban design, when evaluating the thermal performance of the green roofs. That is especially relevant for climates with defined summer and winter seasons, as for subtropical Porto Alegre. Results from this section open up a window for further investigations, with parametrical studies gradually increasing the level of a green strategy, until reaching a limit, where benefits exist for both the summer and the winter seasons.

[63] In Chapter 5, in addition to the one-year, evaluations on the Typical summer week and Typical winter week were made.

7.3 Influence of coupled simulations on the results



This section evaluates the influence the coupled simulation method had on predicting the effect of green roofs on indoor thermal comfort. The same models used in Section 7.1 were adopted for the analysis in this section: Case 0 (Original roof in the Original site) and Case 5 (Green roof in the Dense green site), for the Typical summer day. The comparison was performed as follows:

- Firstly, the indoor thermal comfort resulting from simulations considering data from the weather file was quantified;
- Secondly, coupled simulations were performed, substituting initial meteorological data from the weather file by output data from the outdoor microclimate simulations.

For both Case 0 and Case 5, the coupled simulation did not change the percentage of time in comfort according to the ASHRAE Standard 55. The values were remained the same, as follows:

- Case 0 had 70.8% of hours in comfort and 29.2% of hours in discomfort by warmth;
- Case 5 had 100% of hours within the comfort range limits.

The calculation of degree-hours showed a small difference in Case 0 (from 9.2 cooling degree-hours, it increased to 11.2 cooling degree-hours with the coupled simulation), while it remained the same in Case 5 (zero degree-hours). In order to analyse the differences indoors more in detail, an assessment of the T_{op} was made. Results showed the influence of the coupled simulation on the indoor temperatures, as presented in Table 7.2. For Case 0, T_{op} increased with the coupled simulation but for Case 5 it decreased, showing a clear influence of the two scenarios on the site.

When the coupled simulation was performed, the substitution of Case 0 by Case 5 showed a difference in the relative improvement of maximum T_{op}, and in the averaged T_{op}. Also, in Case 5 the thermal amplitude was reduced.

Table 7.2: Comparison between the T_{op} in Case 0 and in Case 5, without and with the coupled simulation (CS), Typical summer day

Variables	Without the CS (º)			With the CS (º)			≠
Daily values (ºC)	Case 0	Case 5	≠	Case 0	Case 5	≠	Without & with CS (º)
Average T_{op}	26.3	24.9	-1.4	26.8	24.4	-2.4	-1.0
Maximum T_{op}	30.6	26.4	-4.2	31.1	25.5	-5.6	-1.4
Minimum T_{op}	23.3	23.6	0.3	23.3	23.4	0.1	0.2
Amplitude T_{op}	7.3	2.8	-5.0	7.8	2.1	-5.7	-0.7

While not changing the percentage of time in comfort according to the ASHRAE Standard 55, results in T_{op} showed the influence of the outdoor microclimate on the indoor thermal comfort. The results made it clear that using coupled simulations lead to more realistic predictions of the indoor thermal comfort.

7.3.1 Concluding remarks

The analysis made in this section helped to clarify the relationship between outdoor microclimate and indoor thermal comfort, in the simulated cases. The comparisons made between with and without the coupled simulations confirmed the importance of taking the microclimate into account when evaluating the thermal performance of a building or a group of buildings, or one of its elements (as the green roof). That can be especially relevant for more complex urban environments. In this study, Case 5 represents an environment with higher complexity than Case 0, due to the green strategy applied. As a result, differences in maximum and minimum T_{op} (thus, also in the thermal amplitude) when using or not the coupled simulation were more significant in Case 5 than in Case 0.

Bridging the current gaps between thermal simulations in different scales is highly relevant. Developing more studies in the field of coupled simulation is the path for increasing knowledge about those gaps, including predictions of different scenarios, actual and future (related to climate change, for instance). Regarding the software compatibility, as stated by Peng & Elwan (2014), the conversion of data from ENVI-met receptor outputs to a weather data file for EnergyPlus is straightforward. New features are required, though, to automatize the slow and potentially error-prone manual process currently employed.

8 Conclusions

This research aimed to contribute to the knowledge about green roofs in Brazil. More specifically, the investigation intended to explore the potential increase of indoor thermal comfort, under different green roof configurations and microclimate scenarios. A considerable part of the building stock, as well as new social housing projects, are made by naturally ventilated single-storey houses, with no compliance with adequate thermal comfort levels. Thus, this investigation aimed to estimate the improvement in thermal comfort green roofs could provide, for those building projects.

An economy in the energy used by the residential sector can be obtained by the adoption of constructive solutions that increase the indoor thermal comfort in passive ways. That is especially relevant if adopted on a large scale. The motivation to explore the potential thermal benefits of extensive green roofs was due to their lower maintenance and reduced weight on the roof structure, compared to the intensive ones. With less costs involved, extensive green roofs are suitable for social housing projects.

8.1 Impact of extensive green roofs on indoor thermal comfort

It was concluded that green roofs have a potential to increase the indoor thermal comfort considerably in the studied twin-houses in Porto Alegre. Compared to the Original roof, the Baseline green roof (LAI 1 and 150mm of substrate depth) led to an increase of 9.1% of the time in thermal comfort during one year, according to the ASHRAE Standard 55.

8.2 Influence of the vegetation and substrate layers on the thermal performance of the green roofs

The LAI and substrate depth proved to have a significant impact on the thermal performance of extensive green roofs. The higher density of plants (LAI = 5) was more beneficial to increase the thermal comfort in the summer than in winter, due to the combination of shading from leaves and transpiration of plants, cooling the air above the roof. The higher substrate depth was beneficial in both seasons, but it was more important in the winter, increasing the thermal insulation of the green roof system and consequently reducing the heat loss through the roof.

For the whole year, the best combination of the gardening layer features was the vegetation with the lower density (LAI 1) and the deepest substrate for extensive green roofs (150mm depth). Despite the best performance of the green roof with LAI 1 (achieving 66.6% of hours in comfort, according to the ASHRAE 55 Standard), LAI 5 was also beneficial for the indoor thermal comfort (achieving 62.4% of hours in comfort). Therefore, it can be concluded that a broad spectrum of vegetation can be specified, in the climate of Porto Alegre. For the whole year perspective, a positive effect of extensive green roofs on indoor thermal comfort can be obtained with plants from low to a high density.

8.3 Performance of green roofs with different levels of building envelope insulation

In the summer season, there was an important improvement of indoor thermal comfort by adding green roofs to the Original envelope. For the winter season, though, the poorly insulated building envelope led to significant heat losses that could not be compensated for by the use of green roofs. Results confirmed the suitability of green roofs to increase the indoor thermal comfort of social-housing projects, especially in one-storey buildings. Green roofs would be beneficial both to new projects built according to the Brazilian Standard envelope, and to the existing building stock, with envelopes with thermal properties very similar to the Original envelope. For the latter, extra insulation in the building envelope would increase the benefits provided by the green roof in the winter season.

8.4 Influence of microclimate and green roofs on indoor thermal comfort

The green roofs performed better when in the Dense green site. Results showed that in summer, the effect of trees on the site reduced the heat gain through the roofs, enhancing the contribution of green roofs on the indoor thermal comfort. In summer, where the differences between results were higher, the green roof in the Dense green site decreased 4.3ºC in the maximum T_{op}, compared to the Original roof. In the same period, the green roof in the original site registered a drop of 2.8ºC in T_{op}.

In winter, the same dense green strategy showed a slight decrease in discomfort by cold indoors, although a foliage with a low density was modelled. Still, it is possible to conclude that green roofs perform better when integrated in a green strategy where the buildings are partially shaded by trees. The green strategy where the green roofs would be included should consider cooling and heating needs, in Porto Alegre.

Simulations of thermal comfort do not predict the development and maintenance of the green roofs. As this research was based on computer simulations, it presents *tendencies of thermal behaviour,* rather than exact results. Regarding results about the influence of shading on the green roof´s thermal performance, careful attention must be paid. If oriented to the south, for instance, most species used in green roofs may not develop properly.

8.5 How the green roofs impact the microclimate in the surrounding area

In this study, the effect of green roofs on the microclimate was small and very local, both horizontally and vertically. At pedestrian level, the biggest reduction in T_{air} achieved with the substitutions of the Original roofs by the Green roofs in the Original site (Case 3) was of 0.4ºC. The effect was slightly bigger in summer and basically negligible in winter, (which is positive in the climate of Porto Alegre).

An important conclusion from this research addresses the optimal composition of a green roof, according to the intended impact on thermal comfort. The best combination of features might depend on the aim of obtaining indoor thermal comfort, good microclimate, or both. Exemplifying that, the Leaf Area Index of the green roof with the best contribution on the indoor thermal comfort in Porto Alegre was 1, because it had a cooling effect in summer but also allowed the penetration of the solar radiation through the vegetation, in the winter. To achieve the best cooling effect on the outdoors in summer, the LAI 5 would be better: such a high density has shown to have a negative impact in winter, but this effect is after all rather small.

More intense use of green roofs than the one adopted by this research (i.e., more green roofs in the site area) might result in more significant effects. Findings from this investigation, though, have led to conclude that green roofs, as the only green strategy, would not give a significant cooling effect on the surrounding areas.

8.6 Contributions to knowledge

This investigation is the first combining microclimate and indoor thermal comfort in a Brazilian city. Also, it is the first study addressing green roofs, with that approach. A reduced number of studies have simulated the contribution of green roofs on the indoor thermal comfort in Brazil, like the one conducted by Dias (2016). The same can be said about simulations evaluating the impact of green roofs on the microclimate, like the one performed by Rosseti et al. (2015). To date, neither a simulation study to investigate indoor thermal comfort, nor simulation of outdoor microclimate, were made for Porto Alegre.

Internationally, the majority of studies involving green roofs have presented results for warm climates, or for the summer season only. This research was developed for a subtropical city that presents a warm summer and cold winter, and evaluated results for the whole year and the two extreme seasons. The need for trade-offs for both the green roof configuration and the green strategy on the site were identified due to the discomfort by cold and by warmth in Porto Alegre. The awareness of these trade-offs fills gaps in the literature on urban green spaces and indoor thermal comfort in Brazilian subtropical cities.

Simulation studies have, as previously discussed, limitations in reproducing physical phenomena, as they need to be translated into mathematical equations. As this investigation was performed exclusively based on simulations (thus, on predictions), a contribution given was the concern to increase the correctness of inputs. That was achieved by the preliminary studies (as, for instance, the ones evaluating the influence of the ground temperature and solar radiation).

8.7 Future research recommendations

Publications addressing the LAI of different species of trees in Brazil (natives or not), especially deciduous, are quite rare in scientific studies. The same is true for vegetated species recommended for green roofs (as grass and flowers). One recommendation for future research is the creation of a database informing the LAI of vegetation species, as it would be extremely beneficial for future simulation studies.

To date, no studies on green roofs using measured data to evaluate the indoor thermal comfort or the outdoor microclimate were found in Porto Alegre. Another recommendation is, therefore, to perform field studies, providing information about the growth of plants in a green roof, and about the maintenance spent. That would allow validation of green roof studies in Porto Alegre, as found in the literature about other locations in the world.

Many studies recommend, for green roofs, species with a low need for water and a high tolerance to solar radiation as Sedum, for instance. It is also recommended future investigation on plant species with a minor need for solar radiation, suitable for the use in green roofs.

The green roofs were beneficial for the indoor thermal comfort in Porto Alegre during the whole year. This was not the case with the addition of dense trees in the site. The majority of studies about green strategies only addresses the cooling effect in the summer season, and do not present the impact in winter. As suggested in section 6.3.1, future studies could perform parametric studies evaluating the limits of green strategies to provide positive effects that overcome adverse effects, in Brazilian climates. That would be highly relevant for the climatic zones 1, 2 and 3, which are the coldest climates in the country (Subtropical climate).

As mentioned in Section 6.15, the addition of the surrounding area to the simulation opens a possibility for new studies, analysing the influence of distinct consolidated environments at the neighbourhood scale. Thus, adjustments in the boundary input weather data at the mesoscale could also be provided, being useful for more realistic results in both indoor and outdoor simulations.

The comfort zones from ASHRAE are general and not specific for Porto Alegre. It would be beneficial to determine the actual comfort zones of Porto Alegre, so another recommendation is to investigate them through a questionnaire survey.

The partial shading of the green roof by trees was beneficial to the indoor thermal comfort. A real green roof could confirm until what extent the shading would not have a negative impact on the vegetation development and maintenance. Findings from this investigation indicate the need for more research on partial shading of built green roofs in Porto Alegre.

Except for the one-year assessment, simulations were performed for the Typical summer and winter weeks, and days. As the name says, they represent the typical climatic conditions on summer and winter. Thus, they were considered the most appropriate to predict an extended period of the climate of Porto Alegre. If the extreme weeks and days, or the average monthly data from the warmest and the coldest months were used instead, results would be diverse. Despite, the trends of the thermal behaviour would be the same, differences found between variables would probably be higher, for all parametric studies performed. A future study evaluating the building energy efficiency with extensive green roofs could be conducted, using the extreme and not the typical weather data as the input boundaries. The study of the extremes would be useful to energy-efficiency calculations.

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Appendix A

Figures A.1 to A.8 show technical drawings of the project.

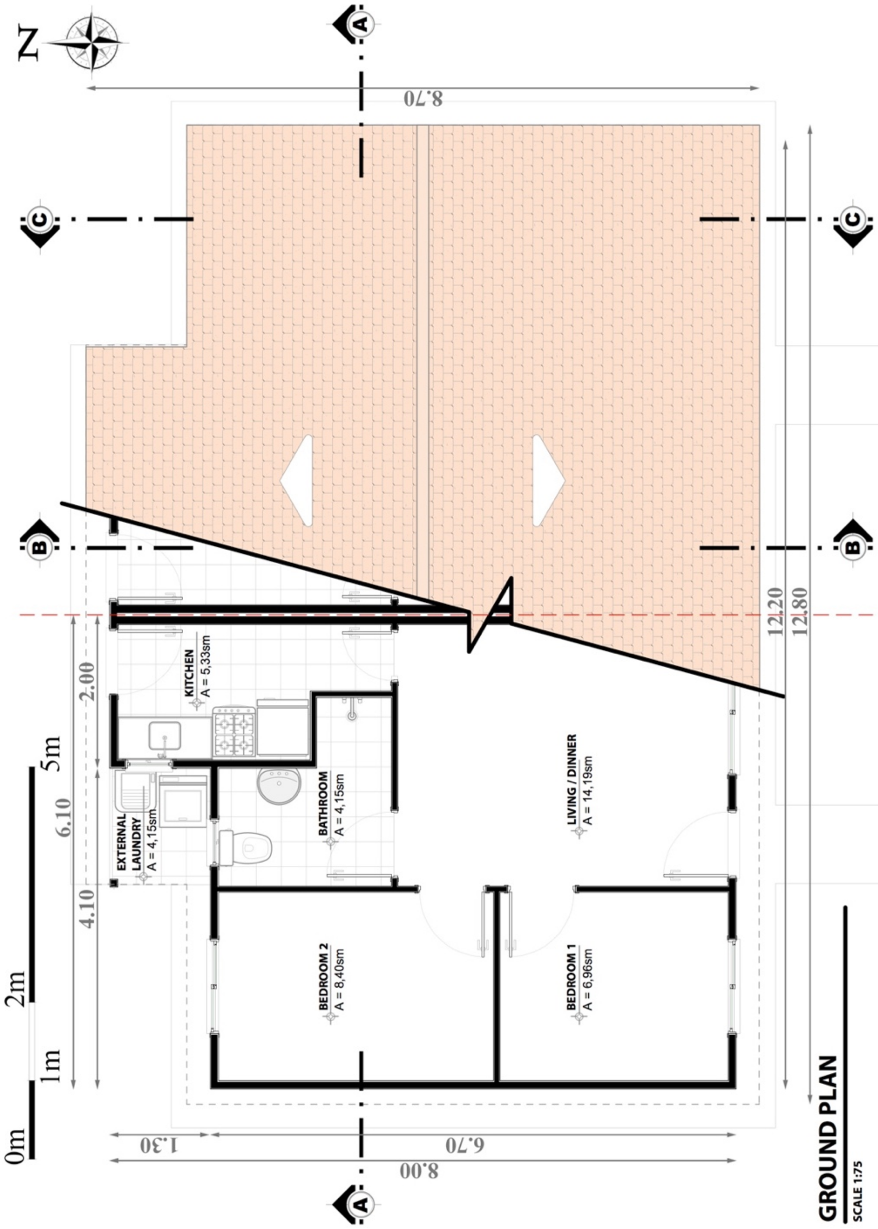


Figure A.1: Ground Plan

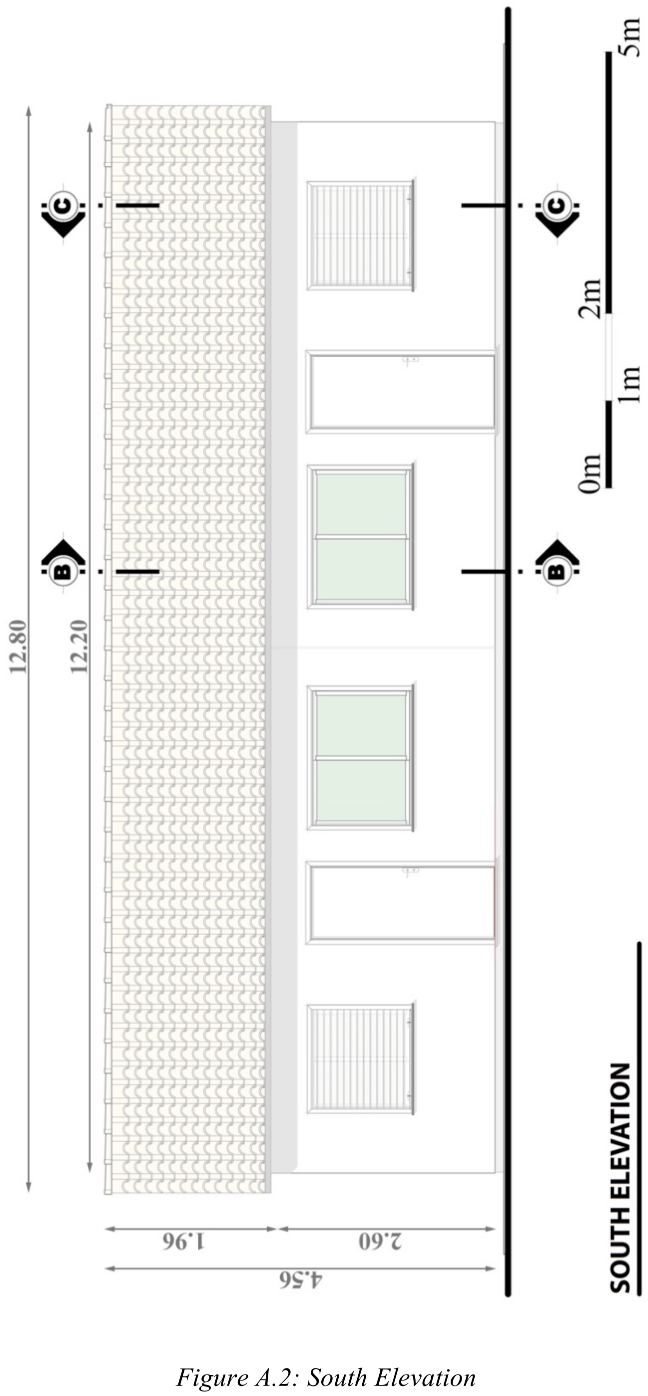


Figure A.2: South Elevation

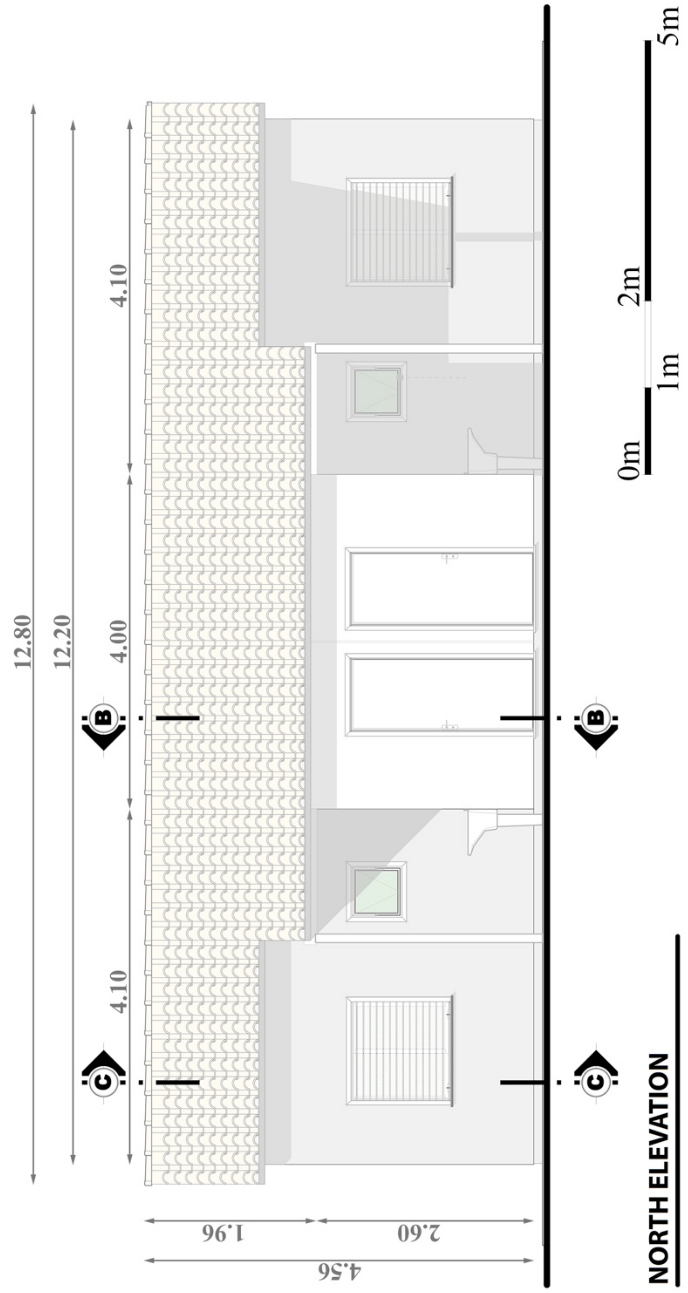


Figure A.3: North Elevation

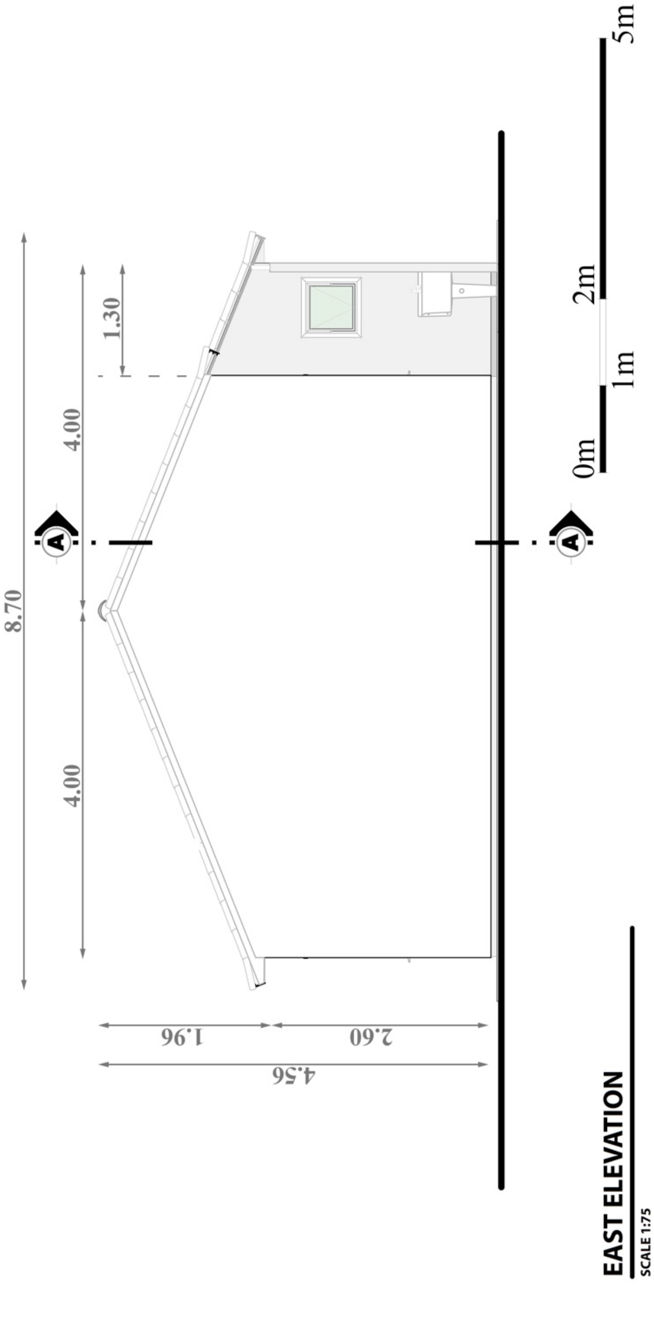


Figure A.4: East Elevation

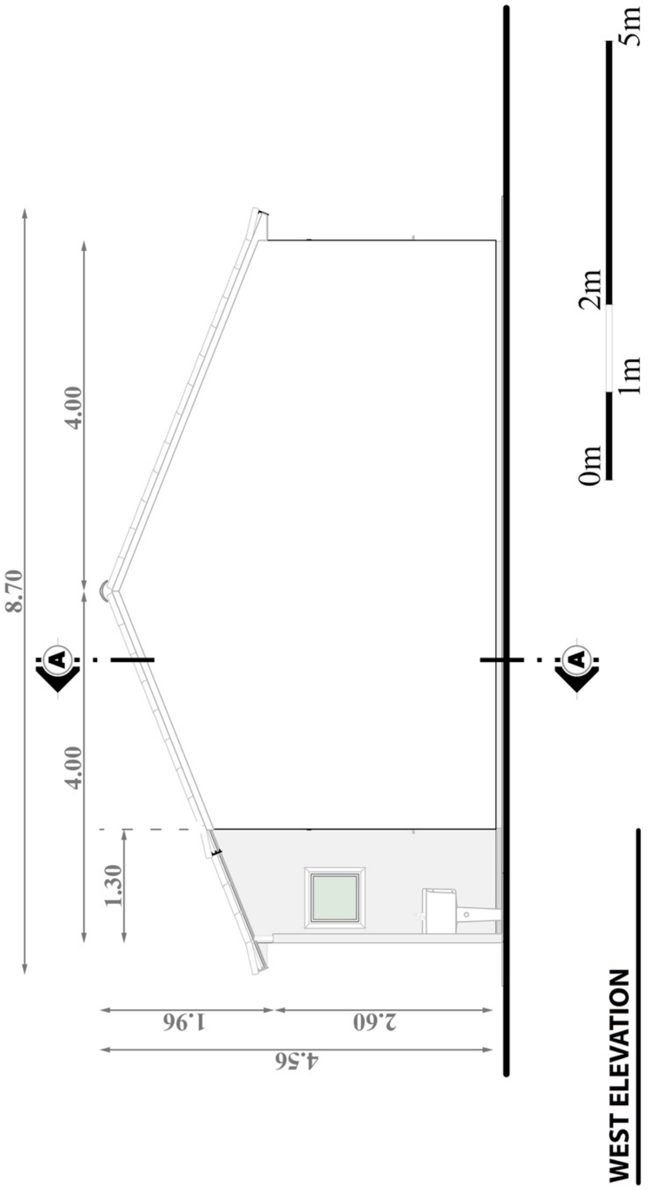


Figure A.5: West Elevation

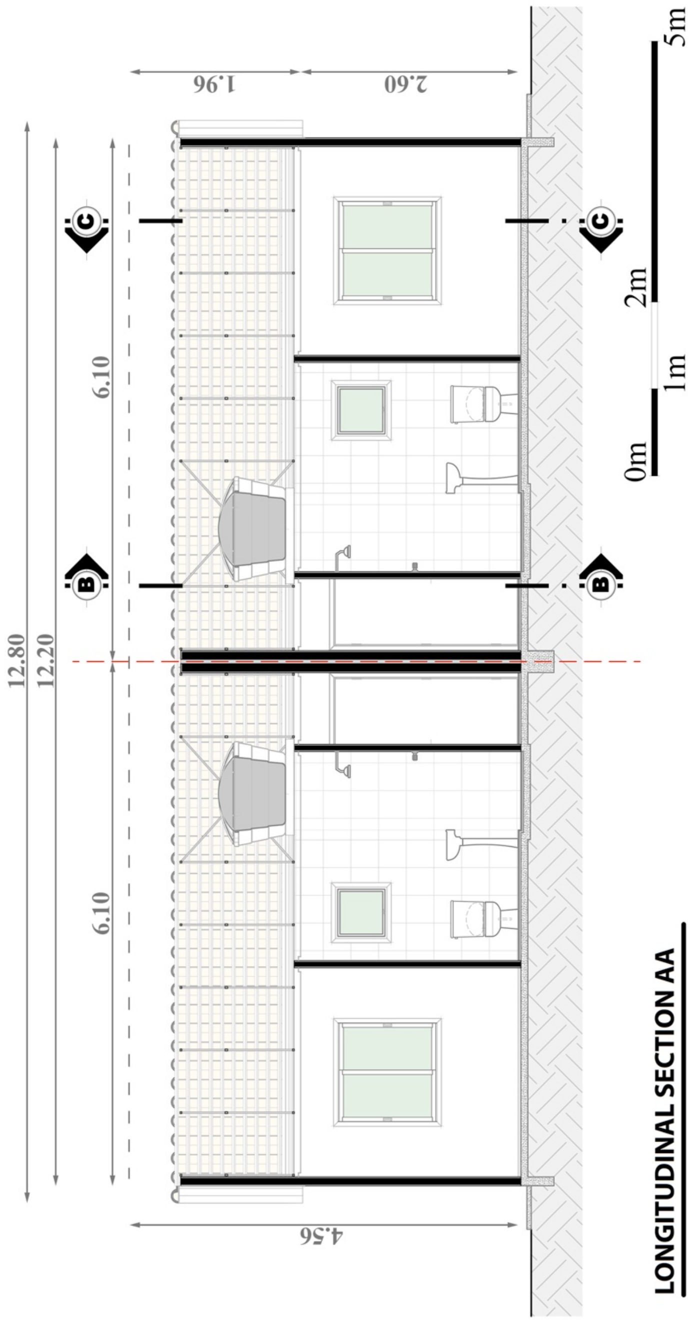


Figure A.6: Longitudinal Section AA

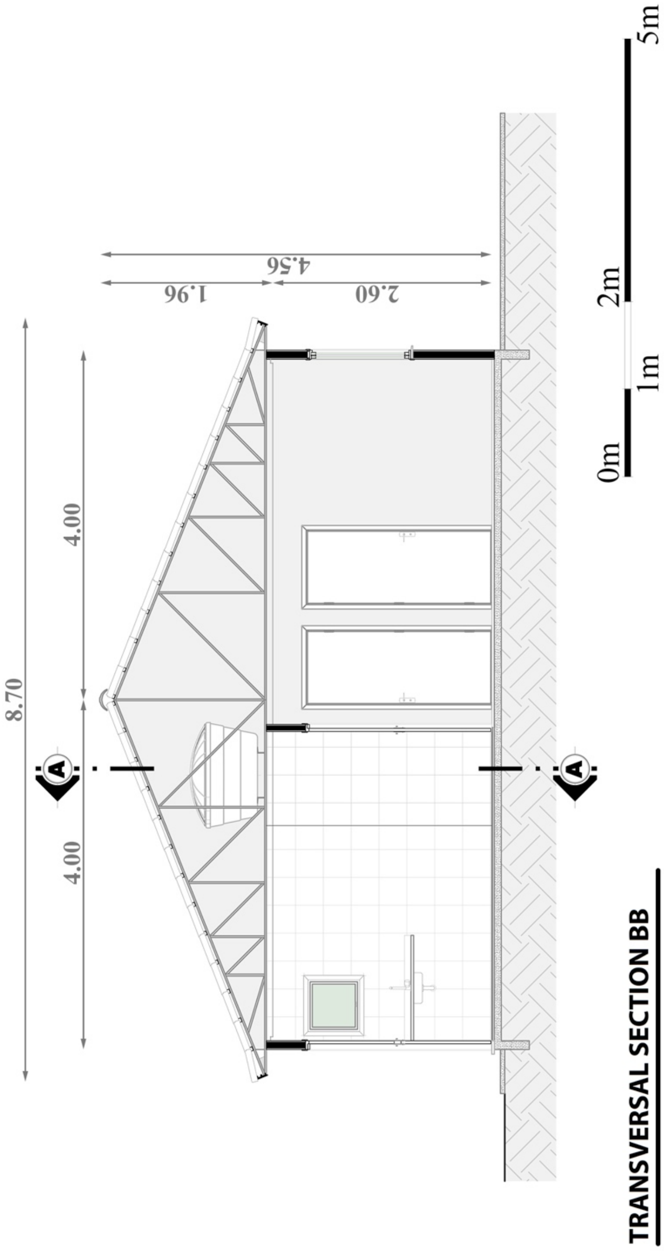


Figure A.7: Transversal Section BB

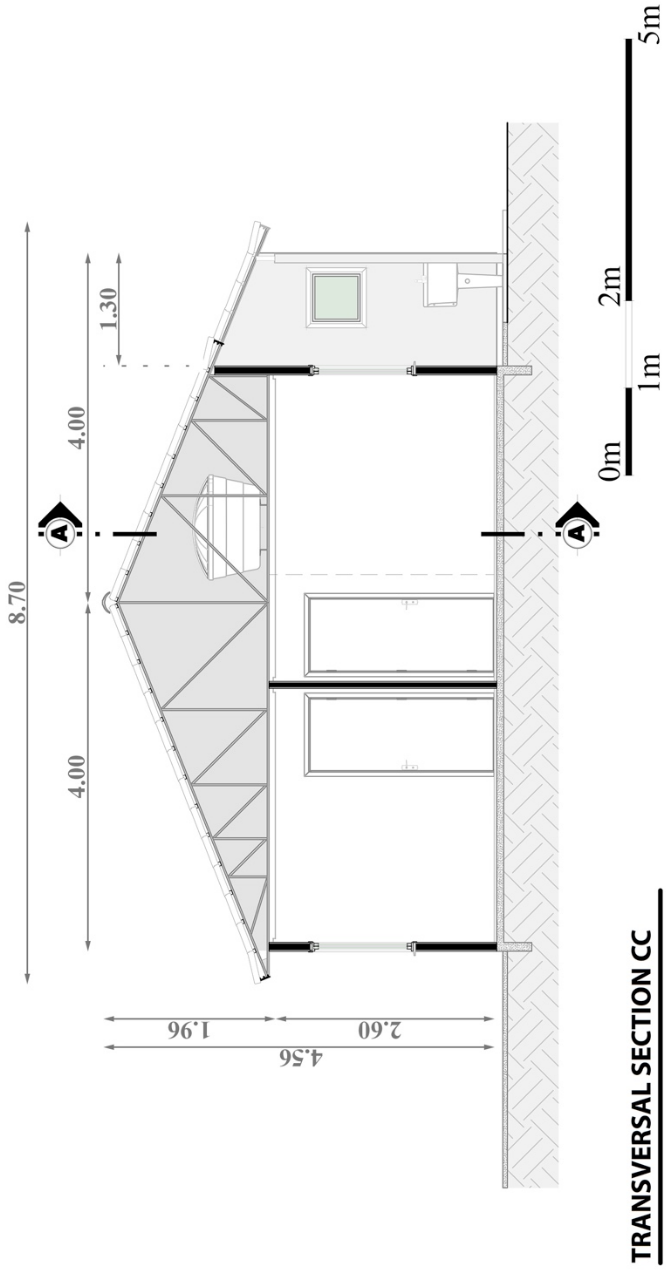


Figure A.8: Transversal Section CC

Appendix B

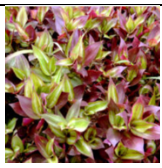
Suggested vegetal species for green roofs in Porto Alegre according to Ecotelhado (2018)

Table A.1 presents a list of vegetal species indicated for green roofs by Ecotelhado (2018), a Brazilian green roof company located in Porto Alegre.

Table A.1: Vegetal species indicated for green roofs in Brazil (Ecotelhado, 2018)

Zoysia japonica (Popular name: "Grama Esmeralda")	
	Family: *Poaceae*. Origin: Asia. Lower than 150mm height; develops well with direct solar radiation; perennial; low maintenance needed. Not indicated for places with intense use (transit), either for shadowed areas).
Asparagus densiflorus sprengeri (Popular name: "Aspargo")	
	Family: *Asparagaceae.* Origin: Africa. Size between 400 and 600mm; perennial; frequent watering – no waterlogging – and half shadow needed; multiplication by division of clumps and by seeds; cold tolerant.
Axonopus compressus (Popular name: "Grama São Carlos")	
	Family: *Poaceae*. Origin: Brazil. Lower than 150mm height; develops well with direct solar radiation or partially shaded; perennial; needs frequent irrigation and does not tolerate well dry-periods.
Arachis repens (Popular name: "Grama Amendoim")	
	Family: *Fabaceae*. Origin: Brazil. Size between 100 and 300mm; develops well with direct solar radiation and half shadow, perennial, no periodic pruning, not resistant to trampling; tolerates dry, but does not tolerate frost.

Bulbine frutescens (Popular name: “Bulbine”)	
	Family: *Asphodelaceae*. Origin: Africa. Size between 300 and 600mm; develops well with direct solar radiation and half shadow; perennial; frequent watering - no waterlogging; multiplication by division of clumps and seeds.
Callisia repens (Popular name: “Dinheiro em Penca”)	
	Family: *Commelinaceae*. Origin: Central and South America. Size between 50 and 250mm; Half shadow needed; perennial; frequent watering - no waterlogging; multiplication by division of rooted branches or cuttings.
Chlorophytum comosum (Popular name: “Clorofito”)	
	Family: *Agavaceae*. Origin: Africa. Size between 200 and 300mm; develops well with direct solar radiation and half shadow; perennial; frequent watering – no waterlogging; multiplication by division of clumps or seedlings formed in the inflorescences.
Clusia fluminensis (Popular name: “Clúsia”)	
	Family: *Clusiceae*. Origin: Native species of Brazilian SE and NE regions. Size until 6m; develops well with direct solar radiation and half shadow; perennial; frequent watering – no waterlogging; multiplication by cuttings, watering or seeds.
Plectranthus neochilus (Popular name: “Boldinho”)	
	Family: *Lamiaceae*. Origin: Mediterranean. Size between 300 and 900mm, with velvety leaves and bluish flowers; very resistant; easy propagation by cuttings, it develops better with direct solar radiation.
Lantana camara (Popular name: “Lantana”)	
	Family: *Verbenaceae*. Origin: Central and South America. Size between 900 and 1200mm; frequent watering – no waterlogging; cold tolerant; multiplication by cuttings and seeds.

Tradescantia zebrina (Popular name: "Lambari")	
	Family: *Commelinaceae*. Origin: North America. Size between 300 and 400mm; Half shadow needed; perennial; multiplication by cuttings; frequent watering – no waterlogging.
Sphagneticola trilobata (Popular name: "Vedélia")	
	Family: *Asteraceae*. Origin: Native species of Brazil. Size between 100 and 300mm; develops well with direct solar radiation and half shadow; perennial; multiplication by division of clumps; rustic – tolerates droughts and waterlogging.
Tradescantia zebrina purpurii (Popular name: "Lambari Roxo")	
	Family: *Commelinaceae*. Origin: Native species of Mexico. Size between 150 and 200mm; develops well with direct solar radiation and half shadow; frequent watering – no waterlogging; rustic; multiplication by cuttings and already rooted undergrowth.
Tropaeolum majus (Popular name: "Capuchinha")	
	Family: *Tropaeolaceae*. Origin: South America. Size between 100 and 300mm; develops well with direct solar radiation; frequent watering – no waterlogging; rustic; multiplication by seeds; edible plant.
Tulbaghia violacea (Popular name: "Alho Social")	
	Family: *Amaryllidaceae*. Origin: Southern Africa. Size between 400 and 600mm; perennial; develops well with direct solar radiation; perennial; regular watering – no waterlogging; multiplication by seeds; edible plant.
Verbena hybrida (Popular name: "Camaradinha")	
	Family: *Verbenaceae*. Origin: South America. Size between 100 and 300mm; develops well with direct solar radiation; moderate to moist (but don't use lack of water to control growth); multiplication by division of clumps and by seeds.

Appendix C

Suggested vegetal species for green roofs in Porto Alegre according to Backes (2018)

Popular Name	***Scientific Name***		**Family**
Origin	**Sun**	**Plant Coverage**	**Watering**
a. CRAWLING			
Alho social	*Tulbagia violaceae*		Amaryllidaceae
exotic	sun	middle	few
Alternantera roxa	*Alternanthera brasiliana var roxa*		Amaranthaceae
native	sun	middle	middle
Aspargo-comum	*Aspargus sprengeri*		Asparagaceae
exotic	sun to shadow	good	few
Beldroega-bicolor	*Portulaca oleracea*		Portulacaceae
exotic	sun	good	few
Boldo-anão / boldo-gambá	*Plectranthus neochilus*		Lamiaceae
exotic	sun	optimum	few
Bulbine	*Bulbine frutescens*		Xanthorrhoeaceae
exotic	sun	optimum	few
Carpobrothus / garra de leão	*Carpobrothus edulis*		Aizoaceae
exotic	sun	optimum	few
Clorofito	*Chlorophytum comosum*		Asparagaceae
exotic	half shadow	middle	middle
Coreópsis	*Coreopsis lanceolata*		Asteraceae
exotic	sun	optimum	middle
Dinheiro-em-penca	*Callisia repens*		Commelinaceae
exotic	sun	optimum	middle

Popular Name	***Scientific Name***		**Family**
Origin	**Sun**	**Plant Coverage**	**Watering**
a. CRAWLING			
Grama-amendoim	*Arachis repens*		Fabaceae
exotic	sun	optimum	few
Grama-preta	*Ophiopogon japonicus*		few
exotic	half shadow to shadow	optimum	middle
Helxine/Tapete-Inglês	*Polygonum capitatum*		Polygonaceae
exotic	sun	good	few
Hemigraphis roxa	*Hemigraphis alternata*		Acanthaceae
exotic	sun to half shadow	good	middle
Hera verde	*Hera canariensis*		Hederaceae
exotic	shadow	middle	middle
Kalanchoe	*Kalanchoe tubiflora*		Crassulaceae
exotic	sun	middle	middle
Kalanchoe fantasma	*Kalanchoe fedtschenkoi*		Crassulaceae
exotic	sun	good	middle
Lantana lilás	*Lantana fucata*		Verbenaceae
native	sun to half shadow	middle	middle
Peperomias diversas	*Peperomia spp*		Piperaceae
native/exotic	sun to half shadow	middle	middle
Plectranthus diversos	*Plectranthus spp*		Lamiaceae
exotic	sun to half shadow	middle	middle

Popular Name	*Scientific Name*		Family
Origin	**Sun**	**Plant Coverage**	**Watering**
a. CRAWLING			
Portulaca rosa	*Lampranthus productus*		Aizoaceae
exotic	sun	good	few
Portulaca-grandiflora	*Portulaca grandiflora*		Portulacaceae
exotic	sun	good	few
Portulaca-grauda	*Portulaca sp.*		Portulacaceae
exotic	sun	middle	few
Rosinha-do-sol	*Aptenia cordifolia*		Aizoaceae
exotic	sun	optimum	few
Rosinha-do-sol variegata	*Aptenia cordifolia*		Aizoaceae
exotic	sun	middle	few
Ruellia roxa	*Ruellia squarrosa*		Acanthaceae
exotic	sun to half shadow	optimum	middle
Sedum-amarelo	*Sedum multiceps*		Crassulaceae
exotic	sun	optimum	few
Sedum-branco	*Sedum sp.*		Crassulaceae
exotic	sun	middle	few
Sedum-vermelho	*Sedum rubrotinctum*		Crassulaceae
exotic	sun	middle	few
Tibouchina rasteira	*Schizocentrum elegans*		Melastomaceae
native	sun	good	middle
Tradescantia zebrina	*Tradescantia zebrina*		Commelinaceae
exotic	sun to half shadow	optimum	middle
Tradescantia-roxa	*Setcreasa purpurea*		Commelinaceae
exotic	sun to shadow	good	few
Turnera	*Turnera subulata*		Turneraceae
native	sun	good	middle
Violeta rasteira	*Viola hederacea*		Violaceae
exotic	half shadow	good	middle

Popular Name	***Scientific Name***		**Family**
Origin	**Sun**	**Plant Coverage**	**Watering**
a. CRAWLING			
Vinca verde	*Vinca minor*		Apocynaceae
exotic	half shadow	good	middle
Zefirantes - lírio dos ventos	*Zephyranthes candida*		Amaryllidaceae
native	sun	middle	few
b. LAWNS AND GRASSES			
Grama-coreana	*Zoysia tenuifolia*		Poaceae
exotic	sun	optimum	few
Capim barba de bode	*Aristida jubata*		Poaceae
native	sun	middle	few
Capim - chorão	*Eragrostis curvula*		Poaceae
exotic	sun	middle	few
Grama-de-campo	*Espécies diversas*		Poaceae
native	sun	optimum	middle
Grama-batatais	*Paspalum notatum*		Poaceae
native	sun	optimum	middle
Grama-bermuda	*Cynodon dactylon*		Poaceae
exotic	sun	optimum	middle
Grama-esmeralda	*Zoysia japonica*		Poaceae
exotic	sun	optimum	middle
Grama-sempre-verde	*Axonopus compressus*		Poaceae
native	sun	optimum	intense
Pennisetum-rubro	*Penissetum setaceum cv. rubrum*		Poaceae
exotic	sun	regular	middle
Pennisetum verde	*Penissetum setaceum*		Poaceae
exotic	sun	regular	middle
c. BUSHES			
Agapanto	*Agapanthus africanus*		Amaryllidaceae
exotic	sun	regular	middle

Popular Name	Scientific Name		Family
Origin	Sun	Plant Coverage	Watering
c. BUSHES			
Agave atenuata	*Agave attenuata*		Asparagaceae
exotic	sun	low	few
Alecrim	*Rosmarinus officinalis*		Lamiaceae
exotic	sun	low	middle
Babosa-arborescens	*Aloe arborescens*		Xanthorrhoeaceae
exotic	sun	low	few
Euriops	*Euryops chrysanthemoides*		Asteraceae
exotic	sun	middle	middle
Filodendro rasteiro	*Philodendron renauxii*		Araceae
native	sun to half shadow	middle	middle
Iris japonica franjada branca	*Iris japonica*		Iridaceae
exotic	sun	good	middle
Lavanda dentada	*Lavandula dentata*		Lamiaceae
exotic	sun	regular	middle
Liriops-variegata	*Liriope muscari*		Asparagaceae
exotic	sun	good	middle
Liriops-verde	*Liriope muscari*		Asparagaceae
exotic	half shadow	good	middle
Neomarica candida	*Neomarica candida*		Iridaceae
native	half shadow	good	middle
Pereskia ora-pro-nobis varieg	*Pereskia goddseffiana*		Cactaceae
native	sun	good	few
Pilea aluminio	*Pilea cadierei*		Urticaceae
exotic	half shadow	good	middle
Russélia	*Russelia equisetiformis*		Plantaginaceae
exotic	sun	regular	middle

Popular Name	***Scientific Name***		**Family**
Origin	**Sun**	**Plant Coverage**	**Watering**
d. SPECIES BEING TESTED			
Diodia saponariifolia	*Diodia saponariifolia*		Rubiaceae
–	sun	optimal	middle
Periquito de praia	*Alternanthera maritima*		Amaranthaceae
–	sun	middle	middle
Violeta do campo	*Angelonia integerrima sprengel*		Plantaeginaceae
–	sun	middle	middle
Grama amendoim-vermelha	*Indigofera campestris*		Fabaceae
–	sun	high	few
Evolvulus do cerrado	*Evolvulus nummularius*		Convolvulaceae
–	sun	middle	middle