COMPARATIVE ANALYSIS OF WALL MATERIALS FOR THEIR OPERATIONAL ENERGY PERFORMANCE IN URBAN MID-RISE RESIDENTIAL BUILDINGS: A SIMULATION-BASED STUDY IN ISTANBUL

A Thesis Submitted to The Graduate School of Engineering

and Science of Bilkent University in partial fulfillment of the

requirements for

the degree of

Master of Science

in

Architecture

By

Gülce Erincik

May 2024

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May 2024

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ABSTRACT

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As urbanization continues to drive a substantial share of global energy consumption and carbon emissions, mitigating the environmental footprint of residential buildings in urban areas becomes imperative. Although there are numerous studies focused on designing low embodied-carbon construction materials to mitigate the carbon footprint of the construction industry, there is a significant gap regarding the applications and operational performance of these alternative materials in urban environments, which results in low demand for them in the current construction market. This study focuses on evaluating the operational performance of low embodied-carbon alternative materials when they are used in mid-rise residential building envelopes in urban environments, with a particular emphasis on the energy consumption of buildings for achieving occupant thermal comfort. The study commences with a literature review of low embodied-carbon materials suitable as an infill material for exterior walls, followed by simulation-based assessments using Rhino-Grasshopper and OpenStudio software to compare the operational energy performance of the alternative materials against the conventional materials in Istanbul,

Turkey. The results present the operational performance of the materials considering the local factors such as urban morphology and urban weather of the case study site in Istanbul. They also highlight possible improvements needed for some alternative materials to achieve or exceed the operational performance of conventional envelope materials. Hence, this research provides insights for architects, policymakers, and construction industry professionals by identifying materials with significant sustainability potential for urban environments and emphasizing the need for context-specific adaptations of them. It addresses a critical gap in the literature on the operational phase of low-embodied carbon construction materials and developing low-carbon residential architecture in urban environments.

Keywords: Low-carbon materials, Operational performance, Thermal comfort, Building energy modeling, Residential buildings, Envelope design

ÖZET

KENTSEL ORTA KATLI KONUT BİNALARINDA DUVAR MALZEMELERİNİN OPERASYONEL ENERJİ PERFORMANSLARI YÖNÜNDEN KARŞILAŞTIRMALI ANALİZİ: İSTANBUL'DA SİMÜLASYON TABANLI BİR ÇALIŞMA

Gülce Erincik
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Mayıs 2024

Kentsel alanlar, küresel enerji tüketiminin ve karbon emisyonlarının önemli bir bölümünü oluşturmaya devam ederken, inşaat endüstrisinin büyük bir yüzdelik dilimini oluşturan konut yapılarının çevresel ayak izlerini hafifletmek büyük önem kazanmıştır. İnşaat endüstrisinin karbon ayak izini azaltmak amacıyla, düşük gömülü karbon emisyonlarına sahip yapı malzemeleri tasarımına odaklanan pek çok çalışma yapılmasına rağmen, bu alternatif malzemelerin kentsel ortamlarda uygulanmaları ve operasyonel performansları konusunda literatürde önemli bir boşluk bulunmaktadır. Alternatif malzemelerin uygulama ve kullanım süreçlerine dair bu boşluk, mevcut inşaat piyasasında bu malzemelere olan talebin düşük olmasına neden olmaktadır. Bu tez, kentsel ortamlarda düşük gömülü karbon alternatif malzemelerin operasyonel performansını değerlendirmeye odaklanır ve binalarda kullanıcı termal konforunu sağlamak için tüketilen enerji miktarını dikkate alır. Çalışma, taşıyıcı olmayan dış duvarlar için dolgu malzemesi olarak kullanılabilecek düşük gömülü karbonlu malzemelerin literatür taraması ile başlar. Ardından, İstanbul'da kullanılabilecek alternatif malzemelerin operasyonel enerji performanslarını, geleneksel olarak kullanılan duvar dolgu

malzemeleri ile Rhino-Grasshopper ve OpenStudio yazılımlarını kullanarak karşılaştırır. Sonuçlar, malzemelerin operasyonel performansını, İstanbul'daki vaka çalışması alanının kentsel morfoloji ve kentsel iklim gibi özelliklerini göz önünde bulundurarak sunmaktadır. Ayrıca, elde edilen sonuçlar, incelenen bazı alternatif malzemelerin operasyonel performanslarını geleneksel malzemelerin performansına ulaştırmak için gerçekleştirilebilecek adımlara da işaret eder. Bu nedenle, bu araştırma, kentsel ortamların sürdürülebilirliğine katkıda bulunabilecek potansiyele sahip malzemeleri belirleyerek ve bu malzemelerin yere özgü adaptasyonlarının önemini vurgulayarak, mimarlar, politika geliştiriciler ve inşaat endüstrisi çalışanlarına öngörüler sunar. Çalışma, düşük gömülü karbon yapı malzemelerinin operasyonel süreçleri ve kentsel ortamlardaki konut mimarisinin sürdürülebilirlik yönünden geliştirilmesi üzerine literatürdeki kritik bir boşluğa cevap verir.

Anahtar kelimeler: Düşük gömülü karbon materyaller, Operasyonel performans, Termal konfor, Bina enerji modellemesi, Konut yapıları, Kabuk tasarımı

ACKNOWLEDGMENTS

First and foremost, I would like to express my deepest gratitude to my advisor, Assistant Prof. Aysu Berk Haznedaroğlu, for her invaluable guidance, encouragement, and support throughout this research. Her insights were instrumental in shaping the quality of this thesis, and her unwavering trust in me has been a cornerstone of my academic journey.

I would also like to thank the members of my thesis committee, Assistant Prof. Zühre Sü Gül and Prof. Dr. İpek Gürsel Dino, for their constructive and multifaceted feedback. Their expertise and critical evaluations provided me with new perspectives and greatly enriched the overall quality of my research.

I am deeply grateful to all the professors in the M.Sc. program at the Department of Architecture at Bilkent University for generously sharing their knowledge and perspectives through their distinctive courses. Their dedication to teaching has not only improved my academic abilities and understanding of architecture but also inspired me to pursue versatility and innovation in my thesis.

Last but not least, I extend my heartfelt thanks to my parents and little sister for their love, care, and encouragement, which enabled me to pursue my curiosity about the world. To my grandparents, thank you for being role models in appreciating the world, following one's passions, and persevering through hardships. Finally, I would like to express my gratitude to all the sincere, hardworking, and passionate people I have met to this day. Every good thing relies on the contributions of many others.

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CHAPTER 1

INTRODUCTION

Buildings interact with the environment in their construction, use, and demolition phases by consuming or transforming resources. Renewable energy applications and embodied carbon strategies control the type of resources a building consumes. On top of that, passive design methodologies reduce the consumption of resources. A healthy and efficient architectural design requires a collective knowledge of the resource-consuming activities of a building, occupants' experience and needs, and possible passive design solutions. Our cities, which were essential for the acceleration of cultural and scientific progress back in time and still are home to many social and economic constructions of humanity, require such collective knowledge to overcome the ecological problems that they cause today.

1.1 Problem Statement

The built environment is a tangible result of typical human behavior, in which humans transform natural resources and habitats into something else according to their needs and conscious decisions. The need is sheltering when it comes to architecture. On the other hand, the construction and utilization processes of this shelter may vary tremendously according to the available resources and decisions of the user. Being in a core position between natural resources and the built environment, construction processes have effects on a diverse range of fields such as ecology, economy, human health, and social behaviors. This diverse spectrum that the construction industry is intertwined with

necessitates a high level of consciousness when deciding how to build and the answer always evolves following our timely behavioral patterns and level of scientific knowledge.

The question of how to build more ecologically and healthier has become of vital importance today. Our cities consume enormous natural resources and energy while being constructed, operated, and demolished. The waste of such consumption accumulates way more quickly than it returns to ecological cycles, and some of them continue to pollute natural resources as they decompose. Inefficiently designed buildings consume high levels of nonrenewable energy and contribute to urban heat islands and air pollution in dense urban environments throughout their operational phases, threatening the health of human and non-human occupants.

Material selection has a central role in solving widespread problems related to the whole lifetime of a building, namely the construction, operation, and demolition phases. There are many studies in the literature that focus on designing low-embodied carbon construction materials, which might significantly ameliorate the negative effects of the construction and demolition phases of buildings on ecological cycles. While these developments can not be underestimated, studies focusing on the implementation and operation of these materials are also necessary to utilize them in the construction industry in a widespread manner. A betterment in the operational phases of buildings in our urban environments, by implementing low-embodied carbon materials, can ameliorate resource consumption, carbon emissions, and occupant health and comfort in our urban centers.

1.2 Aim and Scope of the Thesis

This study examines the possibility of ameliorating the operational performance of a building, specifically the mid-rise residential buildings in Istanbul's dense urban environments, by utilizing low-embodied carbon infill materials in the curtain walls. While the low-carbon materials are already beneficial in terms of construction and demolition phases, their effect on the operational phase of a building requires further investigation. While exterior wall materials are highly effective on the thermal conditions of a building, thermal conditioning has the biggest share in the annual energy

consumption of residential buildings. Therefore, the operational performance of the infill materials was represented by annual energy consumption for space conditioning.

This thesis aims to answer four main questions. First, what is the operational performance of low-embodied carbon alternative materials in comparison to the materials that we conventionally use in Istanbul? Second, what is the role of the exterior wall infill materials as a passive design method supporting HVAC systems in mid-rise residential buildings? Third, what is the relationship between the exterior wall U-value and the annual energy consumption of a mid-rise residential building in Istanbul? Lastly, what is the existing residential building stock in Istanbul like, and how can we represent them in a Building Energy Modeling (BEM) environment? In the conducted simulations, representing the urban morphology and urban climate of the selected case study area in Istanbul was an important step for the locality of the results. Hence, the questions of how to represent the urban morphology and the local urban microclimate were also answered throughout the methodology.

This study adopts simulation methodology to estimate the energy consumption levels necessary to achieve interior thermal comfort for each low-embodied carbon material and compares them to the more conventional wall materials in urban environments. To achieve this, the study conducts analysis and simulations both on urban and building levels. More specifically, the urban morphology and the current building stock are represented at the urban scale part of the study, first to estimate the urban microclimate of the selected area and second to enrich the case study building data to represent the majority of the existing building stock in Istanbul. Subsequently, the building-level simulation was conducted with the inputs from urban-level analysis and simulations. OpenStudio was preferred as the simulation environment for building-level simulations. The building-level simulation outputs are exported and compiled in R[1] to compare the operational performance of conventional and alternative materials. Operational performance is represented by the annual energy consumption necessary for the thermal conditioning of the interior spaces, which is distinguishably the most energy-consuming activity in residential buildings and is closely related to the materiality of curtain walls. In

[1] Programming language and interface for data compilation, statistical analysis, and data visualization.

a broader scope, this study aims to contribute to the ongoing scientific field of implementation of low-carbon alternative materials with a focus on energy efficiency and occupant comfort in urban environments.

1.3 Structure of the Thesis

This thesis is divided into six chapters. The first chapter briefly covers the problem statement, aim, scope, and structure of the thesis. The second chapter provides information on basic terminology related to architectural climatology, the carbon footprint of built environments, building energy simulation, and the software used in this thesis. The third chapter includes a literature review focusing on two main topics: the environmental impact of urban environments and infill materials for the exterior walls of mid-rise residential buildings in Istanbul. This chapter explains the relationship between the urban-scale carbon footprint, residential building stock, and envelope materials, while also introducing the alternative and conventional infill materials selected for the simulations in this study. The fourth chapter explains the overall workflow of this study, including the data collection, compilation, simulation design, and processing of the simulation outputs. The fifth chapter presents the results of the study with all the preliminary steps and compiled outputs of the simulations, showcasing the comparisons between conventional exterior wall infill materials and low-embodied carbon alternatives in terms of interior climate conditions and operational energy performance. The sixth chapter emphasizes the major findings of this study and shares insights for future studies.

CHAPTER 2

RELATED RESEARCH TERMINOLOGY

This chapter presents the terminology that the scope of this study formed around. Some of the terminology explained below was used directly in the thesis body, while some of them were included in this chapter because they have a complementary role to the terminology commonly used in the thesis. The related research terminology was presented under four titles, namely “Terminology Related to Architectural Climatology and Building Efficiency”, “Terminology Related to Building Simulation”, “Terminology Related to Carbon Footprint”, and “Software and Computational Tools Used”. These four titles come together to construct the field of study at the intersection of climatology, carbon emissions, and relevant simulation tools in relation to architecture, reflecting the scope of this thesis with introductory information.

2.1 Terminology Related to Architectural Climatology and Building Efficiency

When we look into nature, the nests of living creatures provide them with the necessary comfort conditions throughout the year without producing waste. All the living beings that need shelter build their shelter on their own with the ability to ensure their comfort. Humans also had achieved this for centuries when their shelters were built with local materials and techniques, which were developed over thousands of years. However, today, most contemporary housings are far from achieving occupant comfort without any HVAC system, or sometimes, with an HVAC system, causing high levels of energy consumption. The formed gap between rapidly developing technologies and society's

experience has depleted us of the ability to construct comfortable and efficient urban areas and homes. To fill this gap, the field of climatology in architecture which examines the thermophysical interactions between exteriors, building layers, interiors, and the human body started to attract attention. Some of the terminology focusing on these interactions and their measurements in the field of architecture are presented below with introductory information.

Thermal Comfort: Thermal comfort in architectural studies refers to human thermal comfort as a result of the thermal interactions between the human body and its environment (ASHRAE Technical Committees, Task Groups, and Technical Resource Groups, 2021). Figure 1 summarizes these interactions, which are mostly used as inputs in mathematical models of thermal comfort. Thermal comfort is “the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation” (ASHRAE Standing Standard Project Committee 55, 2020). This assessment of comfort involves a cognitive process shaped by various factors such as physiological, physical, and psychological elements. However, with human biological needs, “comfort occurs when body temperatures are held within narrow ranges, skin moisture is low, and the physiological effort of regulation is minimized”. There are several mathematical models to define and quantify thermal comfort to make it measurable for comparison of design options. The two most well-known models are Fanger's Thermal Comfort Model (PMV-PPD Model) and the Adaptive Comfort Model. The main difference between them is the evaluation method of the results of their thermal comfort equations. Fanger's Thermal Comfort Model aims to obtain a precise range of thermal quantities that provides a “neutral sensation” to occupants. The Adaptive Comfort Model does not specify precise temperature and humidity ranges for comfort but takes into account that people can adapt and feel comfortable in a broader range of conditions (ASHRAE Standing Standard Project Committee 55, 2020).

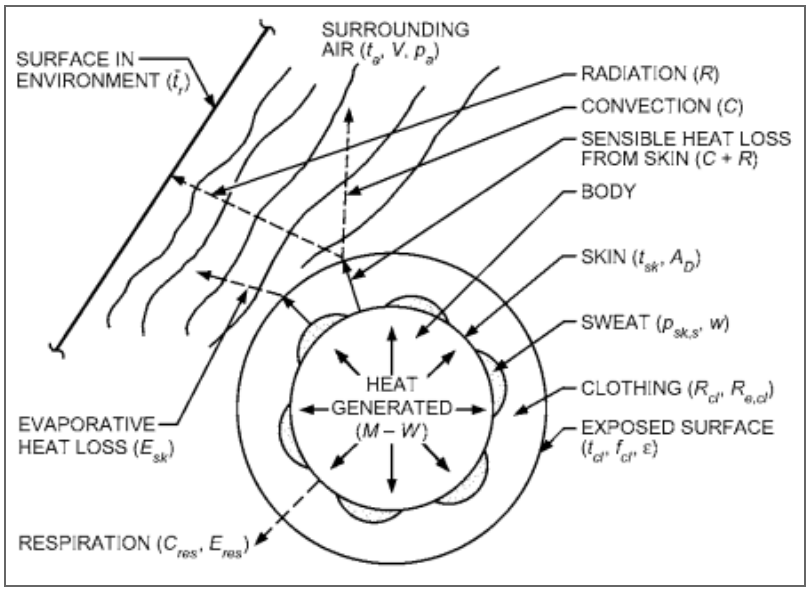


Figure 1. Thermal Interaction of Human Body and Environment (ASHRAE Technical Committees, Task Groups, and Technical Resource Groups, 2021)

Building Energy Modeling (BEM): Building energy modeling refers to the process of creating representations or simulations of a building to optimize energy performance, improve sustainability, and make informed decisions in the design, construction, operation, and demolition phases of a building. These models are used to analyze and predict how different factors impact a building's energy efficiency, renewable energy production, CO2 emissions, operational cost, and the comfort level of occupants. Since the energy efficiency of a building can be influenced by so many independent and interdependent factors, a nearly exact calculation of energy consumption requires too many detailed inputs. However, a lower number of inputs with a lower level of detail might be enough to obtain the necessary results to represent and evaluate a building's performance in parallel with the goals of a study. Hence, each model requires a different combination of inputs following its specific goal. This flexibility of inputs puts the responsibility on the researcher to represent the built environment in the correct level of detail for the accuracy of the results. One method for this issue is to conduct energy models in two phases. First, the calibration of the model is provided by obtaining values comparable with real-world observations and measurements. Then the calibrated model runs again for the intended results of the study. The most widely adopted inputs to energy

models consist of building geometry, facade configurations, envelope sections, construction materials, daylighting, weather data, HVAC systems, renewable energy systems, occupancy schedules, and physics equations that are generally embedded inside simulation software. Most of these factors influence the interior climate of a building, affecting its annual energy consumption for space conditioning. Figure 2 presents an envelope section and its interactions with interior and exterior climate.

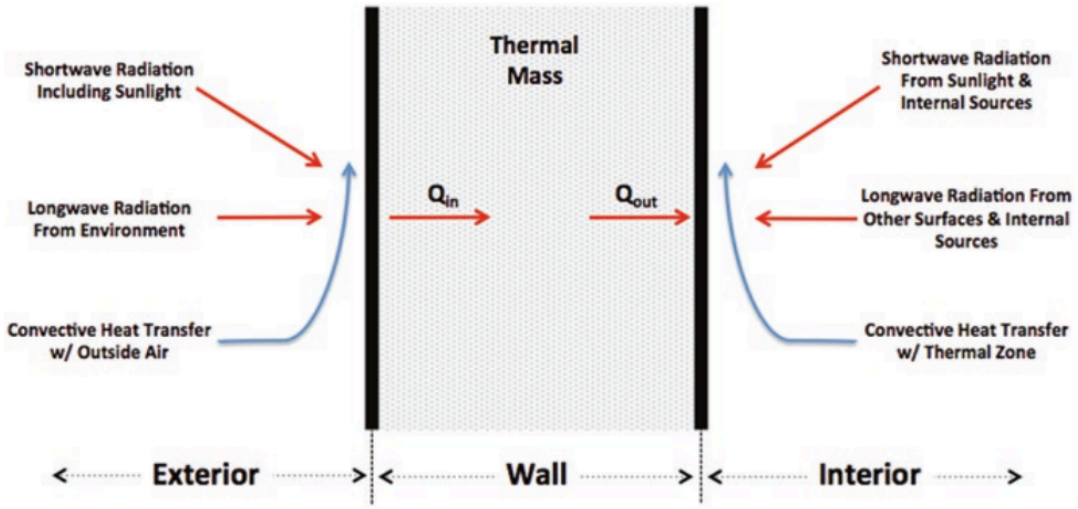


Figure 2. Schematic of thermal interactions between a building's envelope and interior climate (Brackney et al., 2018).

Microclimate: Microclimate is a volume of atmosphere that is differentiated from the macroclimate by the effect of regional factors. Hence, microclimate is called regional climate in some written resources. Building activities such as the localization of industries, communications networks, and airports influence the original macroclimate at the regional level (RYD, 1971). RYD explains that "regional climate", especially in urban areas, is determined by the location of heat and pollution resources such as industries, motor vehicles, airports, and physical regional planning taking into account the prevailing direction of the wind and precipitation. Besides the urban scale regional differentiation, RYD also states that the urban climate changes "in the immediate vicinity of buildings", which resembles a "climatological sheath" around buildings separating and transforming the climate between the indoors and outdoors, as a result of buildings' orientation, structure, and materials. The interplay between buildings and climate persists under the

effects of many factors, forming a unique microclimate. Numerous mathematical models exist to estimate microclimates considering the local factors related to the built environment and the prevailing macroclimate.

Urban Heat Island (UHI): An urban heat island is an urban area that has higher temperatures than its surroundings. The urban heat island is generally detected by measuring "the difference in daily maximum temperature between the urban center and suburban sites ($\Delta T_{u\text{-}s}$) and between the urban center and exurban sites ($\Delta T_{u\text{-}e}$)" (Tan et al., 2010). This temperature difference is primarily caused by the disruptive effect of urban morphologies on air flows and the increased building densities that retain heat, inhabiting the natural urban cooling (Tsoka et al., 2020). Figure 3 presents the climate layers over a typical city center, while Figure 4 shows how air temperatures vary according to the building heights and density. The Urban Heat Island (UHI) effect becomes more perceivable with increased health problems, air pollution, and energy usage in city centers in correlation with climate change since urban cooling gets more challenging with higher initial temperatures (Tan et al., 2010). This increased level of difference in climate conditions between city centers and rural areas mandates the consideration of the UHI effect when conducting research that uses weather data.

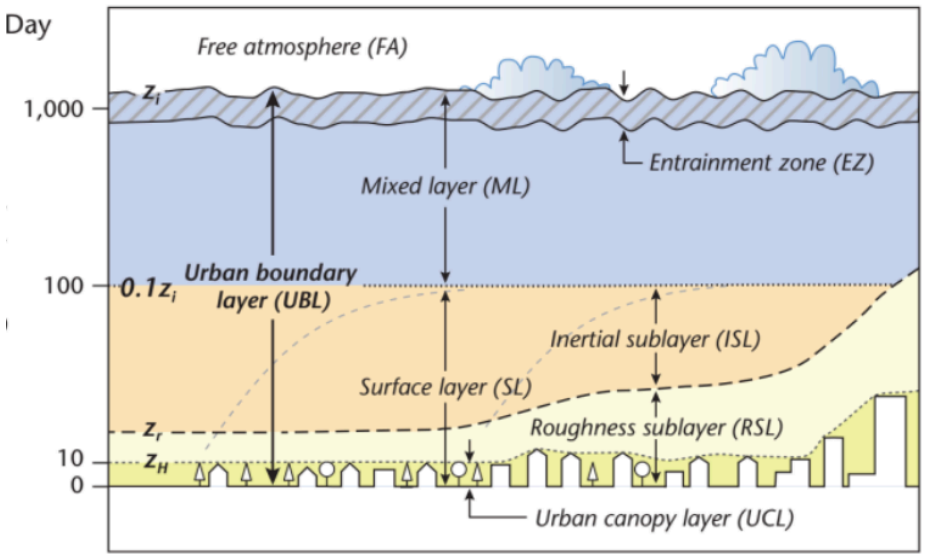


Figure 3. Schematic of typical layering of the atmosphere over a city (Oke et al., 2017).

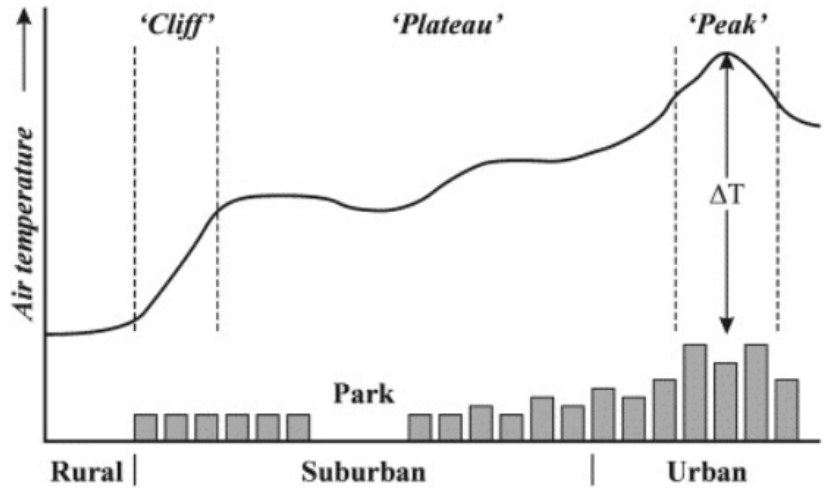


Figure 4. Cross-section of a typical UHI after sunset (Unger et al., 2001).

Urban Building Energy Modeling (UBEM): Urban Building energy modeling refers to the process of creating representations or simulations of buildings at the urban scale to optimize the energy performance of the built environment, improve outdoor occupant comfort and health, and make informed decisions on both building and urban scale. The goals of UBEMs can be summarized as improving natural ventilation and daylighting indoors and outdoors, improving energy efficiency by urban transformations, deciding the amount and location of green areas, and conducting life cycle assessments at the urban scale (Ferrando & Causone, 2019). The most widely adopted inputs to urban energy models consist of buildings' geometry and configuration, facade configurations, surface materials, plant coverage, weather data, HVAC systems, occupancy schedules, and motor vehicle traffic. The physics equations are generally embedded inside simulation software. UBEMs sometimes require considering the urban heat island effect on weather data, which is triggered by dense urban texture and high levels of occupant activity for higher accuracy.

2.2 Terminology Related to Building Simulation

Designing and running building energy simulations requires familiarity with a wide pool of terminology. In this section, some of the terminologies that are also effective in the methodology of this thesis were presented with introductory information. Although

different simulation software might use other names for certain simulation inputs and outputs, the terminologies below are the fundamental ones having similar counterparts in most simulation environments.

Data Enrichment: Data enrichment is the process of enriching the already available urban data with additional resources. Enrichment content aligns with the specific input requirements of the simulation that is going to be conducted. The available data, especially at the urban scale, is mostly very limited. This situation requires enriching the available data methodologically since the outcomes of the simulations are highly dependent on the inputs and the simulation design. To increase the reliability of enrichment processes, some studies developed methodologies that use urban data formats suitable to enrich, such as CityGML, and another format for the altered version, EnergyADE in the case of CityGML (Geiger et al., 2019).

Weather File: Beausoleil-Morrison (2021) defines the weather as the state of the atmosphere. The weather file includes data regarding the observations and interpolations of wind speed, cloud cover, and solar radiation (Beausoleil-Morrison, 2021, 127-142). These observations are mainly obtained via satellites or weather stations located in airports. Weather files can vary according to the source and the time steps of observations even for the same location. While the weather file is meant to represent the boundary conditions of buildings, the accuracy of building energy simulations relies on the accurate representation of these boundary conditions. As a result, the conscious decision of the designer in terms of weather file selection is critical for valid estimations of building performance and occupancy comfort levels.

Thermal Zone: A thermal zone is an area assumed thermally homogeneous when representing it to the simulation software. Dividing a building into thermal zones in a simulation environment is called zoning of a building. Borders of a thermal zone generally overlap with the physical borders of an architectural space. However, the zoning of a building can differ according to the intended level of detail of the simulation results, spatial aspects, and occupancy scenarios of a building.

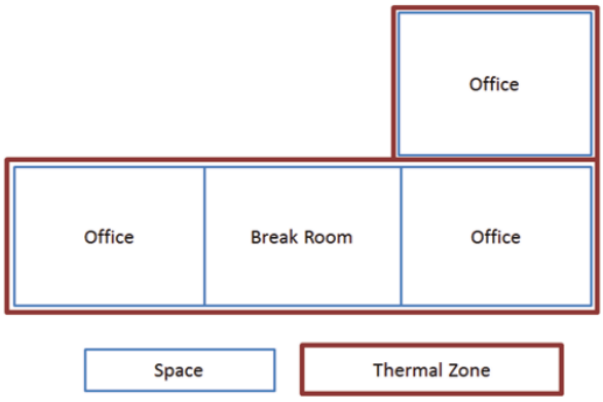


Figure 5. Zoning Example with two Thermal Zones with one or more spaces (Brackney et al., 2018).

A thermal zone can consist of a portion of a large space, a single room, a grouping of rooms, or the entire building (Beausoleil-Morrison, 2021, 33-55). An example of zoning with different zone sizes is presented in Figure 5. Some rules of thumb for zoning might be listed as the similarity of external boundary conditions in terms of facade design and orientation, proximity or connectedness of spaces, similarity of space sizes, variations in internal loads, and controllability (Brackney et al., 2018, 103-126). Although connectivity is not a must for spaces to be in the same thermal zone, discrete rooms are less likely to be similar to each other in terms of thermal conditions. Another rule of thumb is that the variations in internal thermal loads are mostly formed according to the occupancy schedules. More specifically, how a building is being used determines the internal thermal loads that are effective on the interior thermal conditions. The last rule of thumb, controllability, means the separate conditioning of rooms. For example, in a hospital, there might be adjacent and same-oriented rooms with similar occupancy schedules. However, if one of those rooms needs to be a little colder than the other for technical reasons, they need to be located in separate thermal zones for controllability.

Operating Schedule: Schedules define the occurrence pattern of activities at certain intervals. A schedule might show the circadian or seasonal behavior of lighting, occupancy, internal equipment, and appliances that are effective on the internal thermal loads of a building (ASHRAE Technical Committees, Task Groups, and Technical Resource Groups, 2021, 482-495). Some thermal simulation software provides generic

schedules for widespread building uses such as office buildings, residential apartments, or commercial stores. These generic schedules can also be adjusted by hand according to the differentiated activities of buildings, saving the designer from entering the periodic intensity of each internal load one by one.

HVAC System: HVAC stands for heating, ventilation, and air-conditioning. HVAC systems can vary greatly between buildings. Some HVAC systems use air to condition the interior of a building. These systems heat, cool, or dehumidify directly the intake air. Another type of HVAC uses air only for ventilation and conditions the interior “using radiators, radiant floors, chilled beams, heat pumps, fan-coils, or other hydronic devices located within the occupied spaces”. (Beausoleil-Morrison, 2021, 281-304) An example HVAC system schematic conditioning two thermal zones is presented in Figure 6. HVAC systems use energy to condition spaces. Architectural simulation software generally provides two main outcomes. The first is the values that show if the selected HVAC system provided the aimed range of comfort of the space for the occupant. The second is the values that show the energy levels consumed to provide the intended range of occupant comfort. These two outcomes are used to represent the fitness of the selected HVAC system and the efficiency and comfort level of the architectural design. Hence, the correct modeling of the HVAC system to the simulation software carries great importance for the accuracy of the simulation results.

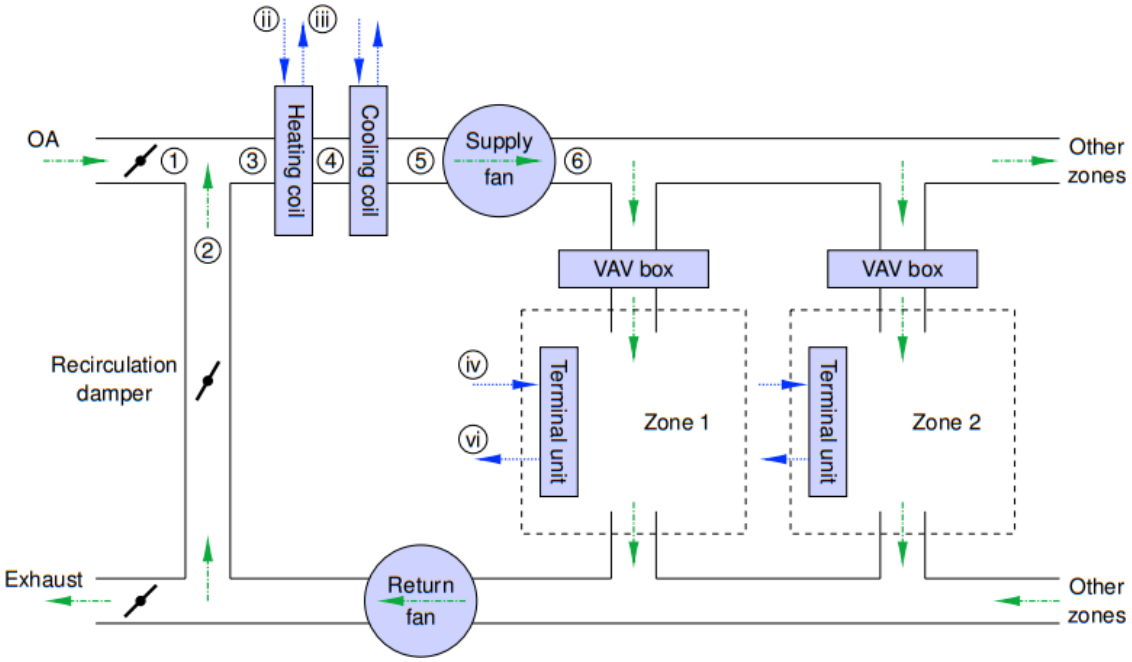


Figure 6. Schematic representation of an example HVAC system with a space of two thermal zones (Beausoleil-Morrison, 2021).

2.3 Terminology Related to Carbon Footprint

Carbon footprint is “the total amount of greenhouse gas emissions (GHG)” (Augusto Morini et al., 2019) and is a scale for the global warming potential (GWP) of an activity or product (Roberts et al., 2020). The unit for carbon footprint is kgCO2e/m2 or kgCO2e/m3 representing the GWP of different phases of a building's life (Sturgis et al., 2017). Although the units utilized are highly similar in most cases, calculation methods of carbon footprint have some diversity worldwide. One method considers the emitted carbon dioxide alone. Another method considers the six gasses identified by the Kyoto Protocol, namely the CO2, CH4, N2O, HFCs, PFCs, and SF6. The third and the most popular one considers the impacts of each GHG gas by using the GWP of gasses expressed in units of kilograms of carbon dioxide equivalent (kg-CO2e) (Fenner et al., 2018).

The EN 15804, the European standard for the sustainability of construction works, divides the whole life cycle of a building into five main stages, i.e. the Product Stage, the Construction Process Stage, the Use Stage, the End Of Life Stage, and the Beyond The

Construction Works Life Cycle Effects with the substages shown in Figure 7. (Sturgis et al., 2017) The carbon footprint of a design decision is generally discussed under two titles, namely the embodied carbon footprint and operational carbon footprint, which are calculated by analyzing the carbon emissions in different life cycle stages of a building. Both are vital for an efficient and sustainable built environment. While Product, Construction, In Use, and End of Life stages were presented under Embodied Carbon in Figure 7, Operational Carbon consists of B6 and B7 substages, which are Operational Energy and Operational Water.

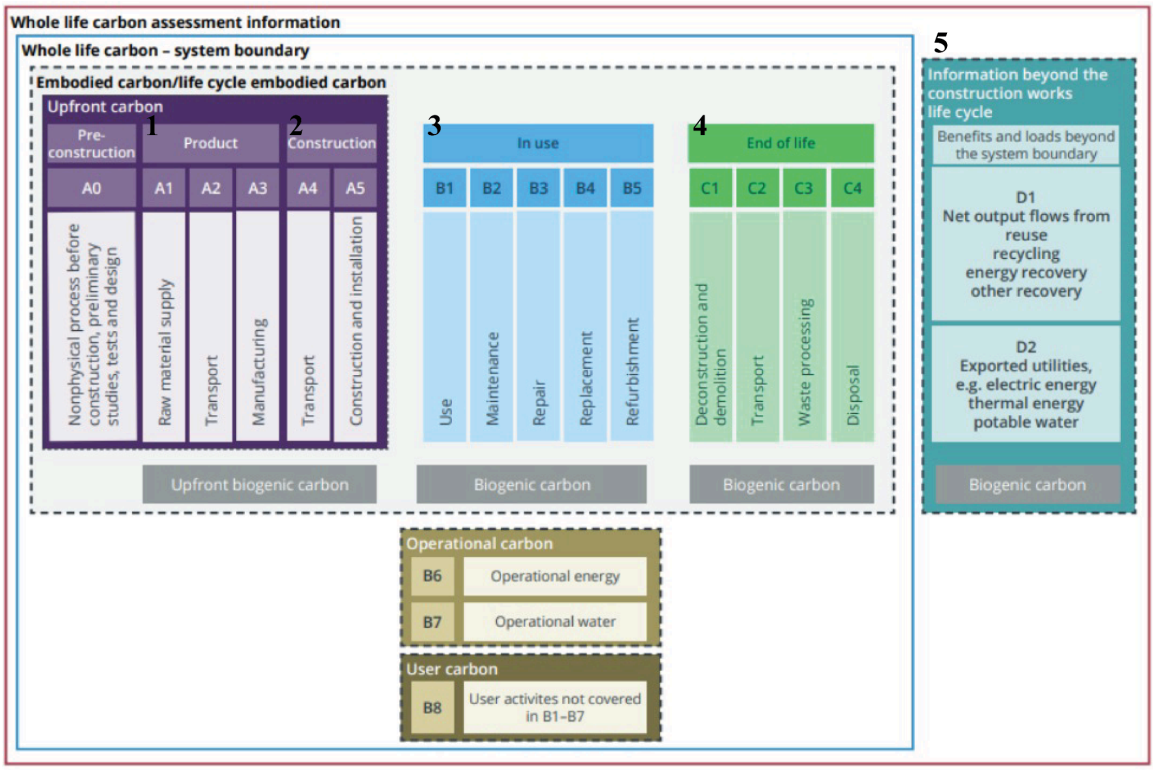


Figure 7. Building life cycle stages adapted from EN 15978, EN 17472, and EN 15643, with additions to illustrate biogenic carbon (Sturgis et al., 2023, p.19).

i) Embodied Carbon Footprint: Embodied carbon footprint is calculated by analyzing a design decision for its direct or indirect carbon emissions in the first four stages of a whole building life cycle. (Sturgis et al., 2023) The first two stages, Product and Construction, include the carbon emissions for raw material supplies, manufacturing, transportation to the construction area, and installation activities. The third stage, Use,

includes the carbon emissions for maintenance, repair, and replacement. The fourth stage, End of Life, includes the carbon emissions for demolition and disposal.

Most low-embodied carbon materials are recently produced and do not have widespread use in the construction industry since they need further assessments for their use-phase behaviors. Although they are mostly referred to as “alternative materials” because of their absence in the mainstream construction industry, some of them are already utilized in constructed projects.

ii) Operational Carbon Footprint: The operational carbon footprint covers the carbon emissions of a design decision for the two sub-stages of the Use Stage, namely the “operational energy” and “operational water” as shown in Figure 7 (Sturgis et al., 2023). This operational energy might stem from appliances such as infrastructure, HVAC systems or lighting, occupant-dependent emissions, and renovations (Teh et al., 2015). Space conditioning, specifically heating and cooling of interiors, has the largest share in the operational energy consumption for residential buildings, while lighting has the largest share in the case of commercial buildings (Lee et al., 2013). Hence, the operational energy performance of a residential building is highly dependent on its envelope design (Alghoul et al., 2017).

2.4 Software and Computational Tools Used

This section provides introductory information about the utilized software and computational tools in this study. Although there are many software for building energy simulation, computational design, statistical computation, and data visualization, some of them are selected for several reasons such as the availability of software documentation, developer reputation, financial accessibility, and compatibility with each other within the unique methodology of this study. Below, each selected software’s definition, utilization goal, limits, and strengths for this study are presented. Further information regarding their role in this thesis is discussed in chapters 4 and 5, “Methodology: Data Collection and Simulation Design” and “Results and Discussion”.

Rhino - Grasshopper and Ladybug Tools: Rhinoceros 3D or Rhino as it is shortly referred to, is a commercial computer-aided design software. It is mostly promoted for

enabling the creation of complex geometries with high accuracy and compatibility with other design software by the developer company (Robert McNeel & Associates (TLM, Inc.), n.d.). Grasshopper is a visual programming environment integrated with Rhino (Davidson, n.d.). While its initial goal is to enable designers to build generative forms with various complexity, it also has a rich add-on library serving many different purposes. One of these add-ons is Ladybug Tools. Ladybug Tools is a collection of free computer applications connecting 3D Computer-Aided Design (CAD) interfaces to simulation engines (Ladybug Tools LLC, n.d.). It includes component sets such as Honeybee, Butterfly, Dragonfly, and EPWMap for building energy modeling, urban energy modeling, daylighting, climate simulations, and occupant comfort estimations. In this study, Honeybee and Dragonfly components are used. The first one, Honeybee, enables building scale simulations and can export files in the OpenStudio file format. Dragonfly enables urban scale simulations, estimates urban heat island effects, and can export weather files in the .epw format, which is the weather file format compatible with OpenStudio.

Rhino-Grasshopper is advantageous for this study for several reasons. Although the building energy simulations are conducted in OpenStudio, the case study building, case study area, and available weather file are required to be altered or enriched before introducing them to OpenStudio. Rhino-Grasshopper provides the necessary environment for parametrically enriching the available data, conducting urban heat island simulations, and exporting 3D models and weather files compatible with OpenStudio, responding to all the mentioned needs of this study.

OpenStreetMap: OpenStreetMap (OSM) is an open-source and online map database. OSM maps do not only represent the physical features such as building footprints, roads, and green areas but also include types and functions of those physical features as “tags” (OpenStreetMap Wiki Contributors, 2023). The OSM files of selected areas all over the world can be downloaded from the online database and they can be imported into Rhino-Grasshopper. Grasshopper definitions can read both the geometry and the attached tags of these OSM files, creating a practical workflow while working with urban-scale data.

CityGML is another file format that is widely used both in building and urban scale studies, generally providing a higher level of geometrical accuracy in comparison to OSM. It is an XML-based data model allowing the storage and sharing of large-scale urban data (Esri, n.d.). CityGML might be accessible in different levels of detail and can even include information regarding facade configurations and roof geometries of buildings in an urban area. They are generally produced for whole cities by academic groups or governments. CityGML was the first preference for this study to obtain urban data with high accuracy and the CityGML file for the selected case study area was obtained from the General Directorate of Mapping (Harita Genel Müdürlüğü) affiliated with Istanbul Metropolitan Municipality. However, the file failed to be utilized for several reasons. First, the most recent version of the file belonged to 2013 and had many discrepancies with the existing buildings in the area. Second, the file had many geometrical issues most probably due to the scanning and data conversion techniques utilized at the time. Some of these geometrical issues, such as lots of planarity issues in the surfaces, make it impossible to run climate simulations relying on planar surfaces and closed geometries. Third, the obtained CityGML file did not include the facade configurations but only the roof geometry. Furthermore, most of the geometrical errors occur in the roof geometries, requiring interventions in the level of remodeling them from scratch. Such an intervention would damage the high geometrical accuracy of the model, which is the most important superiority of the CityGML file format. Hence, the OSM file format which is way more accessible and open to data enrichment was preferred for this study.

OpenStudio: OpenStudio is a free and open-source building energy modeling software. It uses the well-known physics simulation engine EnergyPlus as its simulation engine and provides an easy-to-use interface for both engineers and architects. One significant reason to select OpenStudio as the simulation environment of this study is that it allows a wide range of levels of detail when defining a building for the simulations. Hence, it is suitable for conducting simulations both in the early design stages when there is little definite information regarding the building's physical aspects and use scenarios, and in the use stage, when it is possible to have highly detailed inputs. Early design stage simulations allow comparison of different design options, which is also suitable for comparing wall

infill materials for their operational performance, which is the goal of this study. Further information regarding OpenStudio software and its role in the methodology of this thesis can be found in section 4.2 OpenStudio as a Simulation Software and Simulation Design in OpenStudio in Chapter 4.

R: R is a programming language for data compiling, statistical analysis, and data visualization (The R Foundation, n.d.). It is open-source and free. While its interface is quite simple, commands are given by coding and the function of the environment can be easily extended through the flexible use of commands. It also has some pre-ready packages allowing users to achieve more with less coding. This flexibility of commands also allows for the unique graphs to bring different information together in a comprehensible way. R is used in two important steps of this study. First, it was used for data compilation, basic statistical analysis, and data visualization when examining the existing building stock in Istanbul. Second, it was used to obtain unique graphs of the simulation results when they were not available directly inside OpenStudio, which is the simulation software used in this study.

CHAPTER 3

BACKGROUND

Construction materials, especially envelope materials, have a decisive role in the environmental impact of dense urban environments since they are effective on both embodied and operational carbon footprint of buildings. The background research of this thesis consists of two main parts. The first one is the current environmental impact and future needs of cities. This part (Section 3.1) examines how to measure and discuss the environmental impact of dense urban areas and what is the role of residential buildings in this environmental impact. The second part (Section 3.2) focuses on the detected conventional and alternative wall infill materials for the case of Istanbul. Introductory information regarding each selected material is presented in this section, while the thermophysical aspects necessary for the simulations in this study are gathered together in section 3.2.4.

3.1 Environmental Impact of Cities

Cities are dense human settlements with a wide variety of infrastructure serving occupant needs. They started to be formed as trade and cultural centers even before industrialization. Since then, they continue to grow and their growth is not predicted to stop for most of the cities in the near future. It is predicted that approximately 5 billion of the human population of a total of 8 billion will live in cities by 2030 (Bulkeley, 2013). This continued growth and accompanying density are generally associated with their high environmental impacts, which makes cities and sustainability seem like contradictory

concepts for some. On the other hand, dense urban areas allow to meet a large number of occupant needs in smaller areas, providing efficiency in terms of land use, infrastructure, and even energy consumption (Newman, 2006). Furthermore, urban areas maintain their indispensability by hosting economic and social constructions of humanity, besides providing conditions for cultural and scientific progress. However, these characteristics of urban centers don't change the fact that they are far from sustaining themselves and that they rely on natural resources from regions outside city centers or from other countries (Fry et al., 2018). Hence, while being closely related to the existence, progress, and future of humanity, our urban areas need advancements in their sustainability. This chapter explores the current situation of the environmental impact of cities and the role of residential buildings in cities' total environmental impact.

3.1.1 Measurements of Environmental Impact of Cities

The environmental impact of cities consists of many factors. Benton-Short and Short (2013) examine environmental impact under several factors. The first one is the level of energy used. The authors state that high energy use in cities is the single biggest contributor to cities' environmental impact. The second factor is cities' modifications to the environment itself. Urban heat island (UHI) is one of these environmental modifications. Further information about the UHI effect can be found in Chapter 2. The third factor is air pollution. Human activities and industrial processes emit substances such as carbon oxides, sulfur oxides, hydrocarbons, dust, soot, and lead, resulting in unhealthy atmospheric conditions. Another significant component of the environmental impact is waste production. Mass consumption in cities results in high amounts of garbage, which causes air pollution when burnt or leads to massive landfills when piled away. Lastly, urban areas affect daily and seasonal flows of water due to the impermeable constructed surfaces (Benton-Short & Short, 2013). While not all of these components of the environmental impact are measurable, there are some approaches to quantify and compare the environmental impact of cities. These methods include focusing on the total energy consumption, examining the population to estimate the environmental impact, examining the overall ecological footprint or carbon footprint of a city, conducting

sustainability assessments, or examining the “inputs” and “outputs” of a city by considering its activities as a “metabolism”.

UN-Habitat focuses on the total energy consumption of cities and states that they require an uninterrupted supply of energy to run their activities. As a result, “they consume about 75 percent of global primary energy and emit between 50 and 60 percent of the world’s total greenhouse gasses” (United Nations Human Settlements Programme, n.d.). Newman (2006), on the other hand, focuses on and also criticizes the other three approaches to understanding the environmental impact of cities, namely “population impact, ecological footprint, and sustainability assessment”. According to Newman, the size of the population of a city might correlate, for example, with the energy consumption of the city. However, an anti-population perspective can harm the environment further by causing inadequate city policies. Cities are powered by their population if the necessary infrastructure and services are provided in adequate numbers. Hence, decreasing this population might harm the sustainability of cities entirely. The ecological footprint approach aligns better with the environmental impact of cities. However, focusing solely on reducing the ecological footprint of a city might result in neglecting economic and social sustainability. On the other hand, a sustainability assessment considers the environmental impact while paying attention to social and economic progress. As a result, sustainability assessment might present an overview of the sustainability of cities while preventing harming the environment (Newman, 2006). According to the metabolism approach, which involves “tracking resources that go into the system and products and wastes that leave it”, input and output tend to be similar in terms of biodegradability, etc. for an efficient city. Hence, recycling, renewable energy, and bio-based materials become essential for an ideal urban metabolism (Bai, 2007). All these approaches, although considering different units of consumption and production, aim for cities with lower environmental impacts.

On the other hand, the current environmental impacts of cities will not be the only challenge to deal with in the near future. Urban areas might be “both the victim and culprit of climate change” (Bulkeley, 2013). It is obvious that urban centers are significant contributors to climate change because of the high level of greenhouse gas

(GHG) emissions. However, they are also more vulnerable to potential climate change because of several reasons. First, cities having large macro forms generally cover geographical areas at risk of natural disasters, such as river beds with high flood risks. On top of that, fast population increases cause people, arriving in already overpopulated city centers, to live in those risky areas. Areas that are prone to natural disasters are predicted to be the first to be affected by the changing climates (Bulkeley, 2013). Second, global warming will make cities even warmer than rural areas since urbanization will intensify the effect of global warming with the UHI effect (Kumar, 2021). These vulnerabilities require taking measures both to reduce the environmental impact of cities to slow down climate change and to adapt to the new climate conditions that are already noticeable. However, it is still possible to make cities environmentally sustainable over the longer term. Bulkeley (2013) states that to achieve this, "the individual elements of the city need to be brought together in a planned manner in order to respond to climate change". In relation to the Paris Climate Agreement and 2030 or 2050 carbon goals set by the governments and initiatives, GHG emissions will continue to be an important objective to discuss and reduce the environmental impact of cities (Fry et al., 2018).

There are not many studies aiming to calculate the exact environmental impact of a city to the knowledge of the author since it requires many inputs that are hard to detect and calculate. However, there are studies focusing on energy consumption and carbon emissions in urban centers by industries such as the residential buildings industry. The next section will examine the environmental impact of residential buildings in urban areas in relation to other urban industries and different geographies.

3.1.2 The Role of Residential Buildings in the Environmental Impact of Cities

Operational-phase residential carbon emissions significantly influence the GHG emissions of a city (Welegedara & Agrawal, 2024). Hence, understanding the carbon footprints of residential buildings is crucial for achieving the low-carbon goal of cities (Yan et al., 2018). On the other hand, the environmental impact of residential buildings and their share in the total environmental impact of cities can vary between neighborhoods according to socioeconomic status, geographic location, and local culture (Welegedara & Agrawal, 2024).

In the literature that focuses on urban-scale carbon emissions, only the operational phase carbon emissions of the buildings were considered in most of the cases, ignoring their embodied carbon footprint. However, Yan et al. (2018) consider all the life-cycle phases of residential buildings in Xiamen City, China, and states that the largest CO2 emissions come from the operational stage, followed by the preoperational stage in which the production of the construction materials occurs. According to the results, about 23.88% of residential carbon footprints come from the preoperational stage and about 75% come from the operational stage.

There are also some studies estimating the GHG emissions or CO2 emissions of residential buildings in the major cities of Turkey. Sevik and Sahin (2024) conducted a study for Ankara, Istanbul, and Izmir for the years 2015 to 2020. Their studies, focusing on the operational phases of sectors, show that the residential sector stands out as the sector that makes the biggest contribution to GHG emissions in Istanbul and Ankara. The other industries that they examine include energy industries, commercial/institutional buildings, residential buildings, manufacturing industry and construction, and agricultural, forestry, and fishing activities. The residential sector's percentage within these industries is an annual average of %41 in Istanbul and %42 in Ankara. The residential industry falls to second place with a percentage of %22 in Izmir, while the manufacturing and construction industry has the highest percentage.

In another study, Dino and Akgul (2019) consider the effect of climate change while calculating energy consumption and occupant comfort of residential buildings. Climate change is expected to be as effective on the building scale as it is on the urban scale, which is discussed in the previous section. Dino and Akgul (2019) conducted simulations with a weather date of 2060 projection, finding that there will be an increase in the annual average temperatures of 3.0, 3.0, 3.3, and 3.5 C for Izmir, Istanbul, Ankara, and Erzurum respectively. Building energy simulations using the 2060 weather data show that there will be a reduction in the total energy requirements of buildings while cooling energy requirements will increase. Accordingly, occupant comfort levels will be negatively affected in the summer seasons when proper air-conditioning is not accessible.

As a result, our cities and large building stock of urban residential buildings require further improvements to reduce their environmental impact and increase their resilience towards future climate conditions. Occupant comfort and health are also vulnerable to climate change, while they are already not handled well most of the time even in today's major cities all around the world. Such improvements reducing environmental impact, increasing resilience, and protecting occupant health and comfort require comprehensive studies, considering many scales and life cycle phases of the built environment. While the most energy-consuming phase of residential buildings is detected as the operational phase, pre-construction and construction phases are also highly effective on energy consumption levels while also effective on urban metabolism. Hence, construction materials and passive design methods gain importance for a more sustainable urban built environment. In this regard, the next chapter presents the conventional exterior wall infill materials of mid-rise residential buildings in Istanbul and explores the low embodied carbon materials as alternatives to these conventional infill materials.

3.2 Construction Materials for the Curtain Walls of Residential Buildings

The construction industry is the largest consumer of materials and uses a wider range of material types than other industries (Ahmed & Sturges, 2015, 1-15). This high level of manufacturing, use, and disposal of materials has a significant effect on our world's ecosystems mostly because of high carbon emissions, non-renewable resource consumption, and waste production. On the other hand, a thoughtful use and allocation of these materials, considering their whole life cycle and material properties, may prevent disrupting ecosystems and provide healthier built environments for occupants.

Material properties can be listed as mechanical properties such as strength and stiffness, thermal properties, acoustic behavior, optical characteristics such as transmission and reflection, electrical and magnetic responses, and fire-related behaviors (Doran & Cather, 2014, 1-5). This thesis focuses on operational performance, which is the level of energy consumption occurring in the use phase of materials. The need for space conditioning, namely heating and cooling of space, comprises a significant part of the operational energy usage of a building and is closely related to the thermal properties of construction materials utilized in the building envelopes. Hence, this literature review focuses on the

brief background and the thermal properties of the materials that can be used as an infill in the envelope walls of mid-rise residential apartments. The selection of the mid-rise residential apartments as the case study building typology is a result of Istanbul's dominant building stock and will be explored in the methodology part of this thesis.

The following parts of the literature review examine the materials under the two titles of conventional construction materials and alternative low-embodied carbon materials. Conventional construction materials of exterior partition walls, such as hollow clay tiles and aerated concrete, have a high negative environmental impact although they are very durable, as will be explored in the related part of this literature review. The Foundation of this thesis depends on the superiority of recently developed natural or recycled construction materials over conventional construction materials in terms of their embodied carbon footprint, which covers the manufacturing, maintenance, and disposal parts of a material’s or building’s life cycle. However, there is a lack of information regarding the use phase of these materials. Following their superiority proven in the literature and a long-term intention of the author for wider adaptation of these alternative materials in the architectural designs, this thesis examines the operational performance of the selected low-embodied carbon materials, comparing them with the operational performance of conventional materials in the end. In this way, it is aimed to provide a point of view regarding the operational behavior and energy-related needs of these recently developed alternative materials to take them one step further to their widespread utilization in the construction industry.

Conventional materials examined in this study are selected according to the results of statistical analysis conducted on the Building Permits data from TURKSTAT. On the other hand, the selection criteria of the low-embodied carbon materials consists of four main points. First, as a matter of course, they should be promoted as having lower embodied carbon footprints than conventional construction materials. Second, their raw materials should be available in the country of the case study area and must not come from animal sources. Even if the industry related to the manufacturing of an alternative material or the production of its raw resource is not readily available in Istanbul or Turkey, the possibility of such an initiative was sufficient for this study. The

animal-resourced alternative materials are eliminated since the animal industries are already not sustainable on their own and often involve animal exploitation. Third, selected materials need to be already produced in the brick, block, or sandwich form which are feasible for use in curtain walls of buildings since this thesis does not aim to contribute to the design of the construction material but to its implementation in the built environment. Fourth, the necessary information to define them in the simulation software, such as the thermophysical values of the material, should have been tested and available. Some promising low-embodied carbon materials are eliminated from this study since they do not have all the necessary thermal properties tested and published to the knowledge of the author, and their names will be indicated in the related part of the literature review.

The durability of materials is also important for the sustainability of built environments since it alters the recurring number of production, transportation, and demolition phases. Buildings are products that are expected to last long. Even if some parts of a building require maintenance more often than the other parts, this maintenance should be feasible, and environmental and should not shorten the life of the building itself. In terms of construction materials, durability is the robustness in the face of the operational conditions that they endure (Ahmed & Sturges, 2015, 1-15). This thesis does not include the examination of the durability of selected low-embodied carbon materials since it requires their use in real-world constructions to observe their long-term behaviors toward complex environmental conditions. On the other hand, the fact that low-embodied carbon materials mostly use renewable resources, are easy to demolish and dispose of, have low-cost production processes, and are possible to increase their durability with protective claddings indicates that they also might be feasible in terms of durability and maintenance. Nevertheless, their durability requires further research for detailed information about their behaviors in specific contexts and is the subject of other studies.

Construction materials are also a concern for occupant health in their use and demolition phases. Their interactions with moisture, fungi, bacteria, etc., and whether they release harmful gasses in long-term usage have vital effects on occupant comfort and health, especially in high-density urban environments. Even if those materials do not have

harmful effects on the occupants in their use phases, their behavior in the demolition phase also matters. Buildings are generally demolished as a whole resulting in a great pile of mixed waste of diverse materials, which has low recyclability has and mostly been put into landfills (Ahmed & Sturges, 2015, 357-382). This wholesale demolition is sometimes a bad choice of the authorities in the construction industry, but sometimes it might be forced by a natural disaster, such as an earthquake. Conventional construction materials, which are generally heavy, dense, and brittle, pose a danger to disaster victims during and after a collapse initiated by seismic activity. In the case that the structural system of a building endures an earthquake, partition walls might still lose their integrity, and some exposed layers might be even toxic to breathe. Such mass destructions also pose a problem for the relocation and disposal of huge piles of non-renewable and non-ecological materials. In dense and earthquake-prone areas such as Istanbul in Turkey, non-toxic and easy-to-dispose wall materials become even more vital to implement in construction processes.

3.2.1 Conventional Construction Materials

The conventional envelope materials that are covered in this study are selected according to the data analysis conducted on the Turkish Statistical Institute's (TURKSTAT) building permit data. The data focuses on Istanbul and Maltepe, which is the municipality of Istanbul where the case study building is located, presenting the most widespread envelope materials of residential buildings in those urban areas. For a detailed review of the R code used in the data analysis, please refer to the author's online repository on GitHub (Erincik, 2024). The most widespread envelope materials of residential buildings in Maltepe are detected as hollow clay tile and aerated concrete, as is visible in Figure 8.

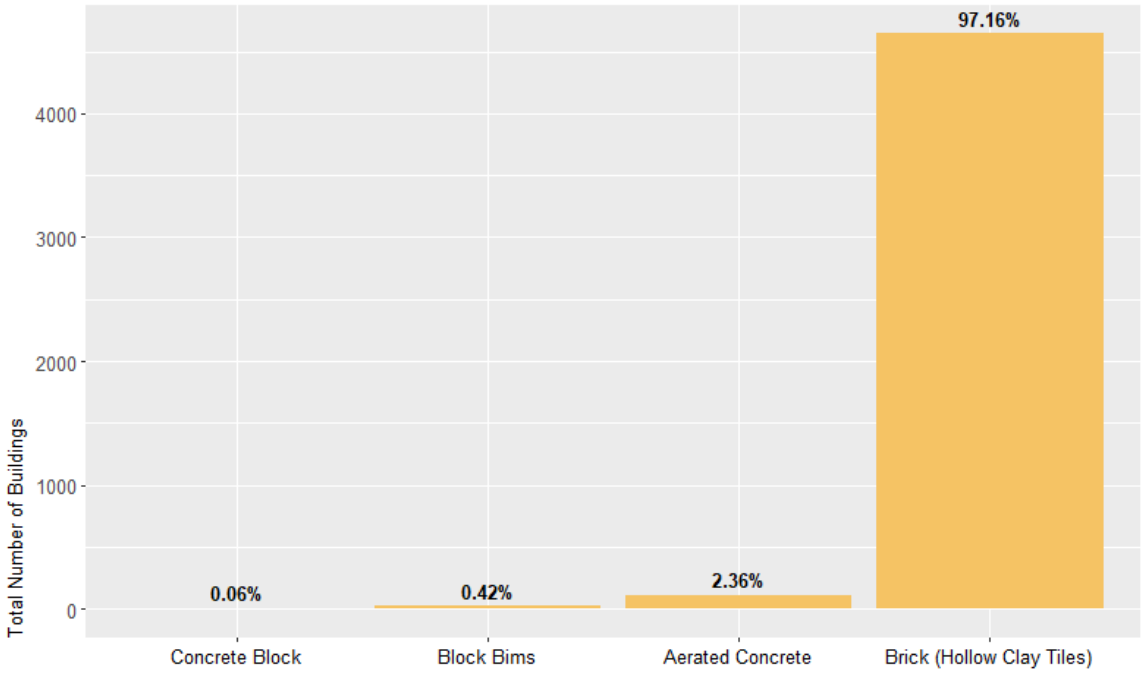


Figure 8. Bar graph showing the total number of 6-storey residential buildings per envelope material for the buildings constructed between the years 2008-2023 in Maltepe.

3.2.1.1 Hollow Clay Tile

Hollow clay tile is a universally adopted construction material comprising fired clay and optional chemical additives. Today, it is mostly used as an unreinforced masonry infill both for interior and exterior partitions (Haldar et al., 2013). Until the spread of iron in building construction in the first half of the 19th century, hollow clay masonry is especially preferred for its fire resistance and superior hygienic qualities since it does not allow other living things to nest inside. It was used on ceilings, floors, and chimneys besides partition walls at that time and was marketed as the right choice for an "ideal fire-proof building". On the other hand, the history of hollow clay tile goes back to the Romans, who used clay pots and hollow bricks to lighten their vaults (Wells, 2007).

By the 1950s, faster and cheaper construction methods supplanted the use of hollow clay tile in some parts of the buildings, as wood and steel studs faced with gypsum board and plywood started to be preferred over hollow tiles in interior partition walls (Wells, 2007). Nevertheless, it is still the most preferred infill material for the curtain walls of buildings

with reinforced concrete structural systems in many parts of the world (Haldar et al., 2013). Today, there are diverse commercial types of hollow clay tiles in terms of their geometry and dimensions. Their thermal behavior can vary in line with their geometrical aspects, such as the number of void rows, thickness of clay material between the voids, in-line voids, and shape of voids (Gondim et al., 2023). Boukendil et al. prove in their study that a hollow clay tile with three cell-width provides a significant reduction in heat transfer from exterior to interior in comparison to one-cell and two-cell tiles with the same cell sizes.

Although hollow clay tiles are very durable and have been widely adopted as different forms of fired clay for a very long time, their higher usage and environmental impact in parallel with the increased human population require consideration of alternative materials for widespread usage in the construction industry. The environmental impact of the hollow clay tile industry can be listed as non-renewable resource consumption, high energy consumption in the process of firing, high water consumption, GHG emissions, and waste generation (Torgal & Jalali, 2011, 131-141). Non-renewable resource consumption here does not refer to the depletion of raw earth material, but to the destruction of landscapes with valuable biodiversity, which is hard to restore to its original state. On top of the production-phase environmental impacts, hollow clay tiles are not easy to reuse or recycle. Since they are brought together with mortars to form walls, their integrity is irreversibly disrupted during building demolition. Although crushed pieces of fired clay can be used as aggregates in concrete production, this utilization corresponds to downcycling rather than recycling. For all these reasons, searching for alternative infill wall materials becomes valuable.

Hollow clay tiles were novel and superior in many aspects such as high fire resistance, hygiene, and durability in the 19th and 20th centuries and there are valid reasons behind their ongoing widespread use worldwide. On the other hand, their high embodied carbon footprint and waste production lead us to consider alternative materials. One important difference between hollow clay tiles and their alternatives is their operational performance, which highly depends on their thermal characteristics and is closely related to occupant comfort. Hollow clay tiles' operational thermal behavior is affected by the

geometry of the tiles and their content's thermal properties, which are made up of fired clay and optional chemical additives. An example hollow clay tile with 4 cells is provided in Figure 9. The thermal values of the hollow clay tile used in this thesis consider both its geometry and material properties and can be found in Table 2 in section 3.2.4.

Figure 9. Hollow clay tile sample (Klinker, 2021).

3.2.1.2 Aerated Concrete

Aerated concrete is a homogenous cement/sand mortar of which the density is lowered by introducing gas into it. Gas-introduced concrete blocks (figure 10) have high porosity and might be subject to shrinkage during the drying process. To reduce this shrinkage, high-pressure steam curing, which is called "autoclaving" might be applied (Taylor, 2013, 41-113). Autoclaved and aerated blocks are then named autoclaved aerated concrete (AAC) and are widely preferred in the construction industry, especially in the UK, Europe, and North America for the external walls, internal load-bearing and non-load-bearing walls, and walls below ground level (Ahmed & Sturges, 2015, 193-207). According to the statistical values obtained in this thesis, it is the second most-used envelope material in Istanbul, Turkey between the years 2008-2023. However, it is well behind the hollow clay tile, which is ranked first.

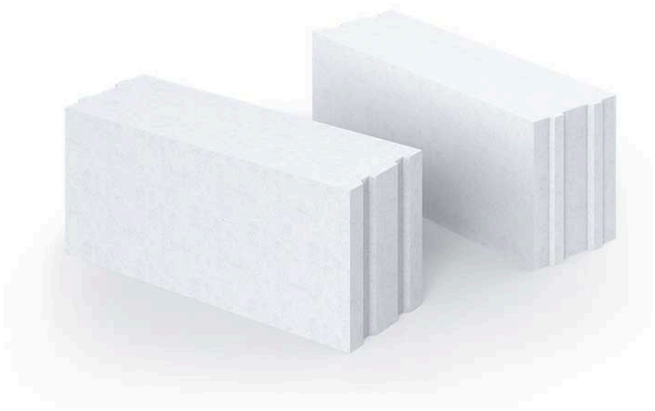


Figure 10. Aerated Concrete Block sample (Ytong, n.d.).

Aerated concrete or Aircrete in other words was developed in Sweden in the 1920s (Ahmed & Sturges, 2015, 193-207). Afterward, the production and use of aerated concrete have spread to more than 40 countries in North America, Central and South America, Europe, the Middle East, the Far East, and Australia (Sethy et al., 2018). The widespread utilization in more than 50 years resulted in many cases proving the material's durability under different climates and conditions. Today it is accessible in many different thicknesses and face sizes. In this thesis, a version with a thickness of 19 cm is preferred for consistency with the selected hollow clay tile to be used in the simulations.

AAC is the aggregate of sand, lime, cement, water, and an expanding agent, which is mostly aluminum powder. The air voids in the AAC blocks can compose up to %70 of the total volume of blocks. Due to its high porosity, AAC has higher thermal insulation in comparison to hollow clay tiles. Higher porosity is related to higher air void, which effectively reduces heat transmission (Zhao & Qu, 2017). Since it is manufactured from non-biodegradable materials, it doesn’t rot or host molds (Kalpana & Mohith, 2020). AAC is more homogenous than ordinary concrete with substances no larger than sand and it has a closed pore structure, meaning that its air voids are not connected to each other most of the time. Its homogenous composition prevents the differential rates of expansion and its independent air gaps make it even more resistant than ordinary concrete (Narayanan & Ramamurthy, 2000).

AAC Block production-phase carbon emissions are 67.05% less than fired clay bricks (Yaman & Rashid, 2021). Together with its higher thermal insulation ability and lower production carbon emissions, it is widely accepted as an eco-friendly material. Although post-demolition AAC is mainly disposed of in landfills currently (Volk et al., 2023), it has some recycling options. AAC blocks can not be reused in their block form directly and the most usable form of AAC waste is crushed stone or powder (Gyurko et al., 2019). In its crushed forms, it can be used as an aggregate in no-fines concrete or non-loadbearing tiles. In its powdered forms, it can be used as a supplementary material in concrete production (Gyurko et al., 2019). Up to 20% of pd-AAC can be recycled to replace Portland cement without compromising strength (Qin & Gao, 2019). Another study shows that recycling pd-AAC directly in the production of AAC is another option for reducing the environmental impact, particularly if cement. However, the new AAC can not consist of the pd-AAC only and still needs to be accompanied by other substitutes (Volk et al., 2023). In general, it can be used as a supplement in cement-using material production and be prevented from ending in landfills. On the other hand, it can not be reused as aerated concrete and loses its product value through the available recycling options.

In conclusion, autoclaved aerated concrete is a widely preferred and superior material, especially in some ways in comparison to hollow clay tile. This thesis also shows that, in Istanbul, AAC was far less utilized than expected between the years 2008-2023 despite its advantages such as smaller production-phase carbon footprint, easy application using less mortar than most masonry materials, recyclability into different construction products, and higher thermal isolation. The thermal values of AAC used in the simulations can be found in Table 2 in section 3.2.4.

3.2.2 Alternative and Low-Embodied Carbon Construction Materials

This part explores the low-embodied carbon materials that are not currently utilized in a widespread manner in the construction industry. Being aware of their superiority in terms of their embodied carbon footprint, this thesis examines their operational performance in comparison to conventional wall infill materials and to each other. The aim of the study is not to prove any material's superiority to each other but to explore their convenience for

widespread usage in urban environments and their specific needs in terms of operational energy consumption. Operational energy on its own is not enough to prefer one material over another, but it needs to be evaluated with other aspects of materials such as embodied carbon footprint, durability, renewability, recyclability, or accessibility in a specific geography. Hence, a material with a slightly higher operational footprint could be preferred over another one with a significantly higher embodied carbon footprint.

This literature review regarding alternative materials has two main goals. The first is preparing the reader to interpret the results of this study more realistically and accurately. Most of the alternative materials have their weaknesses currently, besides their advantages. They are promising, but they need further improvements before their widespread usage in urban environments. This part of the thesis explores those materials' drawbacks, underlying that further mechanical or hygrothermal improvements to any material can also alter their thermal performance, hence, the results of this study. On the other hand, all the relative material values and resources are shared at the end of this chapter, allowing transparency of the utilized material properties. The second goal of the literature review is to point to future studies regarding alternative materials. For instance, a low-embodied carbon material can also be detected as overwhelmingly positive for its operational performance, but might still need some improvements in terms of its earthquake resistance before its widespread utilization, hence indicating the need for further study for its earthquake resistance.

The examined materials are selected if they can be used as an infill material in block or sandwich form in the non-load bearing exterior walls if their material properties that are necessary for the building energy simulations are accessible, and of course, if they are promising alternative materials with lower embodied carbon footprints in comparison to conventional infill materials. The materials that are quite promising as an alternative material but have to be eliminated due to the lack of available information are also mentioned with their missing values in section 3.2.4.

3.2.2.1 Adobe Bricks (Unfired Clay Bricks)

Adobe, also known as mud brick, is one of the oldest construction materials, and its use dates back to 8000 BC (Minke, 2006, p.11). It is a raw earth-based block consisting of sifted soil, water, natural fibers, and optional stabilizers. An example of adobe bricks is presented in Figure 11a. Some of the most well-known characteristics of adobe walls are their low-embodied carbon footprints, ability to regulate indoor thermal and hygroscopic conditions thanks to their material properties, and relatively low operational carbon footprints resulting from the creation of comfortable interiors with less energy consumption (Giada et al., 2019). Varying types and amounts of accessible earth and plant fibers have significant effects on the final durability, mechanical properties, thermal performance, and hygrothermal behaviors of adobe bricks.

Although the earliest applications of adobe blocks were detected in very different parts of the world, the mandatory diversity of local earth and natural fibers led local people to develop their unique adobe bricks with a trial-and-error approach. This site- and use-specific adobe production offered sustainability and durability to the end-product (Castrillo et al., 2016). However, such a local approach does not fit modern mass production and construction methods, especially because of the limited resources of nearby earth materials. The inherent variability of earth's material from place to place makes it difficult to reproduce an ideal recipe for a vast number of times to coincide with the high housing needs of people living in urban centers. Still, there are many constructed projects using excavation soil from the construction site, running many tests beforehand to obtain the ideal brick recipe unique to that soil. Contemporary initiatives, such as the Building Biology & Ecology Institute (YBE, n.d.) in Turkey, present significant examples of the application of raw earth materials including adobe in low-rise contemporary buildings. (figure 11b) However, there are some significant difficulties regarding the consistency and durability of adobe materials detected in the literature, which need to be resolved before their widespread use in the non-load-bearing walls of mid-rise apartments, especially in an earthquake-prone area such as Istanbul.

Figure 11a. Adobe brick sample from a Turkey-based construction materials company (Arda Tugla, 2020). Figure 11b. Adobe brick wall application from a constructed 2-story building in Turkey (Building Biology and Ecology Institute, n.d.).

The most significant contribution of the adobe material would be its humidity regulation for the urban areas of Istanbul. Istanbul has high levels of humidity most of the year, accompanied by alarming levels of air pollution. High urban density, traffic, and humid climate keep the pollutant gasses and heat close to the ground level, creating health problems for living occupants. A study revealed that increasing the relative humidity in a room from 50% to 80% caused unbaked bricks to absorb 30 times more moisture than baked bricks within two days. Additionally, adobes retained their stability even after being exposed to 95% humidity in a climatic chamber for six months (Minke, 2006, p.14). However, their thermal performance highly depends on their moisture content. Unfortunately, simulations generally don't consider the hygrothermal behavior of adobe when measuring its thermal performance (Giada et al., 2019). On top of that, optimization for hygrothermal purposes can reduce the compressive strength of the material. Hence, an ideal recipe ensuring the balance between mechanical properties, thermal performance, and hygrothermal activities should be acquired to use them as a construction material.

Because of the very high levels of interaction between adobe walls and microclimates, adobe has some unique vulnerabilities for damages and they should be known before any application. The first kind of damage is the moisture-driven disintegration of adobe bricks. It occurs when the plant fibers in the mixture rot or the soil content loses its cohesion because of direct exposure to rain or constant moisture (Illampas et al., 2012).

Hence, exterior walls need to be protected from direct contact with rain or any kind of water (Tanaçan, 2008). The second kind of likely damage is the cracking or partial collapse. Cracking or partial collapse in adobe walls is caused by “horizontal movements, in-plane or out-of-plane bending of the walls, and support displacement”, which might be caused by earthquakes (Illampas et al., 2012). In this case, the damage mostly starts with a crack and the wall continues to weaken until it collapses. To avoid collapse, movement should not be entirely restricted; instead, it should be controlled to allow for the dissipation of seismic energy (Ginell & Tolles, 2013). After any damage, adobe walls are required to be restored with a compatible composition of raw earth mixture. Different mechanical properties will prevent the adhesion of materials and shorten the life of the wall (Costa et al., 2021). Another important matter with the adobe infill material is its mechanical compatibility with the structural system of a building. There are examples of constructed projects including adobe bricks as the wall infill and wooden structural systems, with wall thicknesses of 14 to 20 cm (Minke, 2006, 106). However, the mechanical interaction between the reinforced concrete structural system, which is the most common type of structural system in mid-rise residential buildings in Istanbul, and adobe bricks needs to be examined and this is the subject of another study.

Earth material has different names when used in various applications such as rammed earth and adobe (Minke, 2006, 7). Adobe is preferred to examine in this study since it would be more possible to apply in mid-rise apartments in urban environments rather than rammed earth walls, which are quite heavy and require in-situ compression complicating the construction process in densely built environments. Adobe can reduce embodied carbon footprint significantly in comparison to conventional fired earth materials (Shukla et al., 2009). Hence, it is considered in this study as a promising alternative material to be examined for its operational performance despite some unresolved problems relating to its structural behaviors and mass producibility.

3.2.2.2 Cork Blocks

Cork is the outer bark of an oak species called cork oak (Quercus suber L.) and it has been used since antiquity for its floating and sealing aspects. Its market has expanded enormously since the beginning of the twentieth century in parallel with its usages in the

form of agglomerated products (Gil, 2015, 585-629). While the European Union is the largest cork producer with a rate of over 80% in the 21st century, Portugal alone has 50% of the world's cork production (Gil, 2013). The most widespread usages of cork in the construction industry include heat insulation, sound insulation, vibration insulation, flooring, and less commonly, exterior cladding (Knapic et al., 2016). On the other hand, there are significant academic studies and constructed projects using cork blocks as a wall material undertaking all the roles of heat insulation, sound insulation, and infilling. Figure 12a presents an example cork block produced for wall construction, while Figure 12b shows an exterior wall constructed with cork blocks without any exterior cladding or rendering.

Figure 12a. Cork block sample (Studio Bark, 2017). Figure 12b. Wall sample constructed with cork blocks with no cladding (Thorns, 2017).

Cork has a couple of superior material properties stemming from its unique physical structure. It is composed of layers of similar-sized cells with closed porosity, meaning that its cells are not interconnected and are full of an air-like gas occupying 90% of the material's total volume (Gil, 2015). Furthermore, it has cell walls with a chemical composition making it water resistant (Knapic et al., 2016). As a result of this cellular structure, it is a light material with low density, low permeability to liquids and gasses, high compressibility, and very low heat transfer ability. Such a unique combination of material properties with a very low ecological footprint makes it a promising construction material. However, since cork blocks comprise compressed agglomerations of cork fragments with binding materials, the low permeability to gasses and liquids stemming

from the original structure of the cork may show variability between products depending on the compression process (Wilton & Howland, 2020).

Cork is a biodegradable material and has a negative carbon footprint by sequestering carbon in its production phase. It is extracted from each oak tree every 9-14 years, by not harming the tree but stimulating the rapid growth of new bark. This stimulation increases the production of cork by 3.5 to 5 times increasing the sequestration of CO2 in correlation (Gil, 2013). It is also reusable in its construction block form after the end of building life since the blocks are not brought together with mortar but with joints or puzzle-like assemblings. Even if it is not possible to recover the cork products as they are, they can be crushed to obtain cork granules and can be used in new cork products without compromising quality (Gil, 2015).

It is also proven to be durable in certain conditions as a building material, unlike most of the recently developed materials. It is resistant to the action of rodents and insects although it's a plant-based material (Tola, 2014, 137-147). On top of this inherent resistance, a previous attempt to recover expanded agglomerated cork panels from buildings over 50 years old proves that the properties unique to the material remain unchanged over that many years (Gil, 2015, 585-629). Another study experimenting with a one-story constructed cork house documents the durability of cork as a wall material, showcasing its resistance to water and other environmental conditions. The cork house meets or exceeds all contemporary performance requirements while avoiding complex wall sections with a different layer for the infill material and for every insulation need. On the other hand, the cork blocks in this study are rated as Euroclass E fire resistance indicating the need for careful fire safety strategy development. The material also requires further studies on its lightweight and friability to be used as a common wall infill material (Wilton & Howland, 2020).

3.2.2.3 Mycelium Blocks

Mycelium is the fibrous root system of fungi and its primary role in nature is to decompose organic waste (Ghazvinian et al., 2019, 505-514). It displays unique properties such as growing without light, being completely biodegradable, and turning

complex carbohydrates into simple sugars, which means it can grow on agricultural waste. Despite these sustainable aspects, their examination as a construction material doesn't date back much more than a decade (McGaw et al., 2022).

The most prominent features of mycelium as a material are thermal insulation, acoustic insulation, relatively high fire resistance, (Alaux et al., 2024), and being the only bio-based material that allows for casting (Biala & Ostermann, 2022). Figure 13a shows mycelium blocks cast into different sizes. As a result of these features, it is utilized as a material in industries outside of architecture such as packaging, product design, fashion, and architecture as thermal and acoustic insulation panels (Ghazvinian et al., 2019). Many architectural installations use mycelium blocks or allow mycelium to grow in a more free-form way following a pre-assembled structure (Bitting et al., 2022).

Recent studies with the aim of using mycelium blocks in masonry generally concluded that the obtained blocks do not have enough compression strength to be used in masonry walls. On the other hand, the mechanical properties of any mycelium-based material depend on the type of fungi growing the mycelium, the composition of other materials that the fungi feed on, and specific methods adopted in the process of mycelium growth, which indicates that it might be possible to improve their compressive strength with further studies (Bitting et al., 2022). A study shows that compressing the mycelium substrate for seven days under the right conditions and in the right step of the production phase reduces its volume by fifty percent and increases its compressive strength 5 to 6 times higher than the polystyrene, which is a common packaging and building insulation material with high environmental impact (Joshi et al., 2020). However, it should be noted that compression also reduces the lightness and airiness of the material while densifying it, harming its acoustic and thermal insulation abilities (Bitting et al., 2022). Figure 13b presents a wall constructed with mycelium blocks.

Figure 13a. Samples of mycelium blocks (Future Cities Laboratory Global, n.d.). Figure 13b. Wall sample constructed with mycelium blocks from Biohm material company (Fairs & Takada, 2021).

There are three types of engineered mycelium-based materials in the construction industry. The first is pure mycelium material (PMM), which is obtained by harvesting a liquid culture of pure mycelium; the second is mycelium-bound composite (MBC), which is a bio-composite wherein the network of the mycelium binds and transforms substrates coming from agricultural crop waste such as cotton, corn, flax, hemp, and wheat (Bitting et al., 2022). The type and percentage of substrates greatly affect the properties of the resulting material. The third is mycelium-based sandwich composites (MBSC), wherein mycelium is allowed to grow between two laminate skins under convenient conditions and then inactivated by drying. However, it is reported that laminate skins and mycelium cores are very different materials from a mechanical point of view, causing interlaminar shear failure in the laminated skins and core tensile (Girometta et al., 2019).

The first two types, PMM and MBC, allow production in block and panel forms and allow adjusting material properties by experimenting with production methods and substrates. For these advantages, this thesis uses a high-density MBC in the block form in the building energy simulations. On the other hand, it should be noted that the studies to obtain mycelium blocks with the necessary level of durability to be utilized as an infill material continue. Creating a viable product from mycelium requires “balancing biodegradability with an acceptable level of durability; demonstrating compliance with building standards through testing; and developing systems of production that are cost-effective” (McGaw et al., 2022). The future design of such a product might have a

different density from the one that was utilized in this thesis. Hence, its operational performance might differ depending on its altered thermal properties. Still, the mycelium blocks with the highest density and with all the necessary material data available in the literature are selected for this thesis, and provide a foresight for its operational performance in comparison to conventional and other alternative materials.

3.2.2.4 Hempcrete

Hempcrete or hemp concrete consists of hemp shives, also known as hemp hurds which is the inner woody core of the hemp plant, along with a mixture of binder, water, and admixtures (Bruijn et al., 2009). The base of the binder can consist of hydrated lime, natural hydraulic lime, or both of them. In some cases, cement and/or pozzolanic binder is added to accelerate the hardening process and improve the mechanical resistance (Arrigoni et al., 2017). Because of the hemp shives' low density and high porosity, combining hemp with a binder produces a building material that has a comparatively lower density, reduced thermal conductivity, and improved acoustic insulation properties (Bruijn et al., 2009). Currently, hempcrete construction materials are implemented as an infill material in non-bearing walls, as finishing plasters, and as insulators in walls, floors, and roofs by spraying, molding, and precasting them (Arrigoni et al., 2017). Figure 14a presents hempcrete blocks with varying sizes, while Figure 14b shows a wall constructed with hempcrete blocks. The thermal and mechanical properties of hempcrete vary depending on the binder, the quality and length of the hemp shives, the ingredient’s proportions in the mixtures (Arrigoni et al., 2017), and the amount of compression in the production phase (Nguyen et al., 2010). Hence, the content and the production method of hempcrete alter the end product’s implementation method and use case in a building.

Figure 14a. Hempcrete blocks in varying sizes (Hempcrete Spain, n.d.). Figure 14b. Sample wall constructed with Hempcrete blocks (Marshall et al., 2022).

The use of hemp-based fiber technology goes deep into our history, especially for its use in rope and fabrics (Fike, 2019). However, experimental studies on hemp construction materials are relatively new mainly due to hemp's association with Cannabis, which has led to legality issues in the modern world (Essaghouri et al., 2023). Both the industrial Cannabis sativa and medical Cannabis sativa L. are variations of Cannabis sativa L. The latter, also called marijuana, can be used as a drug and is illegal in many parts of the world. Their main difference is the level of Λ9-tetrahydrocannabinol (THC) that they contain, which is the chemical most responsible for the psychoactive properties of marijuana. Industrial hemp generally has less than 0.3 percent THC and, thus, is not preferred to be used as a drug. Their growing conditions also differ. Industrial hemp is grown outside on a large agricultural land, their stalks being planted densely to discourage branching and flowering. Marijuana, on the other hand, is grown inside with controlled conditions for its leaves and female unfertilized flowers with the largest concentrations of THC (Malabadi et al., 2023). The differentiation between hemp and marijuana has encouraged numerous countries to legalize hemp production, leading to an expanding body of research on hempcrete as a sustainable building material (Essaghouri et al., 2023). Currently, hemp as a high carbon-sequestering, easy-to-grow plant with exceptional physical properties, is an indispensable and promising raw material for many industries including the construction industry.

When being utilized in the non-load bearing walls, hempcrete is generally preferred to be used in the precast block form since molding in the construction site takes many days for

it to completely dry before the following steps of the construction. Hempcrete can easily absorb or release water vapor and has a good vapor permeability. These features allow a passive control of thermo hygrometric conditions indoors, decrease the risk of vapor condensation, and increase thermal comfort (Arrigoni et al., 2017). However, if it can not release the vapor that it absorbed previously, mostly because of non-permeable renders, it might cause mold to grow in between construction layers. On the other hand, a vapor-permeable render on the exterior surfaces causes Hempcrete to absorb more moisture than it can release in a short time, causing mold in the long term (Piot et al., 2017). Hence, it is important to prefer non-permeable rendering for the exterior surface and let hempcrete dry enough before covering it with this rendering layer. It is also critical to allow the vapor exchange with interior environments to benefit from its passive regulatory features. Although Hempcrete's interaction with moisture and mold is relatively intricate, it is resistant to microbial attacks and insects.

Although hempcrete blocks are typically used with wood frames in constructed projects, they can also be utilized in metal or reinforced concrete structures (Arrigoni et al., 2017). The density of Hempcrete blocks alters their thermal and mechanical properties (Abdellatef et al., 2020). Better compaction of the particles, either by the appropriate selection of binder ingredients or compression in the production phase, yields a higher-density hempcrete block, improving its mechanical properties. On the other hand, increased density increases thermal conductivity, reducing their thermal performance. Deciding between the improved mechanical properties and deteriorated thermal performance requires a compromise to be made by the designer. Even so, when the blocks are used as an infill material with a structural frame, it is possible to obtain low thermal conductivity blocks with adequate mechanical properties (Elfordy et al., 2008). Furthermore, due to its lower density and lightweight, it is easier to transport and implement on-site.

Hempcrete is a carbon-negative product in terms of its embodied carbon footprint thanks to its hemp content. Hemp is a highly carbon-sequestering, fast-growing plant and adaptable to different climates and geographies. Some studies show that hemp's high level of biogenic carbon sequestration during its growth phase can compensate and even

exceed for all other carbon emissions made from the manufacturing and transportation of Hempcrete, including the manufacturing process of its binder content (Arehart et al., 2020). However, binder selection has significant importance in the embodied carbon footprint of Hempcrete blocks. Some high-density hempcrete formulations can exhibit net-positive emissions, especially due to containing Portland cement (Arehart et al., 2020). Some studies assert that in the end-of-use phase, Hempcrete can be biodegraded, be recycled, or can be incinerated to generate electricity in specialized facilities (Essaghouri et al., 2023). After a demolition, all the Hempcrete blocks can be recycled for a new hempcrete mixture with some extra binder since the lime in the first block has carbonated (Yadav & Saini, 2022). On the other hand, Hempcrete blocks are generally combined with mortar while constructing a wall. The effect of mortar selection on the reusability or recyclability of the material was not discussed in the existing literature to the best of the author's knowledge.

3.2.2.5 Cannabric

Cannabrick is a hemp-based air-dried brick (figure 15a) specifically developed for outer walls with a load-bearing capacity. It is a specialized version of hempcrete with a product name of Cannabrick. In the technical data sheet of Cannabric published by the developing company, it is stated that it consists of completely natural raw materials, which are wooden stalks of hemp as the main components, other vegetable materials, natural and mineral bonding agents, and recycled materials (Cannabric, 2008). Some other studies in the literature state that Cannabric consists of hemp and lime, stating that the lime improves the mechanical properties of hemp but it significantly increases the GWP of the product. Including it in the combination consumes approximately 49% primary energy and 68% water of the total consumption of the production of a hemp-based brick (Brümmer et al., 2018, 249-266). Still, the inclusion of the specific kind of lime in a certain amount makes Cannabric reliable for even load-bearing walls. Figure 15b presents the load bearing walls constructed with Cannabric.

Figure 15a. Cannabric samples (CANNABRIC, 2024). Figure 15b. Walls constructed with Cannabric (Brümmer, 2009).

Only a few academic studies mention Cannabric, probably because information regarding its exact material content and certain material properties are not published by the patent-holder company. However, it is possible to access some primary knowledge and numerical values regarding the material properties directly via the product website. It is also possible to access some projects constructed with Cannabric through the website's database. While no examples of mid-rise multifamily apartments can be found, there are many examples of new buildings or retrofits for one or two-storey single-family residential buildings on this database (Cannabric, 2020). In the technical data sheet of Cannabric, it is stated that the bricks have mechanical qualities allowing load-bearing use in single residential buildings, terraced houses, and public buildings of several floors. There is no indication of use in multifamily apartments with reinforced concrete structural systems when they are used as an infill material rather than a load-bearing masonry wall. However, replacing hollow clay tiles with Cannabric might alter the GWP of mid-rise apartments in urban environments and improve thermal performance and interior air quality. Therefore, further mechanical studies of the material are needed for its application to mid-rise multi-family apartments.

The main ingredient of Cannabric, hemp, is a high-fiber and fast-growing plant especially suitable for arid and semi-arid climates (Ottmann, 2022, 65-66). However, It easily adapts to different climates, altitudes, and soil types and it is one of the earliest culture plants (Brümmer et al., 2018, 249-266). It has air-purifying abilities since it sequesters a significant amount of CO2 (Ottmann, 2022, 65-66) and It does not require any pesticides

and herbicides while growing (Cannabric, 2008). It is a porous material leading to a low thermal conductivity and it is possible to improve its fire resistance by treating it with non-toxic chemical substances (Ottmann, 2022, 65-66). These adaptability to different geographies, environmental-friendly cultivation processes, and material properties of hemp make it a promising alternative material to be used in the construction industry.

According to the technical data sheet, Cannabric has a GWP of - 0.624 kg CO2eq/kg, which is a negative carbon rating. Hence, it does not contribute to global warming through its manufacturing process. After the demolition, recycling or reutilization is possible. However, it is also stated that the bricks can be powdered and served for the production of Cannabric again or hemp mortars only “once more”. As a result, the recycling and reuse options need clarification or further studies to see how many times it can be recycled or what happens to the non-recyclable waste.

In its use phase, Cannabrick creates a healthy interior climate by providing clean air, adjusting the air humidity, and maintaining acoustical comfort. However, it is important to work with mortars, renders, plasters, and paints with similar properties in order to benefit from these properties of Cannabric (Cannabric, 2008). It also has a low thermal conductivity. However, it is recommended to render outer Cannabric walls to protect favorable thermal characteristics on rainy days since they can absorb a certain level of moisture, which increases their thermal conductivity. Furthermore, 30 cm thickness excluding the render is offered for the facade walls (Cannabric, 2008). Based on this information, this thesis utilizes a 30 cm Cannabrick in the building energy simulations. However, the outer render and interior layers of the walls in the simulations were kept the same for each infill material and weren’t replaced with ecological and compatible alternatives since the layers other than the infill layer are constant variables of this study.

3.2.3 Comparison of Materials for Their General Characteristics

This section presents the summary of the information collected in the previous sections related with the selected infill materials (Table 1). Table 1 covers the material properties related to sustainability and the operational phase of building lifecycle. The alternative materials selected for this study are already promoted as having a lower embodied carbon

footprint by the producer companies. This information was not used in Table 1 since not all of the materials have numerical values and the embodied carbon footprint might differ significantly according to the production and construction site locations. Still, an attempt to conduct an embodied carbon footprint analysis of materials unique to this study and excluding the impact of transportation are made. However, no software with an available database that includes all the materials with the material properties used in this study is found. Hence, the exact embodied carbon footprint calculations and the comparisons of these materials is left for another study.

Table 1 includes three main scores for each material property, which are "✓", "-", and "variable". The first one indicates that the material has the property by its nature. The second one, minus sign, indicates that the material does not have the property by its nature but that doesn't mean it is not improvable. The minus sign only shows that the material needs proper adjustments to its content and construction detail design to overcome its weakness in the specific aspect. Most of the materials with minus sign already have treatments for these weaknesses but Table 2 doesn't cover these treated versions since their thermophysical and structural abilities are not examined in this study. The third score, variable, indicates that the material might have the property by its nature, but it doesn't always have it at the necessary level due to the variability of its contents' ratios.

Table 1. Summary of the literature review regarding the selected infill materials.

		Materials						
Evaluation Criteria		Hollow Clay Tile	Aerated Concrete	Adobe Brick	Cork Block	Mycelium Block	Hempcrete	Cannabric
content	Has bio-based/natural raw content	-	-	✓	✓	✓	✓	✓
	Has lime content	-	✓	-	-	-	*variable*	✓
production	Sequesters CO2 in production phase	-	-	-	✓	✓	✓	✓
	Air dried	-	-	✓	-	-	✓	✓
	Oven dried	✓	-	-	-	✓	-	-
	Steam cured	-	✓	-	-	-	-	-
	Compressed	-	-	*variable*	*variable*	*variable*	-	-
application	Suitable for load-bearing walls	✓	✓	*variable*	-	-	-	✓
	Needs cement-based mortar to construct a wall	✓	✓	-	-	-	-	-
use phase	Adjusts interior humidity when used in walls	-	-	✓	-	-	✓	✓
	Resistant to mold	✓	✓	-	✓	-	-	-
	Resistant to insects and rodents	✓	✓	-	✓	-	✓	✓
	Resistant to water or high humidity	✓	✓	-	✓	-	✓	✓
	Resistant to fire	✓	✓	-	-	-	✓	✓
end of life	Reusable	-	-	✓	✓	✓	✓	✓
	Recyclable	-	-	✓	✓	✓	✓	✓
	Downcylable	✓	✓	✓	✓	✓	✓	✓
	Biodegradable	-	-	✓	✓	✓	✓	✓

Having lime content is decided to be highlighted in the “content” part of Table 1 since some materials with high bio-based content include lime to strengthen their mechanical aspects. However, this lime content significantly increases their environmental impact and reduces their thermal performance. Still, it should be noted that having lime content is not necessarily a drawback and it enables some sustainable materials to be used in wall constructions by improving their mechanical strength to the necessary levels. “Production” and “application” parts of the table provide insight about the carbon

footprints of the materials resulting from these phases. The highlighted points such as being air-dried or oven dried are selected since they are processes that might create significant distinction between material carbon footprints. As a result, Table 1 summarizes the general information about the materials used in this study, highlighting their advantages, drawbacks, and potentials before focusing on their aspects that are relevant only to building energy simulations. In this way, it is aimed to provide a general overview of the materials alongside their operational performance to be presented in the results of this study.

3.2.4 Thermal Characteristics of Materials Required by OpenStudio Simulations

The thermal properties required by OpenStudio for the simulations include thickness, conductivity, density, and specific heat. The software also allows indication of thermal absorptance, solar absorptance, and visible absorptance. However, they are kept constant in this study for two main reasons. First, most of the alternative low-carbon materials do not have these values investigated. Second, those aspects are mostly effective when the material is exposed and visible. Since this thesis focuses on only the infill materials of curtain walls and not on the claddings or renderings, the examined materials are never exposed to outdoor conditions directly. Hence, material properties that are effective when the material is exposed are not a concern of this study.

All the material data necessary for the building energy simulations in OpenStudio are presented in Table 2. The red colors in the table represent the unavailable information. Those specific material properties are either never being tested, or the contacted patent holder companies indicated that they are currently confidential. Those materials, although highly promising for sustainable construction, had to be excluded from this study due to their lack of data. They include algae-based cement blocks, K-briq, Sugarcrete, and straw bale panels. K-briq and straw bale panels already started to be used in constructed projects as an alternative to standard hollow clay tiles. K-briq is a brick having 90% of its content consisting of recycled construction waste, hence, has a significantly low environmental impact (Kenoteq, n.d.). It is patented and is currently manufactured by the company Kenoteq. One of the companies that design and produce prefabricated straw bale panels is EcoCocon, which uses compressed straw within wooden frames.

(EcoCocon, n.d.) Further information is available on the technical data sheets presented on their website.

Table 2. Material properties required by OpenStudio to define materials.

conventional materials	1- Roughness	2- Thickness (cm)	3- Conductivity (W/(m.K))	4- Density (kg/m3)	5- Specific heat (J/ (kg.K))	6- Thermal absorptance (kJ/ (m3·K))	7- Solar absorptance	8- Visible absorptance
hollow clay tile		(8.5 - 30 cm) 19 cm	0.692 W/(m.K)	1121 kg/m3	837 J/ (kg.K)			
autoclaved aerated concrete		(10 - 40 cm) 19 cm	0.240 W/(m.K)	750 kg/m3	1000 J/(kg.K)			
alternative materials								
adobe bricks (unfired clay bricks)		(2×10.4) 20.8 cm	0.9 W/(m.K)	1788 kg/m3	545 J/(kg.K)			
cork blocks		30 cm	0.080 W/(m.K)	530 kg/m3	1800 J/(kg.K)			
mycelium blocks		30 cm	0.081 W/(m.K)	57.452 kg/m3	0.369 MJ/(m3*K) 6418.6 J/(kg.K)			
Hempcrete		30 cm	0.07 W/(m.K)	330 kg/m3	1280 J/(kg·K)			
Cannabric		30 cm	0.19 W/(m.K)	1171 kg/m3	1113 J/(kg.K)			
Algae based cement		NA	NA	1600 kg/m3	NA			
K-Briq		10.25 cm	0.74 W/(m.K)	1750 kg/m3	NA			
Sugarcrete		10 cm	0.065 W/(m.K)	NA	NA			
Straw bale panels		30 cm	0.0645 W/(m.K)	110 kg/m3	NA			
	related to surface adhesion					necessary for the visible materials		

The information on the Table 2 regarding hollow clay tile and aerated concrete is obtained from the IESVE (Integrated Environmental Solutions Virtual Environment) database. The materials are represented with the names “Hollow Clay Tile – 3 Cells – CT06” and “Aerated Concrete Block” (IESVE, n.d.). Thicknesses of the materials in Table 2 are determined considering the common sizes utilized in the construction industry in Turkey and considering the suggested thicknesses by the producer companies for the materials that aren’t currently used in Turkey. A thickness of 30 cm is preferred for the bio-based materials, which is a common available product thickness for all of them. However, it should be noted that the thicknesses in Table 2 reflect the ones that are accessed through the literature review and not exactly the ones that are used in the simulations in this study. Exact wall configurations and material thicknesses are determined in relation with the TS825 building code in Turkey titled “Thermal Insulation Requirements for Buildings” and are presented in Table 3.

The data regarding the adobe bricks in Table 2 are taken from the test results conducted in a controlled environment (Fgaier et al., 2015). Data regarding the cork blocks are acquired from the IESVE database again, accessible under the name of cork tiles (IESVE, n.d.). It should be noted that there are much less dense versions of the cork blocks in the construction market (CORKLINK, 2004). Low-density cork performs better in terms of thermal performance and worse in terms of mechanical performance. Since the cork block is utilized as a wall material rather than an insulation material in this study, a denser version was preferred. The information regarding the mycelium blocks is acquired from the test results of an academic study (Xing et al., 2018). The most dense mycelium block detected in the literature and the market is selected for this study. However, an even more dense version might be necessary to use them as an infill material. Further experimental study is necessary to obtain and test a denser version and is not the subject of this thesis. The numerical data regarding Hempcrete is acquired from the technical data sheet of a company producing Hempcrete blocks (HempBlock Company, n.d.). The data regarding the Cannabrick is obtained from the technical data sheet of Cannabric Company (Cannabric, 2008).

The accessible data regarding algae-based concrete is obtained from an academic study (Qiu et al., 2021). For the K-Briq, the related company was generous in terms of sharing the material documentation. Unfortunately, neither of them included the specific heat data. However, these sources are not online and were directly provided to me by the company via email. The accessible data regarding Sugarcrete is obtained from a report provided by the University of East London (Gutierrez et al., 2021). Accessible data regarding straw bale panels are obtained from the brochure titled "Wall System Designed by Nature" published by EcoCocon company (EcoCocon, n.d.). Pointing out missing information about the materials, this table underscores the literature gaps necessary to be studied for further examination of the material’s operational performances in simulation environments. On top of that, it provides transparency regarding the physical and thermal properties of the utilized materials. Material properties might differ between products according to the content percentages and production methods. Hence, one might want to compare a cork block’s thermophysical values with the values that are utilized in this

thesis before making any inferences. Table 2 provides reference for the reader to make such comparisons of materials.

3.2.5 Comparison of U Values of the Wall Sections with Different Materials Considering the Local Building Code

In Turkey, the building code titled as “TS825 - Thermal Insulation Requirements for Buildings” is used for determining the envelope materials and thickness of buildings. TS825 provides the minimum insulation requirements in the form of a maximum U value of building envelopes for different climate regions in Turkey. The code divides Turkey into four main regions according to the prevalent climate, in which Istanbul is located in Region 2. In the same code, the maximum U value (W/m2.K) of an envelope wall is given as 0.6 for Region 2.

In theory, all the materials examined in section 3.2.3 can be used to create a wall section with the same U value, if the correct thicknesses are chosen. Same u-values would result in the same operational thermal performance when excluding the humidity and air-permeability related behaviors of these materials. However, the walls with these same u-values might result in extremely different wall thicknesses and wall weights per unit area, which causes problems both in the infill material product level and the building level structural behaviors. Hence, this study adopts a combined approach for determining the wall section configurations that are going to be used in the simulations, both considering the infill material product characteristics and the TS825 building code.

Table 3 presents the different wall section options with different thicknesses of the infill material layer and the insulation layer varying according to a systematic method. In this method, each infill material might have an Option-1, Option-2, or Option-3 as its wall section that might be selected for the simulations in this study. All the Option-1 sections include a 5.5 cm insulation layer, determined according to the most common infill material in Istanbul, which is hollow clay tile. To achieve this, first the common hollow clay tile thickness of 19 cm in Turkey and its conductivity from Table 2 are entered to Table 3. Afterwards, the information for 25 mm stucco on outside and 12 mm gypsum board are taken from the OpenStudio database where the simulations will take place.

Lastly, conductivity of a typical insulation material in Turkey, which is rock mineral wool, is entered according to the data sheet of the producer company, Izocam (IZOCAM, 2019). The initial thickness of 5 cm is assigned for the insulation material and the total R and U values are calculated for the wall section. However, it is seen that the resulting U value is higher than the maximum U value of 0.6 as stated in TS825 (Turkish Standard Institute, 2009). The insulation thickness is increased to 5.5 cm to reduce the U value under 0.6 and this thickness is kept constant for all the Option-1 wall sections with different infill materials.

In addition, roof construction has an important role in the total operational energy consumption of a building, although it is not a subject of this study. The assigned roof construction's U value is calculated as 0.228, while the maximum U value of a roof section is stated as 0.4 for Istanbul in the building code TS825 (Turkish Standard Institute, 2009). Hence, the U value of the roof construction assigned to the case study building is far below the upper limit defined by Turkish Standard Institute.

Table 3. Determination of material thicknesses according to the wall Section U values.

Wall Sections	Material Layers	Material Thickness (m)	Conductivity (W/mK)	R Value (m²K/W)	Total R Value (m²K/W) of the Section	Total U Value (W/m²K) of the Section	Examination According to TS825	Density (kg/m³)	Weigth per m² (kg/m²)	Total Weigth (kg/m²) (excluding the insulation layer)
Hollow Clay Tile Section Opt.1	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Hollow Clay Tile	0.19	0.692	0.274566				1121	212.99	
	Typical Insulation (Rock Mineral Wool-IZOCAM) R-8.72	0.055	0.04	1.375						
	1/2IN Gypsum	0.0127	0.16	0.079375	1.764219252	0.5668229723	<0.6	784.9	9.96823	270.10063
Autoclaved Aerated Concrete Section Opt.1	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Autoclaved Aerated Concrete	0.19	0.24	0.791666				750	142.5	
	Typical Insulation (Rock Mineral Wool-IZOCAM) R-8.72	0.055	0.04	1.375						
	1/2IN Gypsum	0.0127	0.16	0.079375	2.281319444	0.4383428206	<0.6	784.9	9.96823	199.61063
Adobe Section Opt.1	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Adobe Bricks (unfired clay bricks)	0.104	0.9	0.115555				1788	185.952	
	Typical Insulation (Rock Mineral Wool-IZOCAM) R-8.72	0.055	0.04	1.375						
	1/2IN Gypsum	0.0127	0.16	0.079375	1.605208333	0.622972096	>0.6	784.9	9.96823	243.06263
Adobe Section Opt.2	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Adobe Bricks (unfired clay bricks)	0.208	0.9	0.2311111				1788	371.904	
	Typical Insulation (Rock Mineral Wool-IZOCAM) R-8.72	0.055	0.04	1.375						
	1/2IN Gypsum	0.0127	0.16	0.079375	1.720763889	0.5811372533	<0.6	784.9	9.96823	429.01463
Cannabric Section Opt.1	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Created Cannabric	0.3	0.19	1.578947				1171	351.3	
	Typical Insulation (Rock Mineral Wool-IZOCAM) R-8.72	0.055	0.04	1.375						
	1/2IN Gypsum	0.0127	0.16	0.079375	3.068600146	0.325881494	<0.6	784.9	9.96823	408.41063
Cannabric Section Opt.2	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Created Cannabric	0.3	0.19	1.578947				1171	351.3	
	1/2IN Gypsum	0.0127	0.16	0.079375	1.693600146	0.5904581446	<0.6	784.9	9.96823	408.41063
Cork Block Section Opt.1	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Cork Block	0.3	0.08	3.75				530	159	
	Typical Insulation (Rock Mineral Wool-IZOCAM) R-8.72	0.055	0.04	1.375						
	1/2IN Gypsum	0.0127	0.16	0.079375	5.239652778	0.1908523413	<0.6	784.9	9.96823	216.11063
Cork Block Section Opt.2	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Cork Block	0.3	0.08	3.75				530	159	
	1/2IN Gypsum	0.0127	0.16	0.079375	3.864652778	0.2587554581	<0.6	784.9	9.96823	216.11063
Cork Block Section Opt.3	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Cork Block	0.125	0.08	1.5625				530	66.25	
	1/2IN Gypsum	0.0127	0.16	0.079375	1.677152778	0.5962486025	<0.6	784.9	9.96823	123.36063
Hempcrete Section Opt.1	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Hempcrete Block	0.3	0.07	4.285714				330	99	
	Typical Insulation (Rock Mineral Wool-IZOCAM) R-8.72	0.055	0.04	1.375						
	1/2IN Gypsum	0.0127	0.16	0.079375	5.775367063	0.1731491677	<0.6	784.9	9.96823	156.11063
Hempcrete Section Opt.2	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Hempcrete Block	0.3	0.07	4.285714				330	99	
	1/2IN Gypsum	0.0127	0.16	0.079375	4.400367063	0.227253769	<0.6	784.9	9.96823	156.11063
Hempcrete Section Opt.3	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Hempcrete Block	0.11	0.07	1.571428				330	36.3	
	1/2IN Gypsum	0.0127	0.16	0.079375	1.686081349	0.5930911937	<0.6	784.9	9.96823	93.41063
Mycelium Block Section Opt.1	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Mycelium Block	0.3	0.081	3.703703				57.452	17.2356	
	Typical Insulation (Rock Mineral Wool-IZOCAM) R-8.72	0.055	0.04	1.375						
	1/2IN Gypsum	0.0127	0.16	0.079375	5.193356481	0.1925536989	<0.6	784.9	9.96823	74.34623
Mycelium Block Section Opt.2	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Mycelium Block	0.3	0.081	3.703703				57.452	17.2356	
	1/2IN Gypsum	0.0127	0.16	0.079375	3.818356481	0.2618927816	<0.6	784.9	9.96823	74.34623
Mycelium Block Section Opt.3	25mm Stucco	0.0254	0.72	0.035277				1856	47.1424	
	Mycelium Block	0.13	0.081	1.604938				57.452	7.46876	
	1/2IN Gypsum	0.0127	0.16	0.079375	1.719591049	0.5815336154	<0.6	784.9	9.96823	64.57939
Roof	Roof Membrane - Highly Reflective	0.0095	0.16	0.059375				1121.29	10.652255	
	Typical Insulation R-24.52 129			4.318887					0	
	Metal Roof Surface	0.0008	45.28	0.000017	4.378279668	0.228400211	<0.4	7824	6.2592	16.911455

If the total U value of any Option-1 wall is far below 0.6 with the 5.5 cm insulation layer, the insulation layer is removed from the wall section to check the U value again. If the U value of an Option-1 wall is above 0.6 with the 5.5 cm insulation layer, the infill material thickness is doubled, considering the product thickness of the infill material. Hence, it is considered that the infill material is applied as two rows to overcome the U value inconsistency with the local building code. Option-1 and Option-2 of adobe bricks in Table 3 presents such a situation, in which Option-2 has two rows of the product in Option-1.

Some materials show extra ordinary thermal performance with u values far below 0.6, even without any insulation layer. These materials are cork, hempcrete, and mycelium blocks as seen in Table 3. Thickness of these materials are stated as 30 cm by their producer companies when they are used to construct walls and this study adopts Option-2 wall sections with their original thicknesses. However, Table 3 also presents the minimum thicknesses of these materials to achieve below 0.6 U values in Option-3 wall sections. In this way, it is aimed to present the materials' potential for reduction in material usages and total building weight when they are used as infill materials in exterior walls. The material weights are calculated with their densities stated by their producer companies as discussed in section 3.2.4 and the assigned thicknesses. Still, it should be noted that Option-3 sections in Table 3 show only a hypothetical thickness of these infill materials and compromise from their superior operational energy performance while reducing their thickness. It should also be studied how such a reduction in their thickness results in their durability and structural performance.

As a result, Option-1 for hollow clay tile and aerated concrete are selected for the simulations. Both Option-1 and Option-2 are selected for Cannabric since it is also far below U value of 0.6 in Option-1, but it is very close to 0.6 without any insulation layer in Option-2. Only Option-2 of adobe, which has a double row of the infill material, is selected for the simulations since Option-1 doesn't satisfy the maxim U value of 0.6. Option-2 selected for Hempcrete, cork, and mycelium blocks since they are still far below of the maximum U value of 0.6 and they have the thickness of available products

designed as infill material. The selected wall sections are marked in a green frame in Table 3 and presented as section drawings in figure 16.

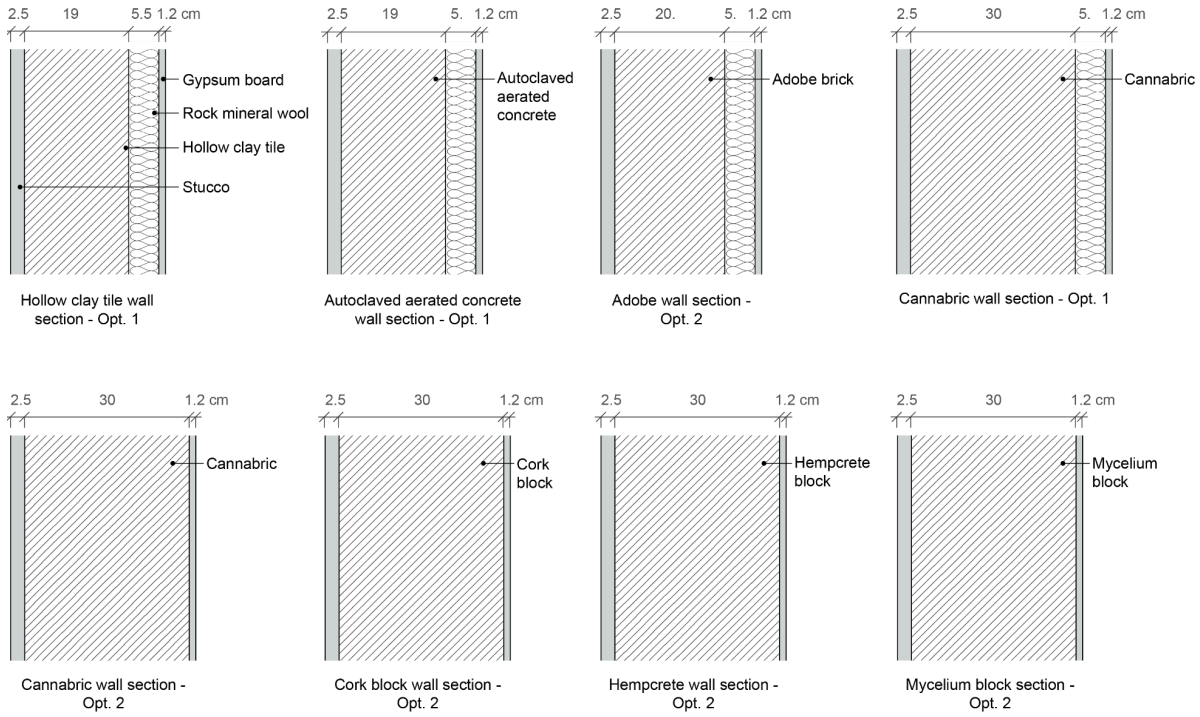


Figure 16. Wall sections selected for the simulations.

This chapter presents the detected conventional wall infill materials and alternative materials for the mid-rise residential buildings in Istanbul, covering their introductory information, thermophysical characteristics, and wall configurations according to the local building code TS825 in Turkey. The chapter also discusses which alternative materials had to be excluded from the simulations due to a lack of thermophysical data. This exclusion highlights gaps in the literature and suggests areas for future research on the operational behaviors of these materials, which could potentially reduce the environmental impact of urban mid-rise residential buildings. In Chapter 4 and Chapter 5, the use of selected materials in simulations and their resulting operational performance will be examined in further detail.

CHAPTER 4

METHODOLOGY: DATA COLLECTION AND SIMULATION DESIGN

This thesis utilizes a between-scales architectural study, focusing on both urban and building scale data. The author aims to compare design options on building scale while considering the effect of urban scale conditions as much as possible. The urban scale data is utilized in two ways. First, the building stock data of Istanbul and Maltepe is compiled and analyzed to select the case study building and to enrich the real footprint of the selected case study building. Hence, the case study building is not used directly as it is but it is simplified first and enriched again to represent a wider building stock. Second, the surrounding built area of the case study building is modeled to capture the building morphology and surface materials. This urban-scale model is then utilized to obtain unique weather data considering the urban heat island (UHI) effect. Both of these steps are explained in further detail in the following subsections of this chapter.

The methodology of the thesis is largely shaped around the input requirements of the utilized simulation software for the intended outcomes. The further goals of the thesis, such as empowering the connection between urban data and building scale results of the study, resulted in an enriched methodology with additional steps to alter the inputs accordingly. For instance, the weather data and 3D case study building model as two vital inputs of the simulations, were altered with additional steps before they are given to the simulation to represent the local urban environment. In those additional steps, R

programming language and Rhino-Grasshopper software were used to alter or enrich the inputs, which will be further examined in the following parts of this chapter. Figure 17 visualizes the overall workflow of this study.

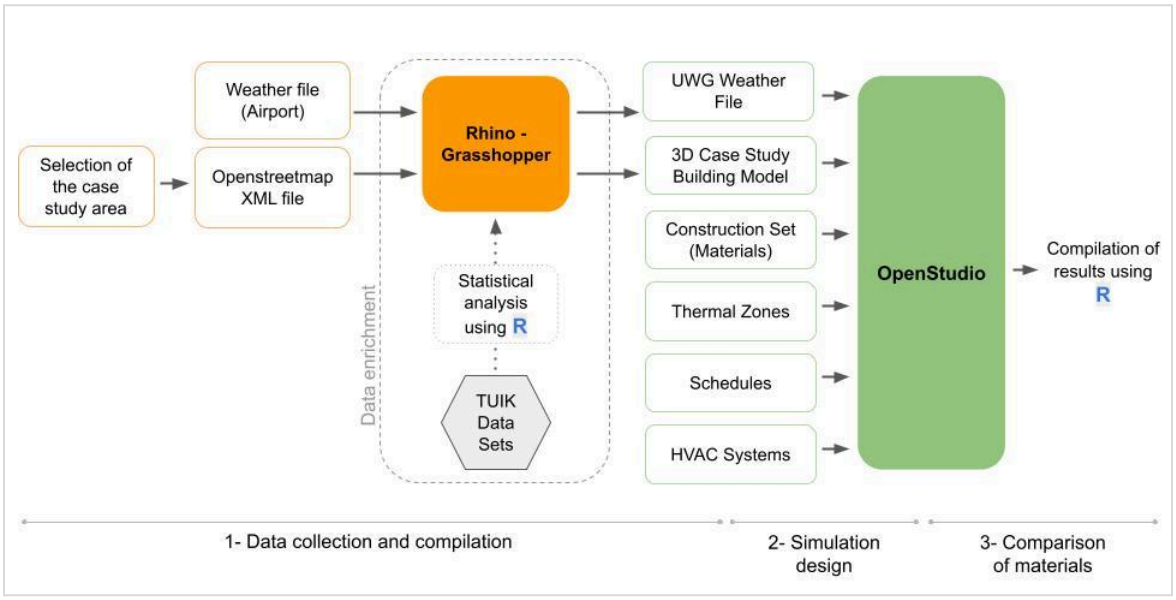


Figure 17. The directed graph presenting the methodology of this thesis.

4.1 Selection and Representation of the Case Study Building and the Site

The first step of this thesis consists of the selection of the case study area and its morphological representation inside Rhino-Grasshopper to obtain a local weather file. This local weather file considers the UHI effect in the area unlike the weather file obtained from a nearby airport. This initial step included both the utilization of readily available data and some data-enrichment processes, which will be explored in the following paragraphs. The resulting weather file is then exported and utilized in building energy simulations conducted inside OpenStudio. Further information regarding the formation of the local weather file and the resulting graphics will be examined under the section 4.3 Weather File.

The case study building and the considered urban area are located in the Maltepe district of Istanbul. Istanbul is the most crowded city in Turkey with an official current population of over 16 million and an extraordinarily large urban macroform. Its urban

morphology has diversity with historical sites, high-rise and mid-rise commercial and residential districts with contiguous or separate order layouts, and a relatively small amount of rural settlements in the outskirts of the macro form. Despite this diversity throughout the macro form, it mostly has high density with little green areas in the central districts of the city, which results in unhealthy indoors and outdoors with high UHI effects, air pollution, and accessibility problems. Such a dense and high environmental impact urban environment requires building-scale measures that can change traditional construction processes to alter the sustainability and occupant comfort of the built areas.

While the ever-increasing population continues to boost housing demand and large old building stock constantly undergoes urban transformation processes in different parts of the city, there are not many measures taken to reduce neither the embodied nor operational carbon footprint of the ongoing construction processes in Istanbul. On the other hand, always transforming building stock creates an opportunity to be a living lab for sustainable building methods. Hence, Istanbul is a city that has both increasing sustainability problems and opportunities to improve solutions to these problems, thus motivating this thesis.

The specific district of Istanbul where the case study area and the building are located, Maltepe, is selected according to four main criteria. First, it is known that it has a relatively young residential building stock with ongoing construction activities, allowing the author to observe the most up-to-date building typologies and develop solutions compatible with contemporary approaches. Second, it has areas with the highest building footprint density in Istanbul, making it easier to observe urban-scale problems such as the UHI effect (Kaya et al., 2012). Urban morphology maps created and published by The Istanbul Metropolitan Municipality showcase the regional density and urban texture in comparison to other areas of Istanbul (IBB, 2017). Third, Maltepe is located in the southern part of Istanbul where a specific sub-climate is dominant. Most of the densely built neighborhoods in city centers are exposed to this sub-climate in Istanbul. Selecting an area with the most occupied sub-climate makes the results of this thesis valuable for a wider setting. Lastly, Maltepe has a detached system of planning. Although there are many districts with adjacent systems of planning in Istanbul, it is well-known that

detached planning is safer for earthquake-prone areas. When the floor slabs of adjacent buildings are at different levels, they hit against the columns of each other and might result in collapse (Bachmann, 2003, 50). Since Istanbul is a city with a high earthquake risk, an area with detached planning was preferred for this study, considering that all earthquake-prone settlements should develop towards a detached planning system.

In Maltepe, a group of building blocks reflecting the common morphology of the area is selected. The selected area is kept large enough to simulate the urban heat island effect, which corresponds to several parallel streets. In addition, attention is given to ensure that the building group consists of young buildings, since the thesis focuses on the building stock constructed after 2008. This selected area is then used to simulate the urban weather that the case study building is exposed to. Simulating urban weather requires a decent representation of the regional morphology. To recreate the selected area with the necessary level of detail in the simulation environment, the building footprints in the area are obtained from the OpenStreetMap (OSM) database as an XML file and imported into Rhino-Grasshopper for further data enrichment processes.

The OSM data in the XML format is introduced to the Grasshopper by using the File Path component. The point data inside the OSM, such as land use, highways, and buildings, is checked using the OSM Data component. Afterward, the point data regarding the buildings is converged into polylines using the Polyline component. Figure 18a shows the point data and the constructed building footprints in the selected case study area, which will be used to simulate the local Urban Heat Island (UHI) effect. The Grasshopper definition of importing and examining the OSM data can be found in Appendix A, Figure A.1. After this step, the polylines forming the building footprints are baked into surfaces, the missing buildings are added using satellite images, and the resulting geometry is reintroduced as building footprints into the Dragonfly addon inside Grasshopper.

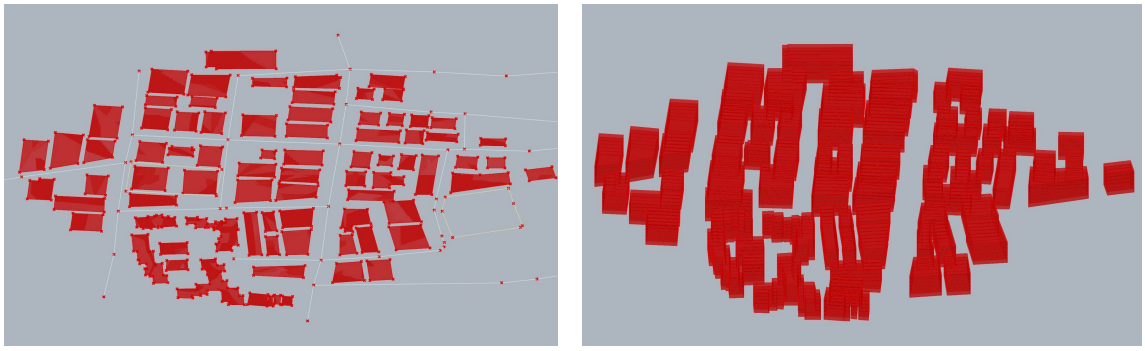


Figure 18a. Building footprints constructed with the OpenStreetMap point data. Figure 18b. Elevated buildings using the Dragonfly addon.

All the enrichment regarding the morphological data is introduced using the Dragonfly and Ladybug addons inside Grasshopper to eventually simulate the heat island effect and create the weather data to be used in OpenStudio simulations. Figure 18b shows the buildings with assigned floor-to-floor heights and the number of floors in Dragonfly. Dragonfly only visualizes these two pieces of information while all the other assignments such as surface materials and window-to-wall ratio exist only in the Grasshopper definition without any visual representation, which can be seen in Appendix A, Figure A.2. Green areas and surface materials are assigned in accordance with satellite images and added as a percentage of the total ground area. Large trees are added with a basic geometry according to their location and size in satellite images. The window-to-wall ratio of buildings is specified as 35%. Following the statistical analysis conducted with TURKSTAT data, the number of stories of buildings is assigned as 6. Further details regarding the data enrichment of the site and the resources of the enrichment data will be discussed in the following sections.

4.1.1 Examining the Residential Building Stock in Istanbul

This study focuses on mid-rise residential buildings as a common housing typology in city centers. Before determining the case study area and the building, the existing residential building stock of Istanbul and Maltepe is studied through data compilation and statistical analysis using the R programming language. First, the Building Permits Dataset (Yapı İzin İstatistikleri) of Istanbul separated by municipalities is obtained from

TURKSTAT. Every constructed building in Turkey needs to have a building use permit to start to be used by occupants. Therefore, the building permits in this dataset are utilized to represent the constructed buildings. The obtained dataset includes construction year, municipality of the building site, the function of the building, number of stories, total number of flats, total core area, total main function area, total area other than the main function and core areas, load-bearing structural system, and wall infill material. The R code used for compiling and visualizing the TURKSTAT data can be found in the author's online repository on GitHub (Erincik, 2024).

As a first step, this data is cleaned from any building typologies other than multi-family residential buildings and data before 2008. The reason for considering the data starting from 2008 is the Earthquake Regulation enacted in 2007. After the devastating 1999 earthquake in Golcuk affecting Istanbul and the whole Marmara Region, the current building code enacted in 1998 was updated with further measures towards earthquake damages in 2007 (Nemutlu & Sarı, 2018). The author chooses to use the data starting from 2008 to consider only the buildings that are compatible with the 2007 building code.

As a second step, the most common number of floors for multi-family residential buildings is detected by finding the mod of the number of floors data for both Istanbul and Maltepe. The most common number of floors for multi-family residential buildings in Istanbul is found as 5 (figure 19). However, this is 6 for Maltepe (figure 20). Subsequently, the case study area in Maltepe is examined through satellite images to compare the existing number of floors with the acquired statistical values. It is seen that the acquired values are highly compatible with the existing urban texture. In an expected way, the case study building in the center of the case study area is also a 6-story building, which will be examined in further detail in section 4.1.2.

The following data compilation and statistical analysis focus only on Maltepe and are conducted with the goal of enriching the case study building's footprint with neighborhood-level data. To achieve this, the building plan properties such as "total area per story", "individual flat area", and "core area per story" for 6-story apartments in Maltepe are obtained by compiling the building permits data using R. Afterwards, the first quartile, second quartile, and median values of these plan features are presented as

box plots to have a more clear profile of the local building stock, eliminating the extreme values and showcasing the data distribution between. However, it should be noted that only the information related to the 6-story multifamily residential buildings with a total floor area between 400-450 m2 is included in the boxplot since the case study building has a floor area between these values and has 5 stories. The medium values are then utilized to enrich the case study-building data.

In the data compilation process, available data in the building permits data are used to obtain some descriptive plan features. The “total area per story” of buildings is calculated by dividing the total area by the number of stories, which exist within the building permits dataset. The "individual flat area" is calculated by dividing the total residential area of each building by the number of flats. The “core area per story” is calculated by dividing the common area of each building by the number of stories. The obtained results are rounded to the nearest integers. The boxplots, displaying the first quartile, second quartile, and median values, are presented in section 4.1.2.

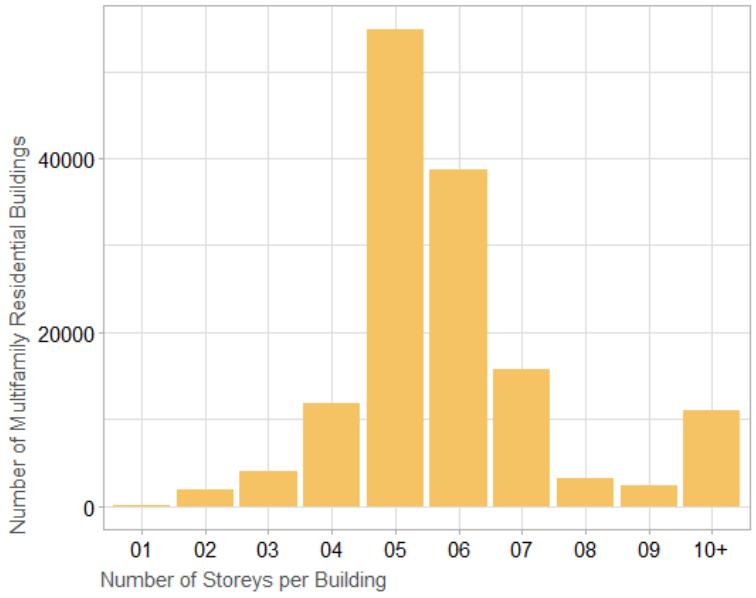


Figure 19. Number of stories of multifamily residential buildings in Istanbul.

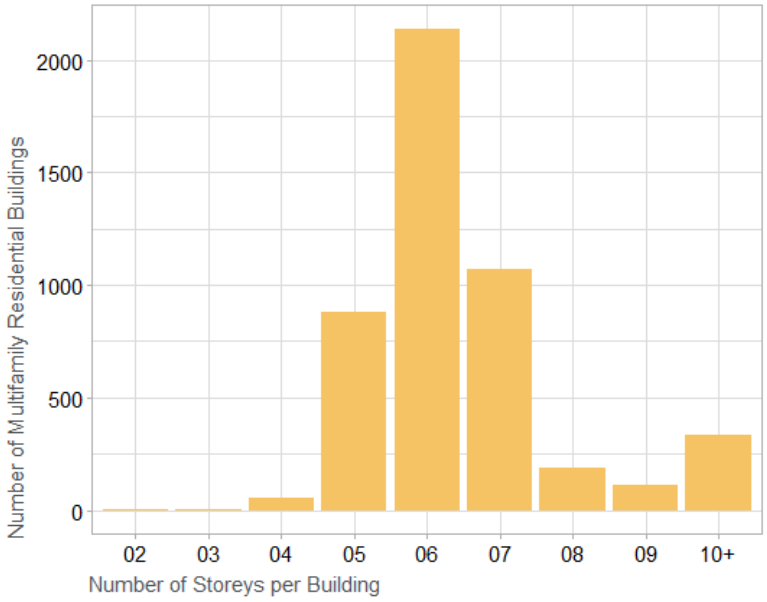


Figure 20. Number of stories of multifamily residential buildings in Maltepe.

4.1.2 Case Study Building and the Data Enrichment Method

The case study building is selected as a relatively new (constructed in 2013) and ordinary example of mid-rise residential building stock in Maltepe. The real building footprint and the real number of stories of the building are used in the study, while the other information such as core area per story and individual flat area are obtained from statistical analysis conducted on the Building Permits data set of TURKSTAT, as explained in the section 4.1.1. In other words, the real building footprint and the number of stories of the case study building are enriched with statistical values representing the common building stock in Istanbul. With this data enrichment process, a simple and symmetrical interior plan scheme is formed. Afterward, the real floor plan of the building is obtained from Maltepe Municipality. The comparison of the generated and the real floor plans of the case study building shows high similarity, validating the use of the developed data enrichment method for this study.

There are some advantages and drawbacks of using the simplistic generated plan rather than using the real plan of the case study building. The first advantage is that the generated plan has four equal flats with different orientations. While the real plan also has four very similar flats with different orientations, their slight spatial differences prevent

treating them as equal experiment subjects to examine the construction material's operational performances. In that case, their operational energy consumptions stemming from different wall infill materials can not be compared to each other without considering the effect of their spatial differences on their operational energy consumptions. However, when they are of equal form and area, their spatial configurations become constant variables. The only non-constant variable in the simulations other than the infill material is the orientation of flats. The variability of the flats' orientation doesn't change the building-level outcomes of the simulations. However, it makes it possible to observe if there is any difference in the material performances of an individual flat because of its orientation. The case study building has four flats with four different orientations in each six stories. Hence, it is possible to see the differences in occupant comfort and the related energy consumption levels of different flats in the simulation results, which both stem from different infill material utilization and the located facade and floor of the flat.

The second advantage of using a generated plan is simulation efficiency. A higher number of spaces and geometry increase the required simulation time and computer power significantly (Brackney et al., 2018, pp. 18). On the other hand, the details in the real plans wouldn't create significant differences in the operational performances of different materials in comparison to each other. The goal of this study is not to calculate the exact yearly energy consumption of a building but to the differences in the energy consumption levels stemming from different exterior wall infill materials. Hence, the generated and simplistic plan is effective and more efficient for this study.

The drawback of using a generated plan over the real plan is the impossibility of calculating the exact operational energy consumption of a flat in the case study building. However, the goal of this study is not to obtain an ideal solution for an individual building but to compare different materials to find out the most promising ones for the selected urban built environment. Hence, it is believed that using a generated plan is convenient for a study in urban environments since the results would be more relatable to a wider range of buildings. It is beneficial to note that there are already some initiatives and academic studies aiming to represent contemporary residential building stock in urban environments by dividing them into typologies. TABULA, one of these initiatives,

uses local building stock databases in European countries to inform local building experts about widespread typologies in contemporary environments (Loga et al., 2017). They consider the energy-related aspects of buildings when defining these typologies and argue that this will help create and implement future energy efficiency and sustainability measures. Similarly, this thesis chooses to approach the case study building as part of a typology that covers a larger group of buildings and is prevalent in the urban built environment of Maltepe/Istanbul.

Creating a representation of the case study building with its surrounding and its introduction into the OpenStudio simulation environment requires several steps. The first step consists of importing the building footprints from OpenStreetMap as an XML file to the Rhino-Grasshopper, as is explained further in section 4.1. Afterward, the footprint of the case study building is defined as a surface inside Grasshopper and enriched with floor plan data from the statistical analysis results in R. The data that are used to enrich the building footprint is presented with boxplots in the figures below. In the first box plot (figure 21a), the middle line of the box shows the median value of individual flat areas for 6-storey residential buildings in Maltepe. The upper and lower lines of the box represent the first and third quartiles of the data. Similarly, the middle line of the second box plot shows the median value of core area per story for 6-story residential buildings in Maltepe (figure 21b). Again, the upper and lower lines of the box represent the first and third quartiles of the data. These two data are mainly used to generate the floor plan of the case study building.

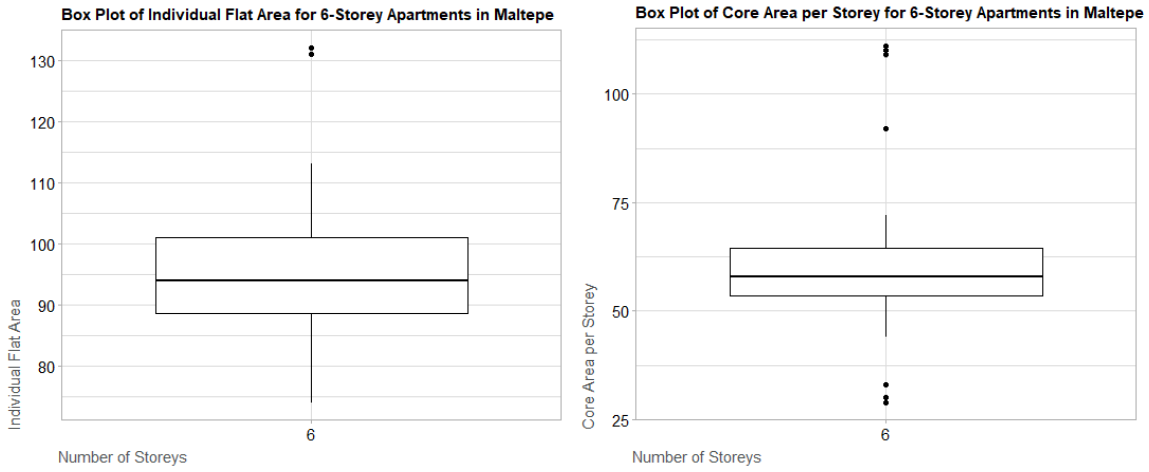


Figure 21a. Individual flat area for 6-story apartments in Maltepe. Figure 21b. Core area per story for 6-story apartments in Maltepe.

The approximate median value of the core areas per story, which is 55 m^2, is used to shape a core in the center of the footprint by using the Scale component in Grasshopper. The core is located in the center without exterior facades to obtain flats with equal facade areas. The area around the core is divided into four symmetrical flats, each with an area of approximately 92 m^2. The areas of generated flats are calculated using the basic Math components in the Grasshopper, presenting that the generated flat areas are highly compatible with the median value of individual flat areas in the related box plot. Afterward, the 2D flat and core geometries are introduced into the Dragonfly addon using the Dragonfly Room 2D component. (figure 22a) The floor-to-floor heights are determined as 3 meters considering that the floor-to-ceiling height would be 2.80 meters. The floors are brought together using the Dragonfly Story and Dragonfly Building From Stories components. These last two steps also classified wall and floor surfaces as interior or exterior. The Grasshopper definition of creating the case study building's basic floor plan and turning it into a building can be found in Appendix A, Figure A.3, Figure A.4, and Figure A.5.

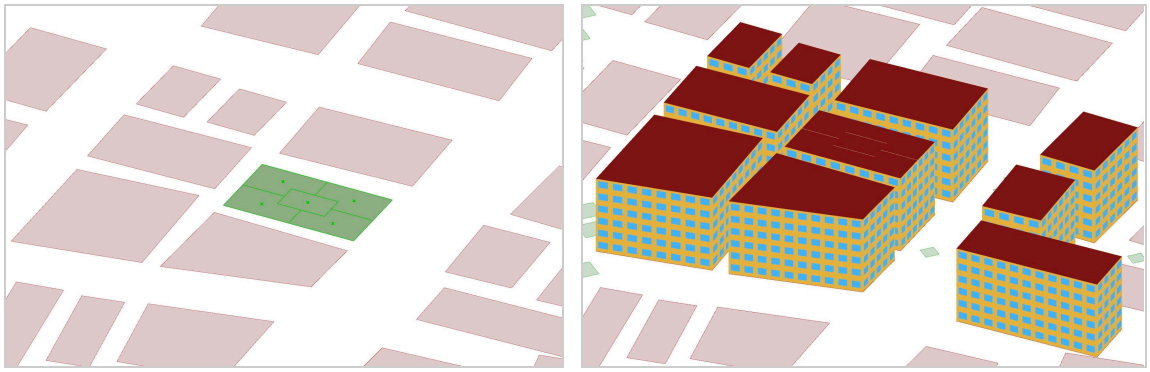


Figure 22a. The case study building with the generated configuration of flats. Figure 22b. The case study building and the surrounding buildings with their generated facades.

The floor heights and window-to-wall ratio (WWR) are also determined in the Grasshopper using the Dragonfly WWR Parameters component. The WWR is chosen from a certain range without depending on any building stock data. There is not any information regarding the widespread WWRs in Istanbul in the data sets of TURKSTAT or the literature to the knowledge of the author. In the Turkish Thermal Insulation Regulations in Buildings (Binalarda Isı Yalıtım Yönetmeliği) dated 2008, there is no clear limit for WWR. However, different rules are defined in the WWR as less than 12% or greater than 60% (Bayındırlık ve İskân Bakanlığı - Ministry of Public Works and Settlement, 2008). There are some studies in the literature using Turkey-based case study buildings. The authors in those studies assign WWRs such as 20%, 40%, 60%, 80%, 100% (Altun, 2022) and 45%, 30%, 15% (Cetiner et al., 2007) to the case study buildings to find the ideal WWR in terms of energy efficiency. Another Turkey-based study shows that an increase in the WWR of a multifamily residential building from 30% to 40% might result in a 20% increase in total heat losses of a building (Koyun & Koç, 2017). On the other hand, a high WWR ratio increases the use of natural light, which is an important factor for sustainable design. Hence, an average WWR of 35% was chosen for this thesis. However, the ideal WWR might differ from building to building depending on many factors and is the subject of another study.

Figure 22b shows the raised building footprints with the assigned WWR for both the case study building and other buildings in its immediate vicinity using the Dragonfly and Honeybee addons. While Dragonfly doesn't visualize the WWR, Honeybee allows more

detailed visualization at the building scale and exports models in the .osm file format to be used in OpenStudio. For this reason, the case study building and the surrounding buildings are introduced into Honeybee using the “Dragonfly Model To Honeybee” component. The Grasshopper definition enabling the transition between Dragonfly and Honeybee addons and exporting the .osm file can be found in the Appendix A, Figure A.6. The Grasshopper definition to represent the buildings surrounding the case study building in the .osm file can be found in the Appendix A, Figure A.7. The reason for including the surrounding buildings in the Honeybee model is that they are going to be used in OpenStudio as shadow elements, as will be further explored in section 4.2.2.

4.2 OpenStudio as a Simulation Software and Simulation Design in OpenStudio

This section focuses on the selection of the Openstudio software as the simulation environment, its input requirements, output options, and the resulting simulation design unique to this study. While the section 4.2.1 examines the characteristics of OpenStudio as a simulation software and the reasons for choosing it for this study, the section 4.2.2 presents the unique input preferences and constant/non-constant variables between simulations conducted to compare different exterior wall infill materials.

4.2.1 Selection of OpenStudio as the Simulation Environment

OpenStudio was first released as a Software Development Kit (SDK) by the National Renewable Energy Laboratory (NREL) to facilitate the development of new Building Energy Modeling (BEM) applications (Brackney et al., 2018, 5-7). International Business Machines Corporation (IBM) defines SDK as “a comprehensive collection of tools that enable software developers to build software applications faster and in a more standardized way.” (IBM Cloud Education, 2021) OpenStudio SDK has an open-source license that allows companies to create and sell their derivative works using the SDK (Brackney et al., 2018, 5-7). This thesis does not use OpenStudio SDK, but OpenStudio API (Application Programming Interface), also known as OpenStudio Application. OpenStudio API is a specialized version of OpenStudio SDK, with an interface and additional aspects to bridge the gap between complex simulation physics, the utilized programming language, and end users. End users of it can include architects, engineers,

policymakers, and even homeowners. It is currently maintained by the OpenStudio Coalition, which was founded to develop the graphical applications of OpenStudio SDK (NREL - National Renewable Energy Laboratory, n.d.). Hence, It is a software that is ensured to continue to be developed.

There are some well-known software to be used in the fields of Building Energy Modeling (BEM) and Urban Building Energy Modeling (UBEM) such as Ladybug addon inside Rhino-Grasshopper, TRNSYS, ENVI-met, IESVE, and commercial software DesignBuilder. However, OpenStudio was preferred for this thesis for a couple of significant reasons. First of all, OpenStudio is free-to-use, open-source software that provides flexibility in terms of the purpose of the simulation. It can be used to compare early design options, estimate occupant comfort with varying comfort models, and calculate the building energy consumption level of an existing building with high precision. Furthermore, thanks to being an open-source software, its abilities can be developed by the users themselves who are eligible to use programming languages. Specialized simulation abilities can be added by preparing and introducing packages called “OpenStudio measures” to the simulation environment. Hence, adopting OpenStudio as the primary building energy modeling tool allows users to enrich the software following their specialized needs.

OpenStudio uses EnergyPlus as its simulation engine, which is a significant factor that makes it superior. EnergyPlus is an open-source whole-building energy modeling (BEM) engine that has been under development since 1997. It was being developed by many esteemed institutions such as the National Renewable Energy Lab (NREL), Lawrence Berkeley National Lab (LBNL), University of Illinois (UIUC), etc. (The U.S. Department of Energy, 2014). It is a comprehensive engine that implements detailed building physics for air, moisture, and heat transfer. It can calculate thermal comfort metrics, lighting, shading, and visual comfort metrics. While the commercial software DesignBuilder also uses EnergyPlus as its simulation engine, OpenStudio being a free and open-source software was preferred over DesignBuilder.

Another prominent feature of OpenStudio is cloud computing. Cloud computing is defined as “on-demand access of computing resources over the internet with pay-per-use

pricing.” by IBM and it allows users to run their calculations on a physical or virtual server without relying on their computer (Susnjara & Smalley, 2024). Hence, the cloud computing option of OpenStudio enables users to run large-scale sampling, optimization, and other analyses without owning a high-performance computer (Brackney et al., 2018, 5-7). Cloud computing wasn’t used in this study since the power of the utilized computer was enough for the conducted simulations. However, since the required level of detail of the simulations was not clear in the early stages of the study, this was an important factor when deciding on the simulation software to be used in this thesis.

In conclusion, OpenStudio has many advantages in terms of accessibility, transparency, developability, simulation precision, and level of detail flexibility. It is convenient for building scale energy modeling both for early design phases or constructed buildings. It is suitable for use together with other software in unique workflows since it can import 3D models and weather files from other sources. Therefore, as a simulation environment, it meets all the needs of this thesis.

4.2.2 Simulation Design in OpenStudio

Simulations in OpenStudio have flexibility in terms of the simulation conditions such as the necessary level of detail of inputs, selection of the outputs, and determination of the constant variables when comparing design options. Each simulation preference can be made via the related setting tabs in the OpenStudio interface. The title of Simulation Design refers to the preferences of the author forming the simulation conditions. Several fundamental decisions can depict the simulation design unique to this study. The next paragraphs will discuss these decisions in relation to the setting tabs in OpenStudio.

One of the primary goals of this study is considering the effect of urban-scale data on building-scale performance while comparing different infill materials. This consideration of urban-scale data required the 3D case study building model and weather data to be enriched or altered with urban-scale data before being introduced to OpenStudio. For this reason, an altered weather file in .epw file format is imported to the simulation environment rather than using the “site tab” in OpenStudio, which enables users downloading online weather files directly inside OpenStudio. Similarly, the 3D case

study building geometry isn't created using the "plan editor" inside OpenStudio. Rather, it is imported as a .osm file using the "geometry tab". Further information about obtaining .epw, and .osm files in Rhino-Grasshopper before importing them is presented in sections 4.1.2 and 4.2. On the other hand, figure 23 presents the appearance of the imported 3D model of the case study building and the surrounding buildings in the Geometry Tab in OpenStudio, which carries different information than their appearance in Rhino-Grasshopper. The buildings are visualized by Surface Type in figure 23, while the surrounding buildings are represented with purple color indicating that they are defined as Shadow Elements.

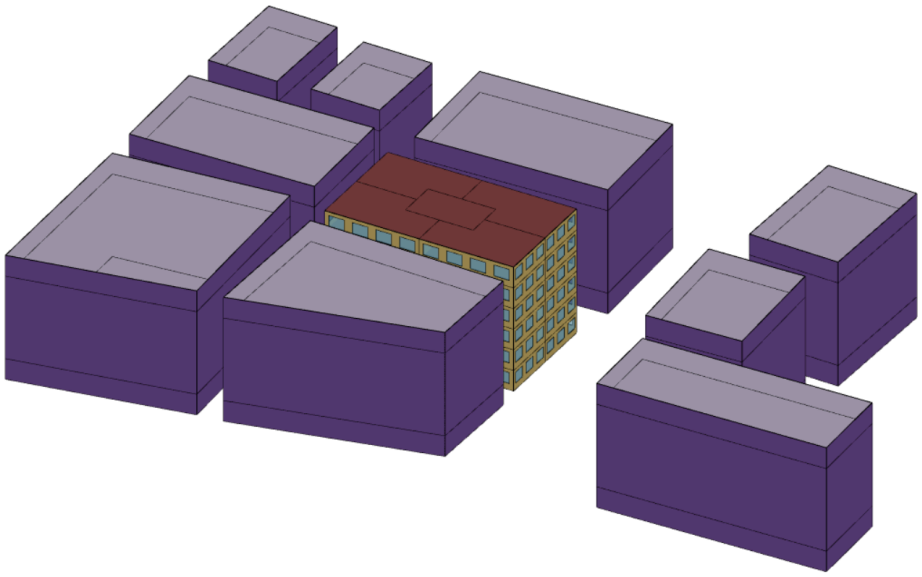


Figure 23. The case study building and the surrounding buildings as shadow elements in OpenStudio.

The Schedules input in OpenStudio defines the building's occupation scenarios in a time-based manner. In other words, it includes information regarding the activity frequency of thermal building loads such as people, lights, and electric equipment. While these loads don't consume energy and release heat directly related to space conditioning, their indirect effect on interior climate is significant. Hence, they need to be considered while simulating building energy performance and occupant comfort. However, it is not feasible for this study to measure the annual activity of each thermal load in the case study building. Thus, the two schedule sets named "MidriseApartment Apartment

Schedule Set" and "MidriseApartment Corridor Schedule Set" from the OpenStudio Library are assigned to the case study building. While the first schedule defines the activity of residential units, the latter defines the activity of the apartment core. This schedule differentiation between the residential units and the core area is found necessary because they have different occupancy timeliness due to the functions of the spaces. Schedule sets and thermal loads used in the simulations can be found in Appendix B.

Natural ventilation is a part of daily life in residential buildings in Istanbul. Hence, estimating annual energy consumption for space conditioning of a building without considering natural ventilation prevents realistic results. Natural ventilation is not defined by schedules but by measures in OpenStudio. A measure called "Add Wind and Stack Open Area" is downloaded from BCL (Building Component Library) and used to define natural ventilation conditions. The minimum indoor temperature for the natural ventilation, in other words, the indoor temperature below which ventilation is shut off, is given as 23.5 celsius degrees. The maximum indoor temperature is given as 25.5 celsius degrees. The maximum and minimum degrees are determined according to another simulation-based study conducted in Istanbul (Dino & Akgül, 2019). All the other values in the measure are left as default and they can be found in Appendix C.

Dividing a building into thermal zones is called "zoning" in building energy simulations. An OpenStudio Thermal Zone object includes information regarding the conditioning method, assigned HVAC system, and overall thermal behavior of a space. The size and orientation of an architectural space affect its thermal behavior. Hence, these spatial characteristics are also important while zoning a building. In this thesis, the total core area and each flat were assigned a different thermal zone, due to their thermal conditioning methods, size, and orientation. The core area throughout the six floors needed a different thermal zone since it is not conditioned, unlike the residential units, or in other words, the flats. Each flat was assigned a different thermal zone due to their different orientation on the same floors, or different exposure to the environmental conditions due to their different heights on different floors. On the other hand, joining a couple of flats into one thermal zone might result in a space too large to be conditioned by an ordinary residential HVAC system, distorting the simulation results. On the

contrary, dividing one flat into multiple thermal zones might result in an increased and unnecessary level of detail for this thesis. Hence, each flat is assumed as a thermally homogenous unit. Figure 24 visualizes the case study building by thermal zones, representing each thermal zone with a different color.

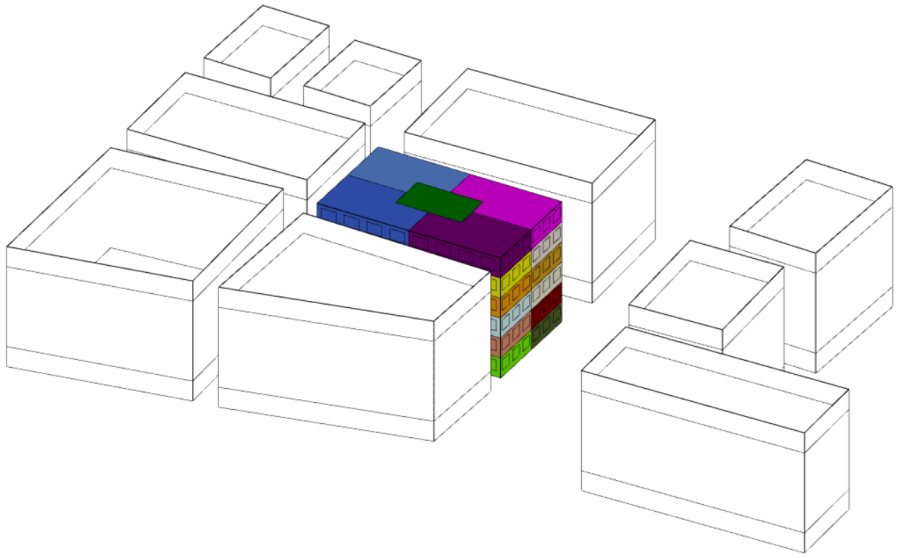


Figure 24. The case study building rendered according to the assigned thermal zones.

Another important step in simulation design is the HVAC system selection. A common HVAC system in residential apartments in Istanbul uses a natural gas boiler for heating and a split air conditioner for cooling. However, no pre-made template is found in OpenStudio suitable for these components. Since constructing such an HVAC system from scratch in OpenStudio requires advanced mechanical engineering information, another HVAC system that uses electricity for both heating and cooling is assigned first, which is a zone HVAC equipment with the name of "Cycling PTAC DX Clg Elec Htg".

The most significant characteristic of zone HVAC systems is to serve only one thermal zone. PTAC in the name of the selected HVAC system stands for Packaged Terminal Air Conditioner, which is commonly used for architectural spaces that require independent conditioning such as hotel rooms (Brackney et al., 2018, 103-119). The most notable drawback of using a zone HVAC is its limited modifiability. For instance, its subcomponents include a fan, cooling coil, and heating coil, and generally can not be

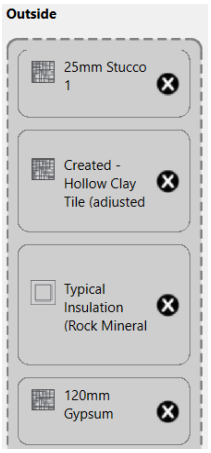
added with new subcomponents (Brackney et al., 2018, 103-119). Similarly, its control algorithms conditioning the space can not be altered drastically and they follow thermostat setpoints to the best of the equipment's ability. As a result of this situation, a high number of unmet cooling hours occur in the conducted simulations if the assigned HVAC system's ability is not compatible enough with the thermal zone. Hence, turning on the Ideal Air Loads is preferred over using a real HVAC system to detect the level of energy consumption for each infill material without having any unmet hours.

Ideal Air Loads is a hypothetical object inside OpenStudio that provides space conditioning using energy. It works without the mechanical restrictions of a real HVAC system that causes unmet cooling or heating hours. Although it creates misconceptions by ignoring the limitations of real-life HVAC systems, it is found suitable for this study since it helps to estimate the exact energy requirements of a space without eliminating the level of energy that isn't consumed due to the unmet hours. The thermostat setpoints and the thermal zoning are key factors in estimating the energy consumption for space conditioning, either using a real HVAC system or Ideal Air Loads. In this regard, the cooling set point is assigned as 24.40, and the heating set point is assigned as 21.70 celsius degrees, in parallel with the mid-rise apartment schedules of ASHRAE[2] standards. The zoning of the building is explained in the previous paragraphs in detail.

To define the construction details of the case study building, an ASHRAE mid-rise apartment construction set for the 3A climate zone[3] is imported from OpenStudio Library.[4] The construction set includes constructions for walls, floors, ceilings, roofs, windows, and doors with editable material layers, as can be seen in Appendix D. Material layers of the "Insulated Exterior Mass Wall" construction are adjusted to compare the operational performance of different infill materials. Hence, all the material layers of the exterior wall other than the infill materials are kept constant throughout the simulations,

[2] ASHRAE stands for American Society of Heating, Refrigerating and Air-Conditioning Engineers, which was founded in 1894. They publish standards, handbooks, and articles covering a wide range of topics related to healthy and sustainable built environments. (ASHRAE, n.d.)
[3] ASHRAE divides the all terrestrial areas into 8 main climate zones according to their regional climate data. Istanbul is located in zone 3A according to this classification. (ASHRAE, 2021)
[4] The whole name of the construction set used in this study is "90.1-2019 - MidApt - ASHRAE 169-2013-3A". The "MidApt" in the name stands for midrise apartments, and the "3A" stands for the intended climate zone of the construction set.

except for removing the thermal insulation layer for some of the wall sections according to their U values. The exact wall sections with different infill materials are determined in several steps as it is explained in section 3.2.5. Examples of wall sections and material definitions used in the simulations can be seen in Figures 25a and 25b as they appear in OpenStudio. The other wall sections used in the simulations can be found in Appendix D. The material properties represented with green color in Figure 25b were kept as generic values for each material due to the limited accessible information of recently developed materials and these properties' irrelevance to the goal of this study. On the other hand, thickness, conductivity, density, and specific heat were altered with information from the literature review in Chapter 3.



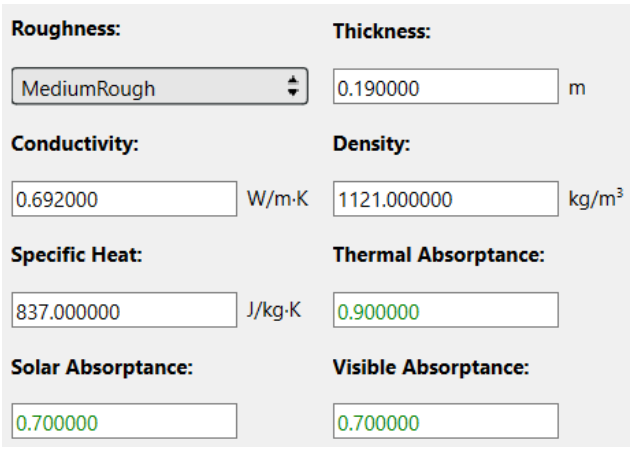


Figure 25a. The wall section with hollow clay tile as the infill material in OpenStudio.

Figure 25b. Material definition of hollow clay tile in OpenStudio.

The last step of the simulation design consists of determining the outputs of the simulation before running it. As the outputs, Surface Inside Face Temperature, Surface Outside Face Temperature, Zone Air System Sensible Cooling Energy, Zone Air System Sensible Heating Energy, Zone Air Temperature, and Zone Air Dry Bulb Temperature are selected with the timestep option. Timestep here refers to a customizable time range in which the simulation produces results repeatedly in response to the selected outcomes. There are also other time range options for repeating the calculations such as hourly, daily, and monthly. Although simulation run time increases with shorter time ranges, a longer time range such as hourly or daily is generally not preferable because of the low

level of detail and the resulting low accuracy (The Board of Trustees of the University of Illinois and the Regents of the University of California through the Ernest Orlando Lawrence Berkeley National Laboratory, n.d.). Hence, the timestep option with 6 timesteps per hour is preferred over longer time ranges. Another important point about the timestep is that the weather files generally have hourly data. However, the Input-Output Reference of OpenStudio states that the time range of weather files does not have to be used as the simulation timestep since EnergyPlus manages to interpolate the weather data for use at shorter timesteps (The Board of Trustees of the University of Illinois and the Regents of the University of California through the Ernest Orlando Lawrence Berkeley National Laboratory, n.d.). After selecting the timestep option as the time range for selected outputs, each output will use its predetermined time step providing the necessary level of detail for accuracy.

Input-Output Reference of OpenStudio states that two of the selected outputs, Surface Inside Face Temperature and Surface Outside Face Temperature correspond to the temperature of the surface's inside and outside faces, in degrees Celsius. Zone Air System Sensible Cooling Energy and Zone Air System Sensible Heating Energy represent the sensible cooling and heating energy in Joules that is supplied by the system to the related thermal zone for the selected timestep. Zone Air Temperature is the average air temperature at the selected timestep. Zone Air Dry Bulb Temperature or in its other name, Zone Outdoor Air Drybulb Temperature is calculated at the height above ground of the thermal zone centroid for each thermal zone (The Board of Trustees of the University of Illinois and the Regents of the University of California through the Ernest Orlando Lawrence Berkeley National Laboratory., n.d.). This zone air dry-bulb temperature is requested since HVAC Load Profiles request monthly outdoor air dry bulb temperatures to be obtained (NREL- National Renewable Energy Laboratory, n.d.). All these output selections help to observe if the thermal zones are managed to be kept in the comfortable thermal range for occupants and to observe the annual operational energy consumptions with different infill materials. While some of the aimed results and the related tables and graphs are directly examined inside OpenStudio through the Results Tab, some of the outputs are exported and visualized using R as will be explained further in section 4.4.

4.3 Weather File

Weather files define the climatic conditions that a building is exposed to, as explained in section 2.2. One common format for the weather files is the .epw format, which can include hourly, daily, weekly, or timestep climatic data for a selected time range. Weather data are generally recorded in airports or other wide and open areas outside city centers. Afterward, they are compiled into weather files by adjusting their data frequency. Today, weather files for locations worldwide are readily accessible online.

A weather file can be directly imported to Open studio using the link https://energyplus.net/weather in the "site" tab of OpenStudio. This link leads the user to the database of EnergyPlus which includes weather files for most of the settlements all over the world. However, these weather files mostly consist of data recorded in weather stations in ports or airports, which have different weather conditions than urban centers. For this reason, this thesis doesn't directly use downloaded weather data from a nearby weather station but explores a methodology to estimate the local urban microclimate surrounding the case study area and the building.

The UHI effect is one of the most important factors altering a regional climate into a local climate in urban environments, which was explained further in section 2.1. The UHI effect can occur in built areas because of the heat-retaining surface materials, low percentage of green areas, hindrance of natural air flow, etc. that prevent the natural cooling process of urban environments. This inability to cool down creates a differentiated microclimate bubble over the high-density urban areas, which is called the UHI effect. On the other hand, using an airport weather file in building energy simulations neglects the local microclimate in urban environments. Hence, considering the UHI effect in the weather files carries great importance for the accuracy of the simulations dealing with urban areas.

One of the methods to consider the UHI effect is the Urban Weather Generator (UWG) simulation module developed by the Massachusetts Institute of Technology (MIT). The simulation module can work stand-alone or in Rhino-Grasshopper. It estimates local hourly urban canopy air temperature and humidity levels (Nakano et al., 2015) using the

local urban morphology, surface materials, and vegetation parameters including tree coverage, motor vehicle traffic density, and weather data from a nearby weather station. In this thesis, a weather file from the Sabiha Gokcen Airport is used as input to the UWG.

UWG is a convenient tool to obtain a local weather file for this thesis for two main reasons. First, it can export weather files (in .epw file format), which can be imported into OpenStudio. Second, the case study area and building data enrichment steps were also realized in Rhino-Grasshopper. Since UWG also requires 3D urban input, it is efficient to conduct the 3D model and weather file preparation processes in the same software, which is Rhino-Grasshopper. The 3D geometry reflecting the urban geometry of the case study area is constructed in Grasshopper using the building footprints from OpenStreetMap (OSM) and the enrichment data from statistical analysis conducted in R for this thesis, as it is further explained in section 3.1. Afterward, the obtained geometry is introduced into the Dragonfly addon inside Grasshopper to run the UWG simulations. The relevant Grasshopper definition, which provides the steps for preparing the UWG and exporting the results, can be found in Appendix E.

The dry bulb temperatures in both the airport weather file and the UWG weather file are visualized using Ladybug Import EPW and Ladybug Monthly Chart components. Figure 26 presents the obtained monthly chart that allows us to see the difference between the urban weather file and the airport weather file, showcasing the significant UHI effect. Monthly Per Hour on the x-axis of the graph presents the average days of each month along with the month's name. Each month covers 24 hours of time range. In other words, the graph presents the monthly average of hourly data. In this case, the data consists of the dry bulb temperatures. Therefore, each month in the chart represents a day constructed with the monthly average of hourly dry bulb temperatures. The red line represents the monthly average of hourly data for the urban weather file, while the blue line represents it for the airport weather file. Although there is not much difference between the highest temperatures of an average day, it is possible to see a noticeable difference between the lowest temperatures. As expected, the average days in the chart show that the temperatures are the highest just after midday, are lower towards midnight, and have minimum values towards the early hours of the morning. The minimum

temperatures of the day occur at night when the urban area naturally cools. However, the urban weather file consistently exhibits higher minimum temperatures than the airport weather file, likely due to the reduced cooling ability of urban areas resulting from the Urban Heat Island (UHI) effect.

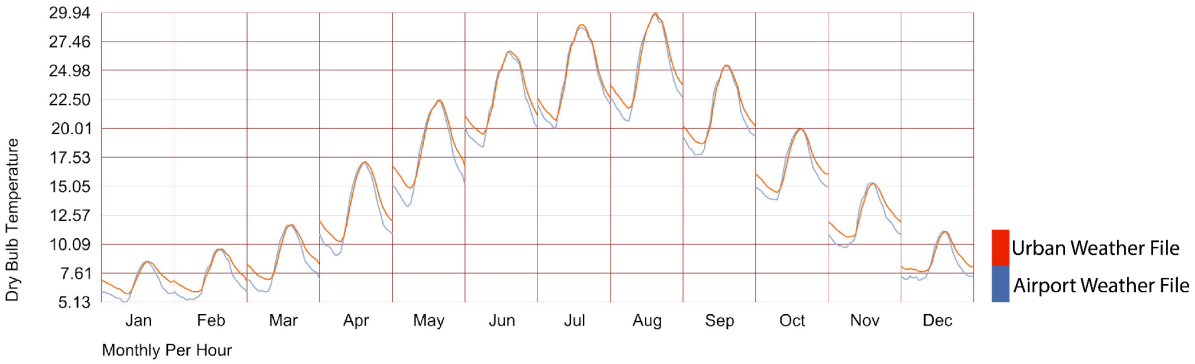


Figure 26. Graph showing the average day per month in terms of dry bulb temperatures both for the airport weather file and the urban weather file.

4.4 Compilation and Presentation of OpenStudio Simulation Results

The results of this thesis are examined either directly inside OpenStudio or by compiling and visualizing the simulation outcomes in R programming language. Inside OpenStudio, outcomes are examined with OpenStudio table and graph templates that are constructed automatically after running the simulations and constructed according to the selected outcomes of the simulations. The Results Tab in OpenStudio presents two main types of outcomes, which are OpenStudio Results and EnergyPlus Results. The first one includes the tables and graphs that are only involved in OpenStudio, while the second includes results directly from the EnergyPlus simulation engine. The OpenStudio result templates that are used in this study are the table of "Zone Conditions" and the graphic of "HVAC Load Profiles". These templates do not directly respond to the research questions of this study, but they provide insights if the simulations work correctly. The EnergyPlus results that are used are the table of "End Uses" in the report of "Annual Building Utility Performance Summary" and the tables of "Zone Sensible Cooling" and "Zone Sensible Heating" in the report of "HVAC Sizing Summary".

Some outcomes are passed into R software to compile and visualize the results of each simulation for different exterior wall infill materials. First, the annual energy consumption levels of the case study building for cooling and heating are exported for each material. Second, the User Design Load per Area (W/m2) for heating and cooling from the "HVAC Sizing Summary" are exported for each material to compare the effect of different infill materials on the HVAC sizing. Since this study uses Ideal Air Loads rather than a real-world HVAC system, HVAC sizing summary carries importance in terms of observing the effect of a thermal zone's orientation, number of floors, and infill materials on its thermal conditions. HVAC sizing summary presents the peak thermal conditions for each thermal zone, which are used to autosize an assigned HVAC system or to determine the level of air loads if Ideal Air Loads is activated. In regard to this, the difference between peak cooling and heating values of different thermal zones might provide insights about the varying design needs between flats of an ordinary mid-rise residential building in Istanbul, while also underlying the role of different infill materials as a passive design method. Hence, peak heating and cooling design loads are exported to present the thermal conditions of flats with different orientation and number of floors and to compare the effect of different infill materials on the thermal conditions of these flats. Chapter 5, examines each type of outcome in further detail by also presenting the results of this study and their discussion.

CHAPTER 5

RESULTS AND DISCUSSION

This chapter presents and discusses the results obtained from the conducted simulations. The obtained results allow us; first, to compare thermal zones for their thermal behaviors due to their orientation and the number of floors that they are located; second, to compare the effect of different infill materials on these different thermal behaviors of the thermal zones; third, to compare infill materials for their overall operational performance; lastly, to examine the relationship between the U values of the obtained wall sections and the resulting annual energy consumptions of the case study building. Section 5.1 presents the results regarding the first and second comparisons while also making connections to HVAC system requirements of the thermal zones. Section 5.2 presents the results regarding the operational performance of the materials and section 5.3 focuses on the relationship between the U values and annual energy consumption.

The operational performance of the infill materials is represented by the annual electricity consumption for space conditioning in the units of kWh and kWh/m^2 in the results. Although OpenStudio provides results in GJ's for annual energy consumptions, the results are converted to kWh and kWh/m^2 to increase comparability with other studies in the literature. The results in the prepared graphs presenting the electricity consumption for heating and cooling separately allows us to examine the summer and winter performance of materials respectively. Some simulation results are examined directly in OpenStudio, while some of them need further compiling and data visualization in another software, which is R in the case of this study. The R code for compiling and visualizing

the OpenStudio results can be found in the author's repository on GitHub (Erincik, 2024), while the obtained tables and graphs are presented and discussed in this chapter.

5.1 Analyzing HVAC Sizing Summary for Each Infill Material

This study uses two tables from the HVAC Sizing Summary report in OpenStudio, which are titled Zone Cooling and Zone Heating. The Zone Cooling table includes information such as the calculated design load, the user-specified design load, the calculated design air flow, etc. for each thermal zone, while the Zone Heating table includes the same information for heating activity. The information that is presented in both of the tables is used for HVAC sizing by OpenStudio when an autosized HVAC system is assigned to a thermal zone. Auto-sizing is done to obtain an HVAC system suitable for the allocated thermal zone, as far as the system components allow. However, it is seen in the early stages of this study that even when an auto-sized HVAC system is used, unmet heating or cooling hours occur. Hence, Ideal Air Loads are used rather than using a real HVAC system. However, the HVAC Sizing Summary still carries important information for this study, although a real HVAC system isn't utilized.

When Ideal Air Loads are used, the HVAC Sizing Summary report provides insights into the unique thermal behaviors of thermal zones and their required HVAC size. Ideal Air Loads require auto-sizing too, but it doesn't have the physical limits of a real HVAC system, which prevents it from having unmet hours. Hence, Ideal Air Loads assumes that a perfect HVAC system exists and is auto-sized according to the assigned thermal zone. As a result, this report is found convenient to examine different thermal conditions of the flats with different numbers of floors and orientations. Afterward, all the infill materials are examined to see how they perform in the thermal zones with the highest heating or cooling loads. This second step is expected to present the role of alternative infill materials as a passive design component to support HVAC systems and reduce their mechanical requirements. Hence, the goal of this step is not to estimate the changes in the energy consumption of an HVAC system when different infill materials are used, but to estimate the changes in the maximum heating and cooling loads, which is effective on the HVAC system sizing itself. The graphs showing the maximum heating and cooling loads for each thermal zone in relation to their number of floors and orientation are presented in

section 5.1.1, while the graphs showing the effect of different infill materials on the thermal zones with the highest heating and cooling loads are presented in section 5.1.2.

User Design Load per Area (W/m2) from the Zone Heating and Zone Cooling tables is used to examine the maximum heating and cooling loads of the thermal zones. The more common units for energy consumption are kWh or kWh/m2. However, the User Design Load reflects an instant peak load and can not be converted into an hourly amount. Hence, the information is kept in W/m2 for each infill material. The first graphs that are constructed with User Design Load data are focused on only hollow clay tiles to compare the thermal zones/flats with different number of floors and orientations, while the latter graphs compare different infill materials for their effect on the thermal zones with the highest cooling and heating loads. For a detailed review of the R code used in constructing the graphs, please refer to the author's online repository on GitHub (Erincik, 2024).

5.1.1 Zone Cooling and Heating Loads by Number of Floors and Flat Orientation

This section examines each thermal zone, which are the 24 flats on 6 floors with four different orientations, for their maximum heating and cooling loads. This study focuses on mid-rise residential buildings in urban environments of Istanbul and the results unique to this specific building typology are aimed. Accordingly, the results in this section are expected to discuss the effect of a number of floors and flat orientation on the flat’s thermal conditions, since height and orientation are two effective factors in the interior climates of mid-rise residential apartments. To analyze the changes between these independent flats, the thermal zones of the case study building are simulated with hollow clay tile as the infill material. Figure 27 presents the zone cooling loads for each flat on each floor, while Figure 28 presents the same information for heating. Zone cooling and heating loads represent the instant peak loads throughout the simulation year, which is used to size HVAC systems or determine the ideal air loads.

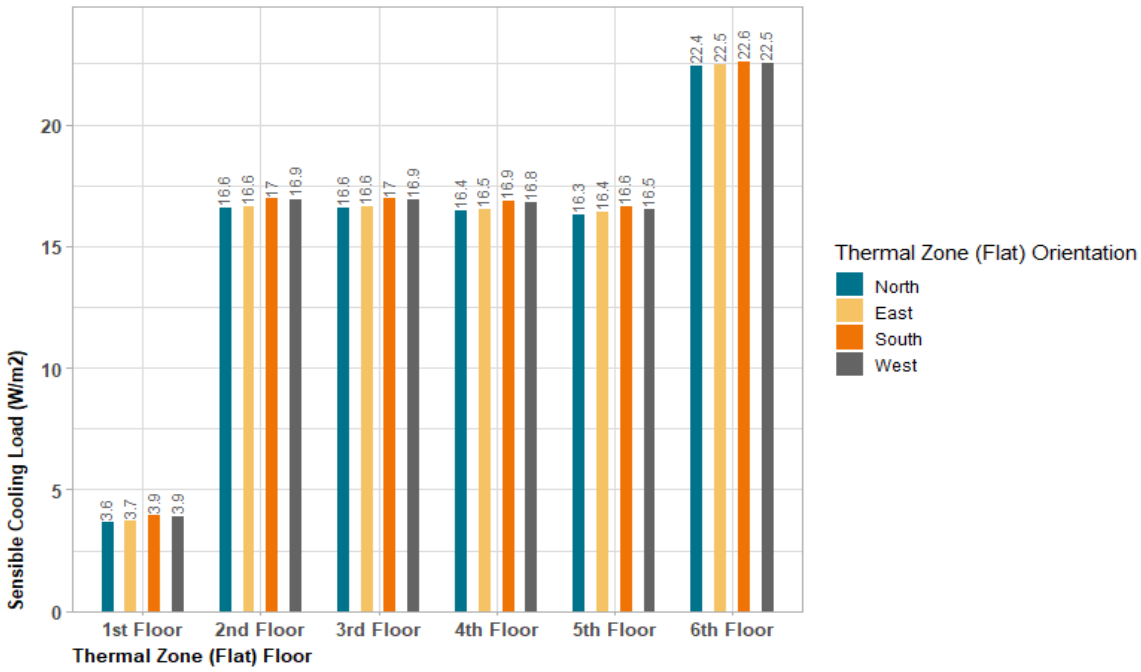


Figure 27. Zone Cooling Load by flat orientation and floor for hollow clay tile as the infill material.

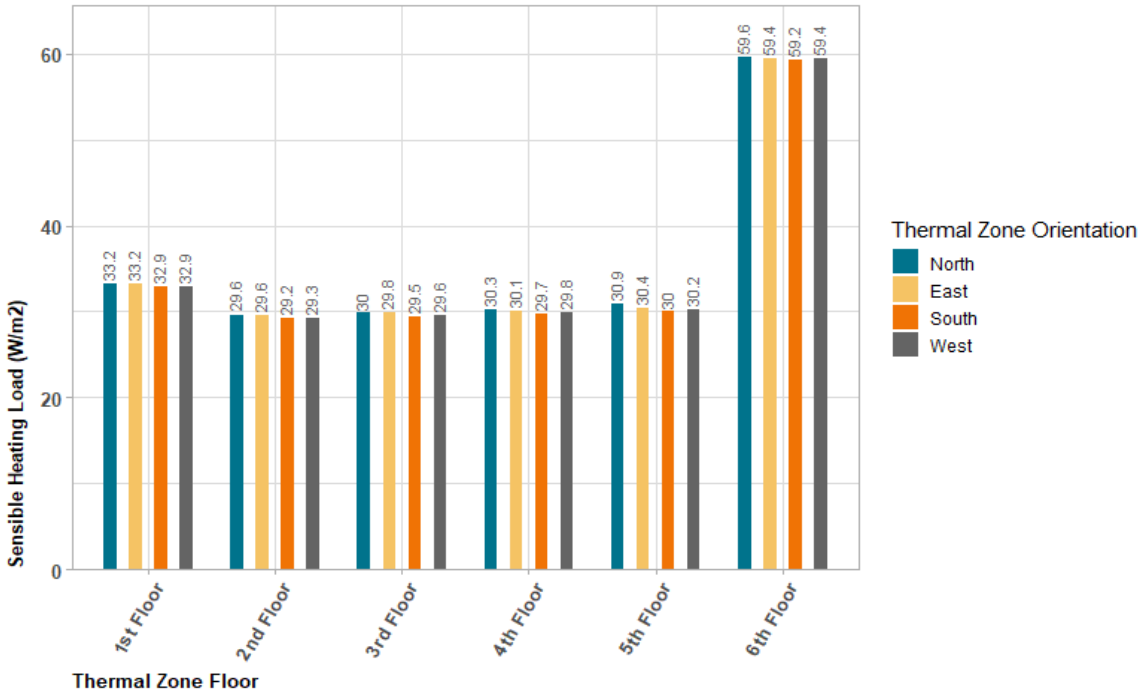


Figure 28. Zone Heating Load by flat orientation and floor for hollow clay tile as the infill material.

Figure 27 presents the peak zone cooling loads for hollow clay tile as the infill material. The colors of the bars in the graph represent the orientation of the flat, while the x-axis shows the number of floors in which a flat is located. Four main outcomes can be distinguished in the graph. First, of all the floors, the south-facing flat has the highest peak cooling load with little difference from the west-facing flat. Second, the four floors between the ground and top floors seem to have very similar peak cooling loads for all the facades, although the values decrease slightly from the lower floors to the upper floors. However, it should be noted that even such a small difference between the peak loads can result in significantly higher annual energy consumption and a need for stronger HVAC systems. Third, the ground floor thermal zones have significantly lower peak cooling loads in comparison to all the other floors. Lastly, the top floor thermal zones have significantly higher peak cooling loads in comparison to all the other floors.

Similarly, figure 28 presents the peak zone heating loads for hollow clay tile as the infill material. This time, north-facing flats have the highest peak heating loads on all the floors as expected. The four floors between the ground and top floors have very similar heating loads in all the facades, increasing from the lower floors to the higher floors. The ground floor thermal zones have higher peak heating loads than the 2nd, 3rd, 4th, and 5th floors, but with a smaller difference than they have in Figure 27. On the other hand, the top floor thermal zones have significantly higher peak heating loads in comparison to all the other floors, with a bigger difference than they have in Figure 27.

As a result of these outcomes, these graphs indicate the necessity of making design decisions considering not only the different orientation of the flats but also their height from the ground level. This consideration is especially important for mid-rise buildings in urban environments, when the building height and the urban morphology are effective on interior and exterior microclimates and energy consumptions. Accordingly, the latter graphs in section 5.1.2 will present the comparison of the peak heating and cooling loads in the 1st and 6th floors for each exterior wall infill materials, as an indication of their operational advantages or drawbacks variable between different thermal zones.

5.1.2 Zone Cooling and Heating Loads by Infill Materials

This section presents the peak heating and cooling loads for the 1st and 6th floors of the case study building for each infill material. The 1st and 6th floors are selected to compare the infill materials since these floors have significantly higher or lower heating and cooling loads as discussed in section 5.1.1. Figure 29 shows the peak cooling loads for the 1st floor, which already has the lowest cooling loads in comparison to all the other floors. Cork blocks and hempcrete blocks appear to be the most advantageous ones to lower the cooling loads of the 1st floor even further. On the other hand, figure 30 presents the peak cooling loads for the 6th floor, which has the highest cooling loads with a significant difference from the other floors. On the 6th floor, the cork block appears to be the most advantageous one with a slight difference from the hempcrete block. In both figures 29 and 30, Cannabric with additional insulation layer, mycelium, hempcrete, and cork blocks appear to be more advantageous than the conventional infill materials, which are hollow clay tile and aerated concrete. The wall section with adobe bricks as the infill material appears to be the worst-performing one in terms of cooling loads on both floors.

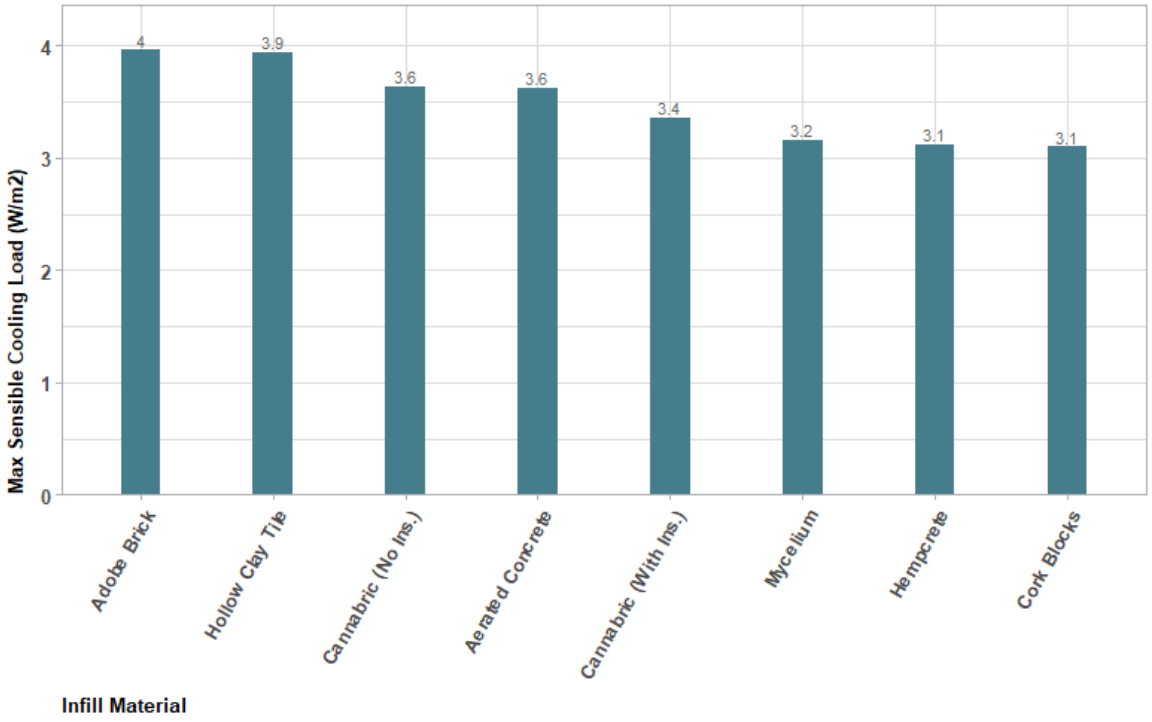


Figure 29. Maximum zone cooling loads for the 1st floor by infill material.

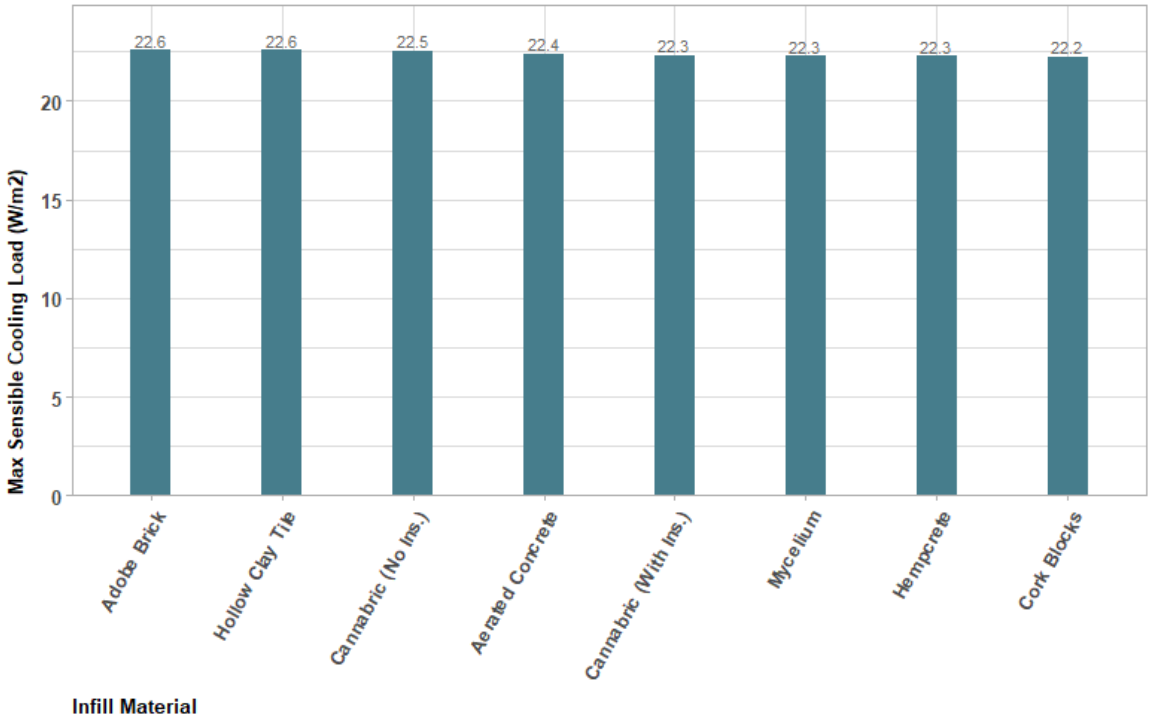


Figure 30. Maximum zone cooling loads for the 6th floor by infill material.

Figure 31 shows the peak heating loads for all the infill materials for the 1st floor, which has higher peak heating loads than the 2nd, 3rd, 4th, and 5th floors. Figure 32 shows the peak heating loads for all the infill materials for the 6th floor, which has by far the highest peak heating loads in comparison to all the other floors. On both the 1st and 6th floors, hempcrete blocks appear to be the most advantageous one in terms of heating loads, while it is the cork blocks in terms of cooling loads as presented in Figures 29 and 30. In a similar way to cooling loads, Cannabric with an additional insulation layer, mycelium, cork, and hempcrete blocks appear to be more advantageous than the conventional infill materials, which are hollow clay tile and aerated concrete. However, Cannabric without an insulation layer becomes the worst-performing one in terms of heating loads, while adobe brick was the worst-performing one in terms of cooling loads. These performances of the infill materials varying between peak heating and cooling loads indicate that the performance of a material is not only related to its insulation abilities but also to the seasonal environmental conditions and the relevant thermal needs of the thermal zones.

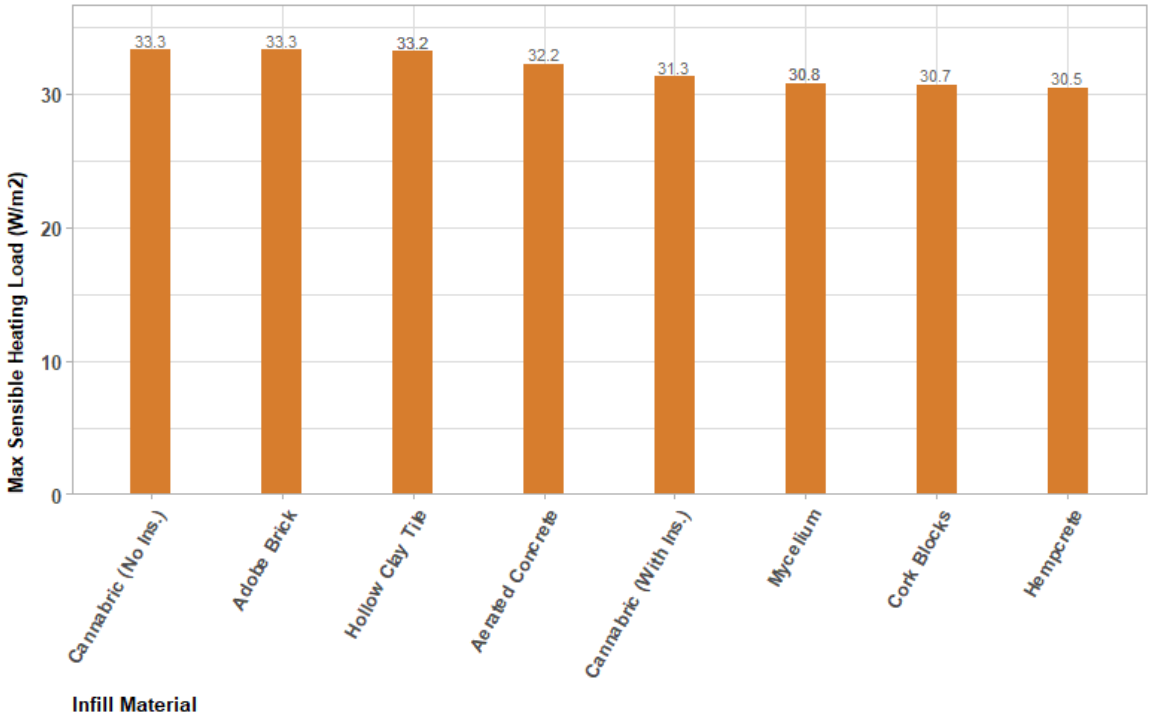


Figure 31. Maximum zone heating loads for the 1st floor by infill material.

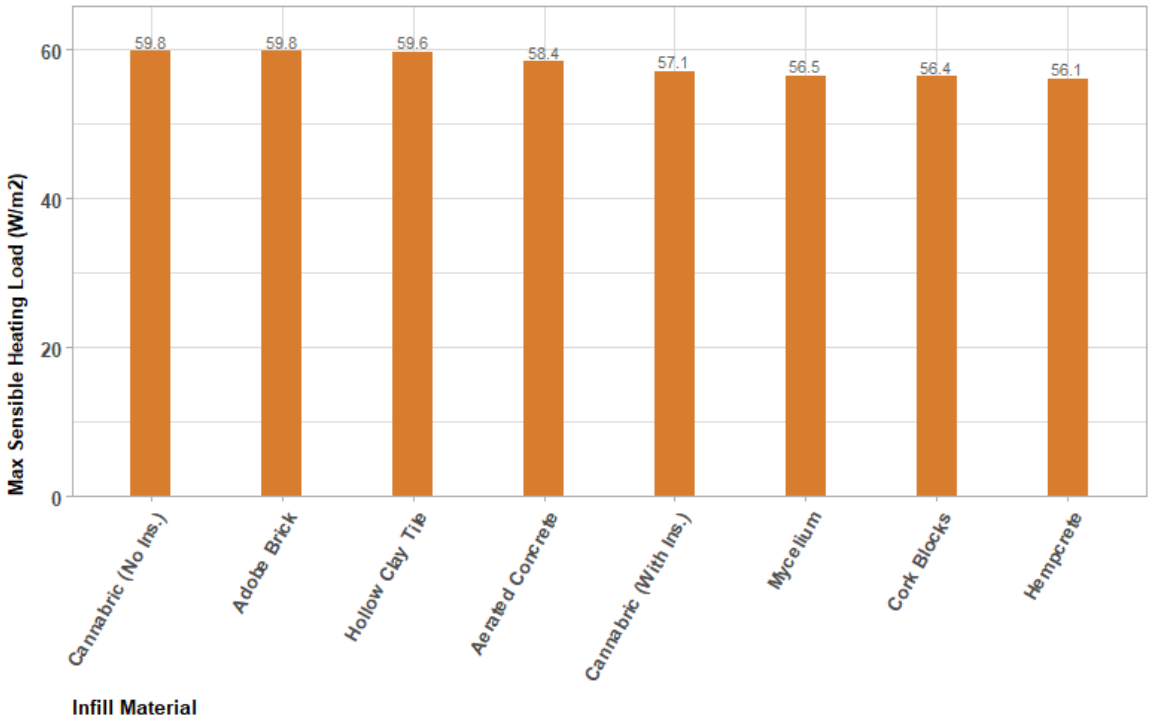


Figure 32. Maximum zone heating loads for the 6th floor by infill material.

As a result, some alternative wall infill materials cause lower peak heating and cooling loads, while the conventional ones, namely hollow clay tile and aerated concrete, result in higher peak heating and cooling loads in comparison to most of the alternative infill materials. The worst-performing materials vary between heating and cooling loads, highlighting the importance of considering local environmental conditions when selecting materials. The maximum heating and cooling loads determine the capacity of the HVAC system required for buildings, playing a crucial role in occupant comfort throughout the year. A less powerful HVAC system, when adequately sized for the assigned thermal zone, can result in both reduced operational costs and a lower initial investment. Therefore, the infill materials are compared based on their effect on the peak heating and cooling loads of thermal zones located on different floors. However, the graphs presented in this section only show a comparison of instant peak loads and do not reflect the overall operational energy consumption of the case study building. The annual operational energy demands for each material will be compared in the following section, representing the operational performance of all the selected exterior wall infill materials.

5.2 Analyzing Annual Energy Consumptions for Each Infill Material

The operational performance of a building is measured by the level of energy and water that it consumes, as stated earlier in section 2.2. On the other hand, an envelope material relates to the building's operational energy consumption for space conditioning. Hence, the operational performance of a construction material can be examined through the annual energy consumed for space conditioning. HVAC systems can be designed to condition the space in terms of humidity, temperature, and CO2 levels. However, thermal conditioning has by far the largest share in the operational energy consumption of residential buildings, followed by lighting as the second highest source of energy consumption as discussed earlier. For this reason, this thesis compares conventional and alternative low-embodied carbon exterior wall infill materials for their operational performance, which is represented by the case study building's annual energy consumption for space heating and cooling. Accordingly, this section presents the graphs showing the annual energy demands of the case study building for heating, cooling, and their total value in kWh and kWh/m^2 for each wall infill material. For a detailed review of

the R code used in constructing the graphs with OpenStudio simulation results, please refer to the author's online repository on GitHub (Erincik, 2024).

Figure 33 presents the annual energy consumption of the case study building in the form of kWh, while Figure 34 presents the annual energy consumption in the form of kWh/m^2. While the former shows the total annual consumption for an ordinary mid-rise residential building in Istanbul, the latter provides the energy consumption per m^2, making it easier to compare the results with other studies and buildings. The values are exported from the Annual Building Utility Performance Summary report in OpenStudio in GJ and converted to kWh and kWh/m^2 . To convert kWh to kWh/m2, the total energy consumption per hour is divided by the conditioned residential area of the case study building, which is the total area excluding the unconditioned core area. The values exported for all the infill materials are collected in an .xlsx file and imported into R to create the bar plots comparing the operational performance of the infill materials, which can be seen in figure 33 and figure 34.

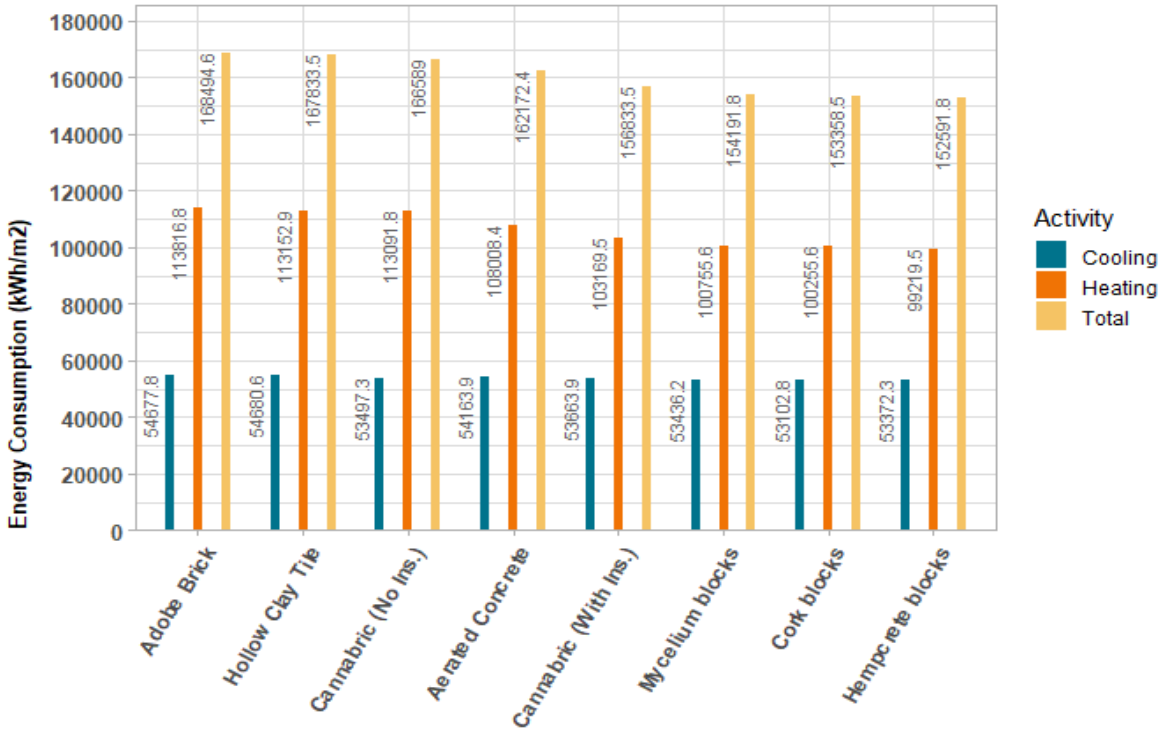


Figure 33. Annual energy demands for space conditioning (kWh).

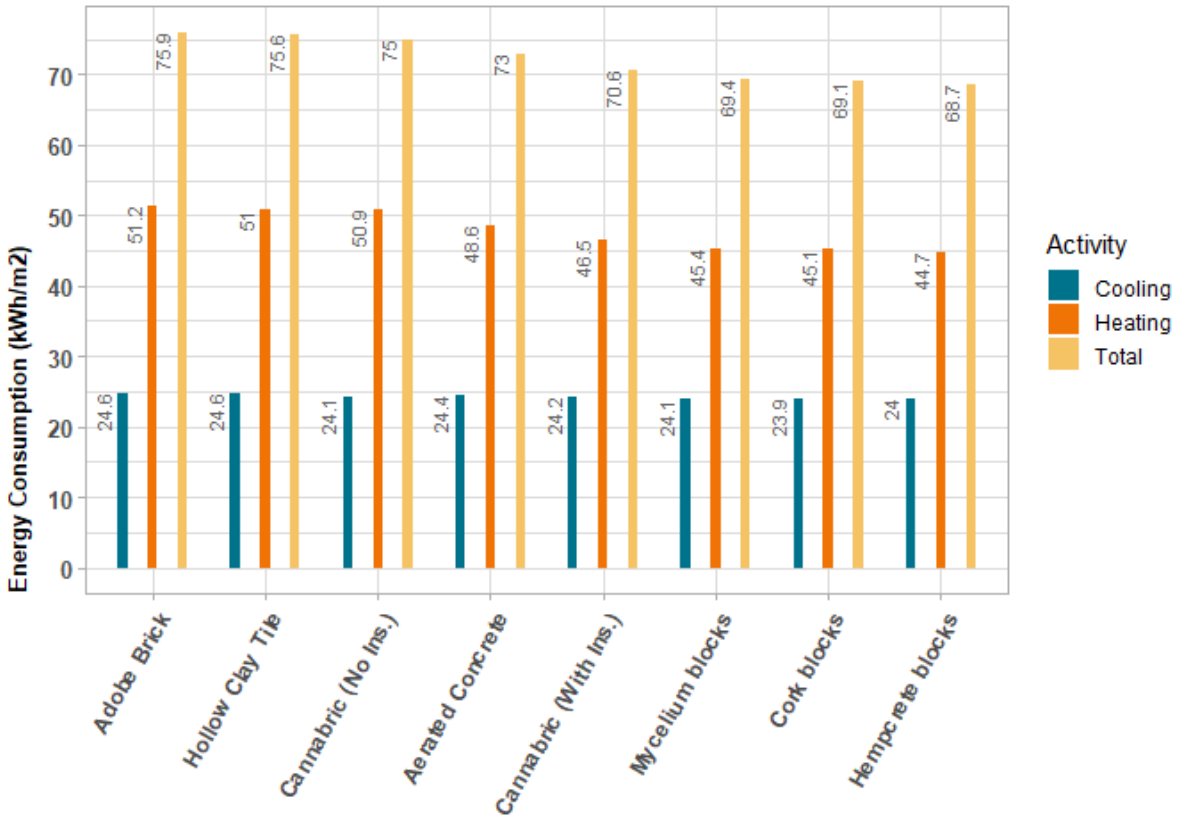


Figure 34. Annual energy demands for space conditioning (kWh/m^2).

The x-axis of the graphs in Figure 33 and Figure 34 shows the wall sections with their infill materials selected in section 3.2.5. The blue in the graphs represents the energy consumed for cooling, while the orange represents the energy consumed for heating. Hence, the reader can analyze how the heating and cooling energy demands vary between different infill materials besides the total energy consumption. Figure 33 indicates that the low embodied carbon alternative materials such as cork, hempcrete, and mycelium blocks are also more efficient in terms of operational performance with a significant difference. The only low-embodied carbon material that performs more poorly than the conventional wall materials, which are hollow clay tile and aerated concrete, is adobe bricks. This might be due to the lower product thickness of the adobe bricks in comparison to the other bio-based infill materials. However, since the adobe is also the heaviest one among the selected bio-based materials, increasing its thickness beyond standard measurements isn't taken into account in this study. One common methodology of using adobe bricks is coupling them with a layer of straw bale insulation. However, because the insulation

material type was kept constant in the conducted simulations, wall configurations consisting of adobe bricks and straw bale insulation aren't considered.

Figure 33 presents that biobased materials have significantly lower heating energy demands, while they have cooling energy demands very similar to the conventional materials. Nevertheless, their total electricity demands result in significantly lower annual values. While the Cannabric section without an insulation layer is located between hollow clay tile and aerated concrete, the Cannabric section with the insulation layer has the highest energy demand after aerated concrete. It is followed by mycelium blocks, hempcrete blocks, and cork blocks with very little difference between the three of them. This higher energy demand of Cannabric in comparison to the other low-embodied carbon materials is probably due to Cannabric's high lime content. Lime content provides higher durability while also causing higher thermal conductivity as discussed earlier. Hence, it becomes an advantageous material in terms of durability, while its thermal characteristics decline accordingly.

Hempcrete blocks appear to be the most efficient infill material in terms of total energy demand while it has slightly higher cooling energy demand in comparison to the cork blocks. However, it should be noted that these balance of heating and cooling energy demands resulting in a certain level of efficiency are unique to the mid-rise apartments in the specific urban morphology and climate of Istanbul, and these materials might result in a different balance of heating and cooling loads under different environmental factors. Hence, the results don't prove an absolute superiority of one material over another in terms of efficiency. It should be also noted that the high performance three materials, namely the cork, hempcrete, and mycelium blocks don't have any additional insulation layers in their wall sections in the simulations, as stated in section 3.2.5. As a result, due to the absence of an insulation layer, these wall sections have a carbon footprint even lower than the infill materials could ensure.

On the other hand, it should be noted that the calculated heating and cooling energy consumptions per area for each material show some difference between another study conducted by Dino & Akgul. Dino & Akgul conducts a simulation-based study using EnergyPlus to calculate the annual energy consumption of a mid-rise residential building

for heating and cooling in Istanbul, Ankara, Izmir, and Erzurum. The authors calculate the heating and cooling energy consumption of their case study building in Istanbul as 36 kWh/m^2 and 18 kWh/m^2 (Dino & Akgül, 2019). This difference between the results of this study might be due to the differences between definitions of thermal loads, thermal zone sizes, thermostat set points, weather files, construction sets, or definitions of natural ventilation. However, all the inputs to the simulations in this study are presented in the related sections and appendices, allowing further discussion.

As a result, low-embodied carbon materials such as hempcrete blocks can provide up to 15242 kWh or 6.9 kWh/m^2 annual energy savings in comparison to conventional materials such as hollow clay tile for mid-rise apartments in Istanbul. This difference between the hollow clay tile wall section and the hempcrete block wall section corresponds to approximately 10 percent energy savings annually. Such a difference in operational energy consumption is especially important for urban areas with high building density since it might decrease the alarmingly high carbon footprint of cities significantly. Furthermore, since these alternative materials already have a low embodied carbon footprint, they improve the built environments both in terms of embodied and operational carbon footprints.

5.3 Correlation Between the Exterior Wall U Values and the Resulting Annual Energy Consumptions

The correlation between the U values of the utilized exterior wall sections and annual energy consumptions of the case study building presented in this section is in a supportive role for the results previously discussed rather than serving directly to the hypothesis of this study. A common methodology in the construction industry in Turkey is to design exterior walls according to the total U value of the envelope section. However, the environmental sustainability of a building depends on more complex decision processes, which include consideration of embodied and operational carbon footprints of construction materials rather than dwelling only on the thermal conductivity characteristics of envelope materials. Furthermore, the operational performance of materials is affected by the local climate that the building is exposed to, passive design methods adopted, assigned HVAC system, occupancy scenarios, and occupant behaviors.

Therefore, this thesis provides a more comprehensive comparison of exterior wall infill materials considering the local climate and building typologies in the selected case study area.

Figure 35 showcases how the operational performance-oriented comparison of materials presented in this study differs from juxtapositioning U values. Although the U value of the walls for different infill materials are mostly correlated with the building's operational energy consumptions for space conditioning, the differentiations of U values and thermal energy consumptions are not linear. This nonlinearity indicates that the interactions between wall materials and the environmental conditions are effective on their operational performance, and the effect of these interactions can not be observed only through their U values. The relationship between the U values and the annual energy consumptions are more easy to observe in figure 36, since the U values are expanded by 100 to make its variations more visible. Since the U values are much smaller numbers than the annual energy consumptions, including the real U values in the same graph with annual energy consumption makes it harder to observe their correlation. Hence, figure 39 presents the expanded U values, while figure 35 presents the real values both for annual energy consumptions and wall section U values. For a detailed review of the R code used to construct the graphs below, please refer to the author's online repository on GitHub (Erincik, 2024).

Another reason to compare energy consumption rather than comparing only U values is that U values are a result of physical aspects of materials and are not affected by the accompanying design solutions. On the other hand, examining the operational performance of a construction material allows the consideration of passive design solutions to compensate for extra energy consumption resulting from the utilization of a specific material. In this way, construction materials can be selected for their embodied carbon footprint, even if their operational performance is slightly worse. Afterward, the selected material's energy consumption might be compensated with additional passive design methods or a renewable energy infrastructure compatible with the building typology.

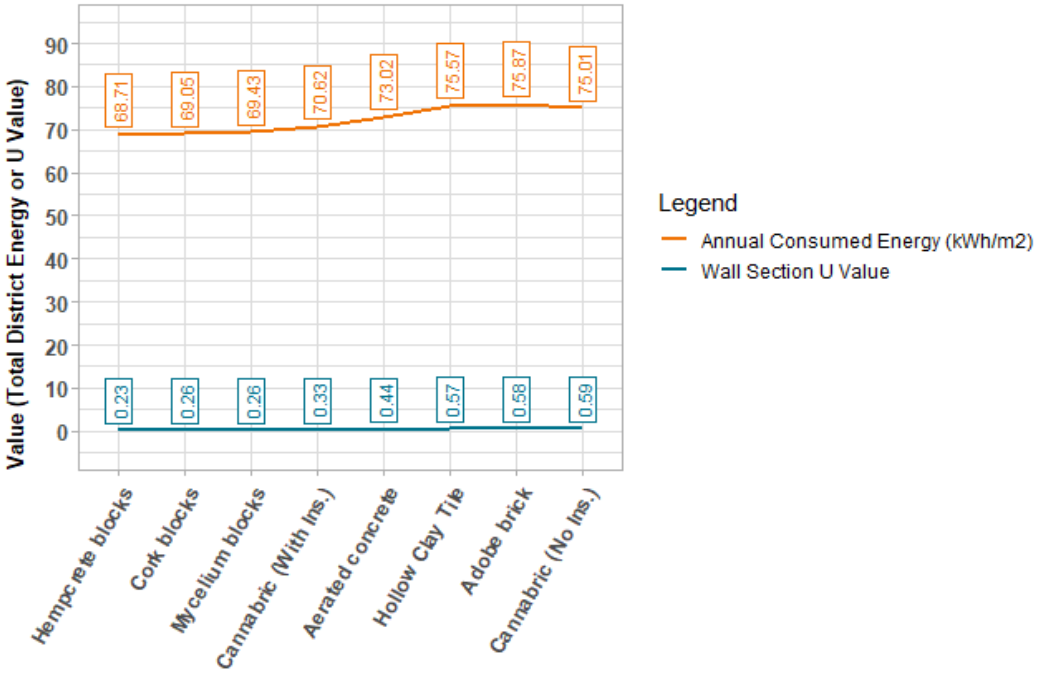


Figure 35. Comparison of annual electricity consumptions for space conditioning and exterior wall U values with each infill material.

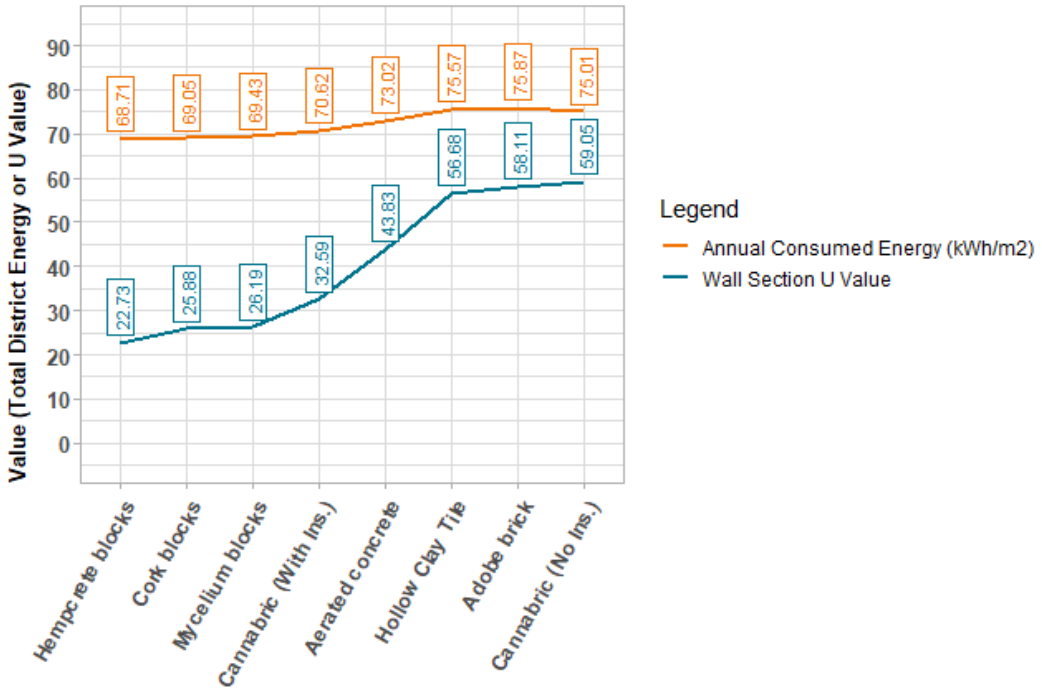


Figure 36. Comparison of annual electricity consumptions for space conditioning and expanded exterior wall U values with each infill material.

CHAPTER 6

CONCLUSION AND FUTURE WORK

This thesis compares conventional and alternative low-embodied wall materials for their operational performance in the exterior walls of mid-rise residential buildings in Istanbul. The study mainly aims to explore the operational potential of alternative low-embodied carbon infill materials for broader use in urban environments. The results indicate that alternative wall materials have significant potential to enable more sustainable urban architecture. The methodology proposes a unique workflow, considering the effects of urban scale characteristics on building efficiency and occupant comfort. The interdisciplinary approach adopted encompasses building energy modeling, urban sustainability, construction materials, and occupant comfort.

The methodology includes five main steps. Firstly, a literature review identifies alternative low-embodied carbon wall infill materials suitable for Istanbul's urban environment, selecting mycelium blocks, cork blocks, hempcrete blocks, Cannabric, and adobe bricks. Conventional materials are identified as hollow clay tiles and aerated concrete based on TURKSTAT data. Secondly, representations of a case study area and building are created by conducting statistical analysis on TURKSTAT data using R and modeling in Rhino-Grasshopper software. In this step, the TURKSTAT data is compiled to represent Istanbul's building stock for the specific residential building typology, enhancing the accuracy of simulations. Thirdly, a local urban weather file is generated to account for the urban heat island effect, which is essential for realistic building energy

simulations. This is achieved by iterating an airport weather file using the Dragonfly addon in Rhino-Grasshopper. The fourth step involves designing simulations in OpenStudio, and the fifth step focuses on compiling and analyzing the simulation results in R.

The simulation results demonstrate that low embodied carbon materials, such as mycelium, hempcrete, and cork blocks, outperform conventional materials in terms of operational energy consumption. These alternative materials show significantly lower heating-related energy consumption, with only slight differences in cooling energy consumption. Furthermore, by assigning each flat a different thermal zone in the simulations, the study highlights the variability of thermal conditions within a typical mid-rise residential building. The related results underscore the importance of considering thermal zone conditions, such as the number of floors and orientation, when selecting materials. Additionally, the study detects a non-linear relationship between exterior wall U-values and annual energy consumption, emphasizing the importance of considering overall operational energy consumption rather than focusing solely on U-values during the design phase.

The thesis addresses four key research questions outlined in the first chapter. Firstly, it investigates the operational performance of low-embodied carbon alternative materials compared to the conventional materials used in Istanbul. Secondly, it examines the role of exterior wall infill materials as a passive design method supporting HVAC systems in mid-rise residential buildings. Thirdly, it explores the relationship between exterior wall R-values and the annual energy consumption of mid-rise residential buildings in Istanbul. Lastly, it assesses the existing residential building stock in Istanbul and how it can be represented in a Building Energy Modeling (BEM) environment. To answer the first question, simulations compare conventional wall infill materials with alternative low-embodied carbon materials. The findings indicate that some low-embodied carbon materials, specifically hempcrete blocks, cork blocks, and mycelium blocks, are more efficient than the conventional ones in terms of operational energy performance. Regarding the second question, it is found that infill material selection can also affect the HVAC system selection by changing the peak heating and cooling loads of thermal zones

significantly. Some alternative materials result in lower peak heating and cooling values throughout the simulation year compared to conventional infill materials. This indicates that using these alternative materials can enhance HVAC efficiency and potentially reduce system size and operational costs. The third question is addressed through a graph illustrating the non-linear relationship between exterior wall U values and annual energy consumption, highlighting that U values alone are insufficient for material selection. Lastly, the methodology section of the thesis provides insights into the existing residential building stock in Istanbul, using data compilation and visualizations to represent it in a BEM environment.

As an extension of this study, future work could first focus on comparing simulation results with real-world applications to enhance the validity of the simulations. This approach is not preferred in the current study, as the methodology relied on abstracting the case study building based on the current building stock in Istanbul and simulation software's input requirements. This abstraction is found necessary to increase the generalizability of the results for mid-rise residential buildings in Istanbul's urban environments. As a result, existing occupancy scenarios in the case study building are not examined individually. Instead, standard schedule sets compatible with ASHRAE standards are applied to all flats in the case study building. However, comparing simulation results with real-world performance could bridge the gap between simulated and actual energy consumption, making the adopted methodology more applicable in the construction industry across Istanbul. Another avenue for future research is to replicate the simulation workflow for different climates within Istanbul to identify the most effective alternative materials for each region. Istanbul comprises three distinct climate regions: sea-shore areas, interior regions far from the sea, and northern areas. This study focuses on sea-shore regions, which encompass the majority of urban settlements. However, analyzing the other climates and their microclimates requires a more comprehensive urban-scale approach, which is reserved for future studies. Additionally, the varied urban morphologies in Istanbul necessitate a detailed classification for simulation purposes, which also warrants further urban-scale research.

Future studies should also consider the detailed design of wall sections using the most promising wall infill materials identified in this study. As this thesis aims for a comparative analysis, the wall configurations for different infill materials are mostly kept constant to ensure objective comparisons. However, replacing conventional render and cladding layers with alternatives that have lower carbon footprints could further enhance the sustainability and performance of the walls. For instance, some bio-based materials, such as cork blocks, offer high breathability and improved interior air quality. Conventional exterior renders may inhibit these benefits, highlighting the need for wall section designs tailored to each infill material.

Given Istanbul's high earthquake risk and urban density, the proposed wall infill materials require further examination for their seismic performance. Future studies should investigate the structural compatibility between these alternative materials and the commonly used reinforced concrete systems in mid-rise residential buildings. Moreover, the compatibility of alternative materials with Istanbul and Turkey's building codes is not addressed in this study due to its scope. As these materials demonstrate their potential, it becomes crucial to adapt building codes to include them. Additionally, the durability of these materials in real-world applications remains to be studied. While these alternative infill materials are advantageous in terms of embodied and operational carbon footprints, their sustainability also depends on their durability. Real-world applications are essential to assess the materials' in-situ durability under various environmental conditions and construction details. Observing constructed projects will provide valuable insights into the lifespan of these materials.

In conclusion, this study demonstrates that some low embodied carbon materials also offer superior operational performance compared to conventional materials when used as infill in the exterior walls of mid-rise residential buildings in Istanbul. These materials hold significant potential for reducing environmental impact, enhancing occupant comfort, and promoting sustainability in Istanbul's urban built environment.

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APPENDICES

Appendix A - Grasshopper Definitions For Representations of the Case Study Area and the Case Study Building

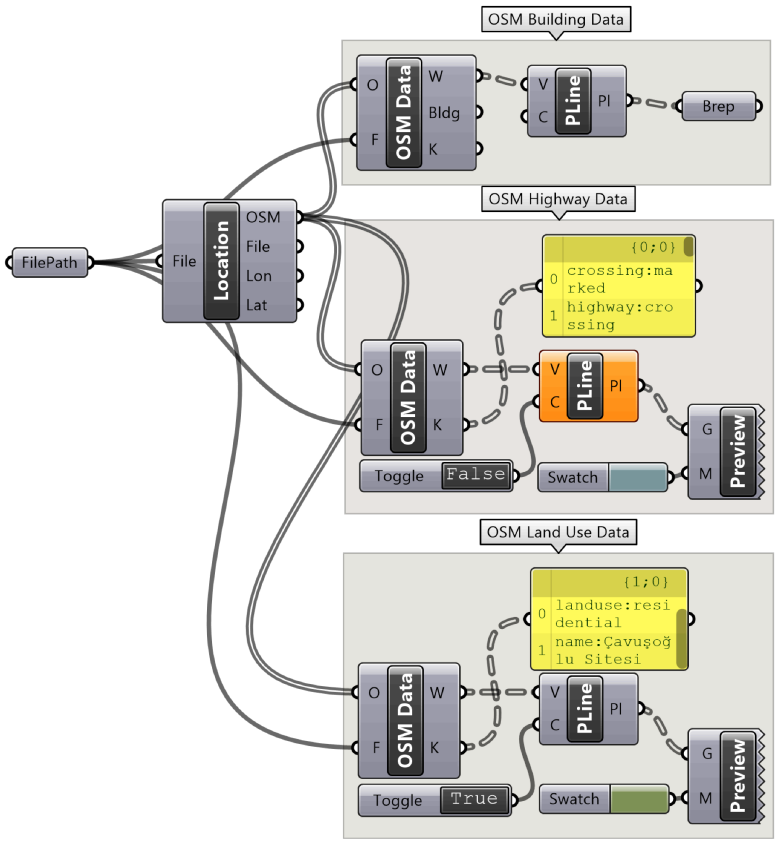

Figure A.1: Grasshopper definition for importing and examining the case study area OSM File.

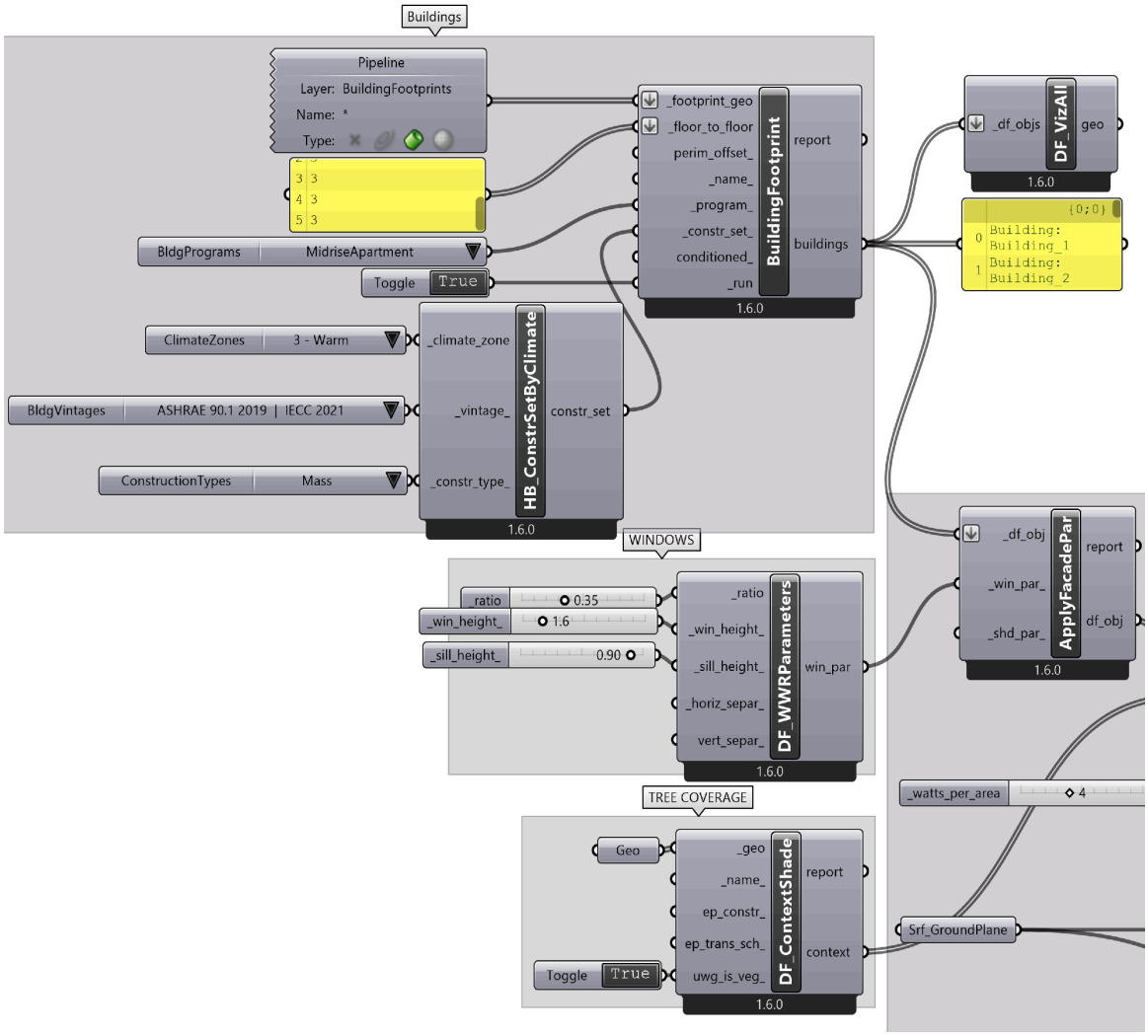

Figure A.2: Grasshopper definition for creating 3D buildings from the imported OSM file with necessary data enrichments.

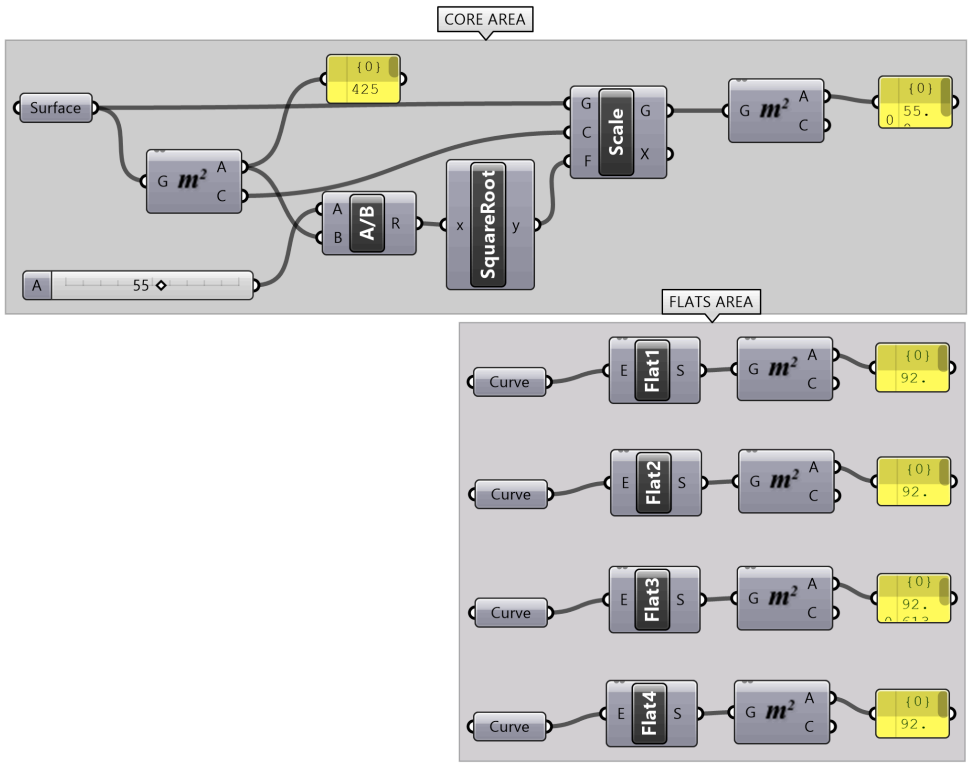

Figure A.3: Grasshopper definition to construct the case study building's core and flats areas.

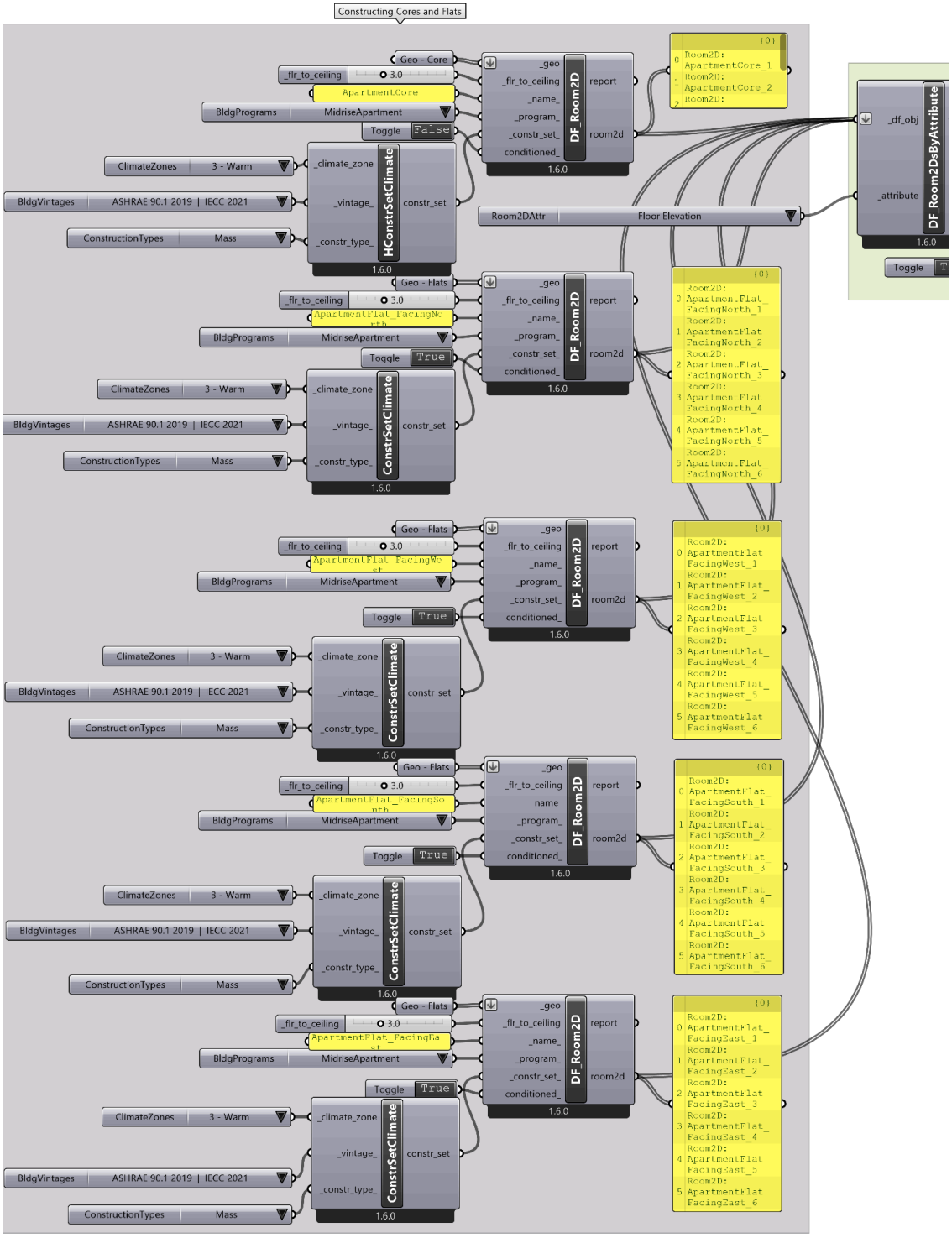

Figure A.4: Grasshopper definition to bring the flats and the core to construct the building floor.

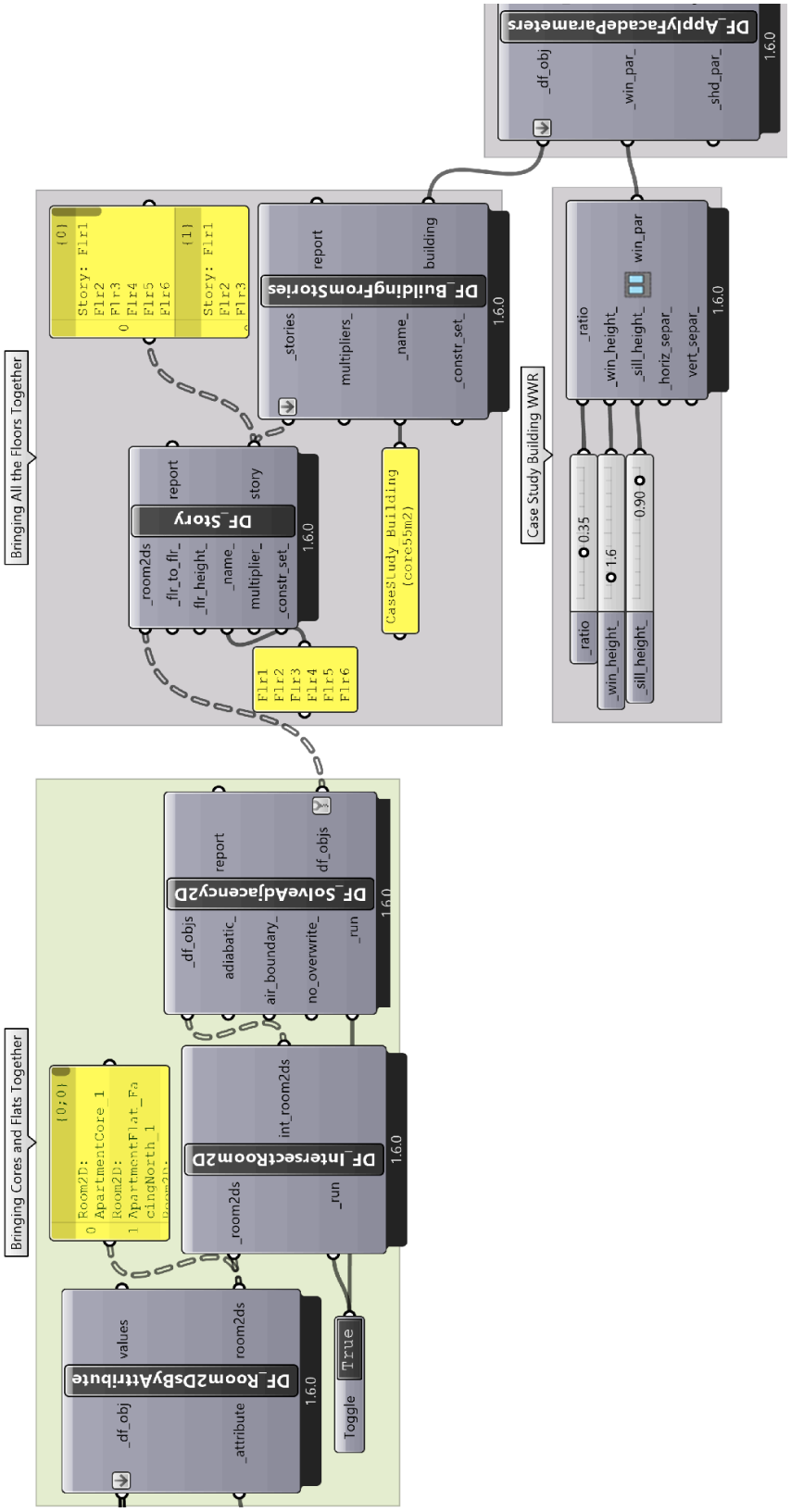

Figure A.5: Grasshopper definition to construct the case study building from the floors.

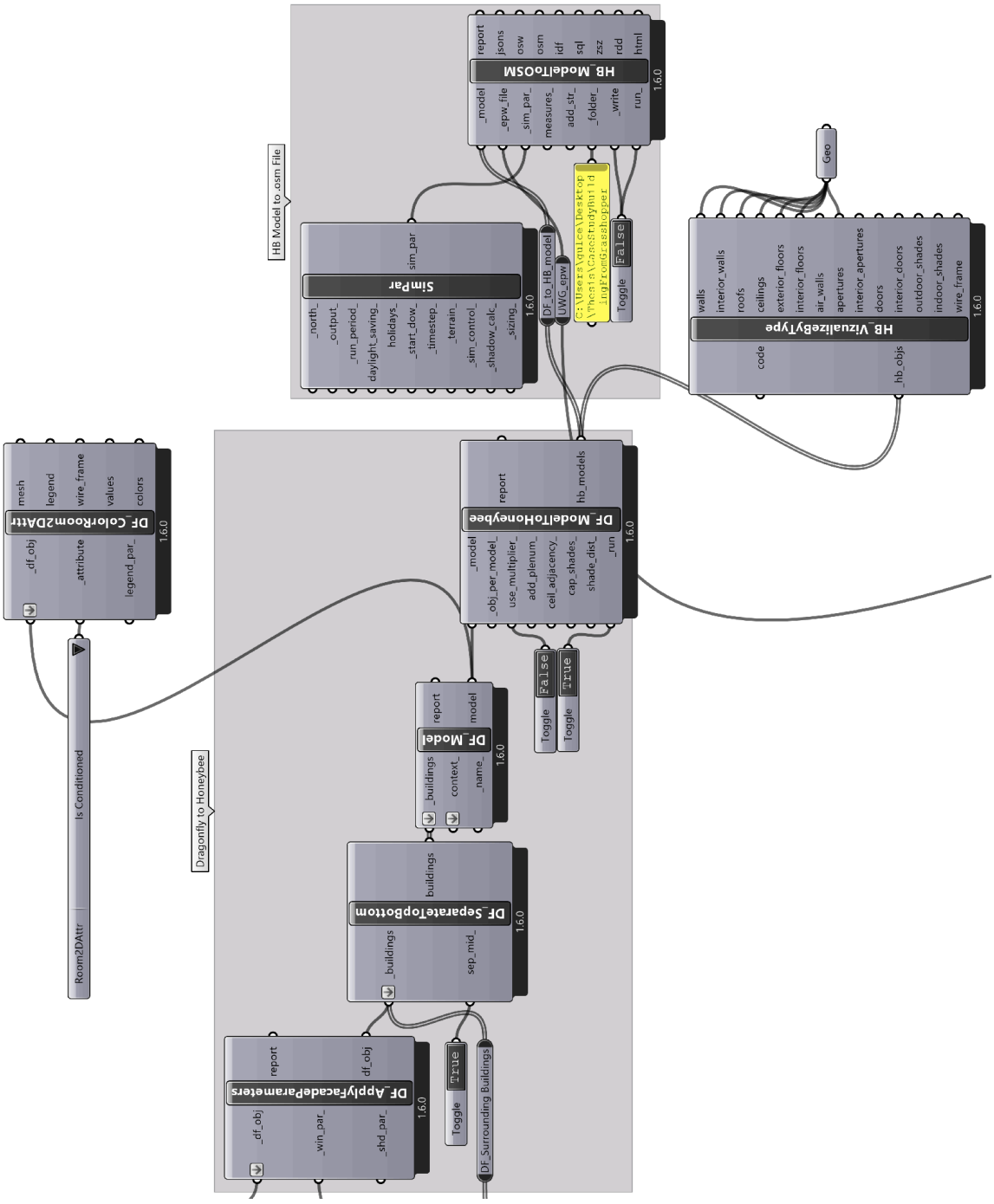

Figure A.6: Grasshopper definition enabling the transition between Dragonfly and Honeybee addons and exporting the 3D building models as a .osm file for OpenStudio.

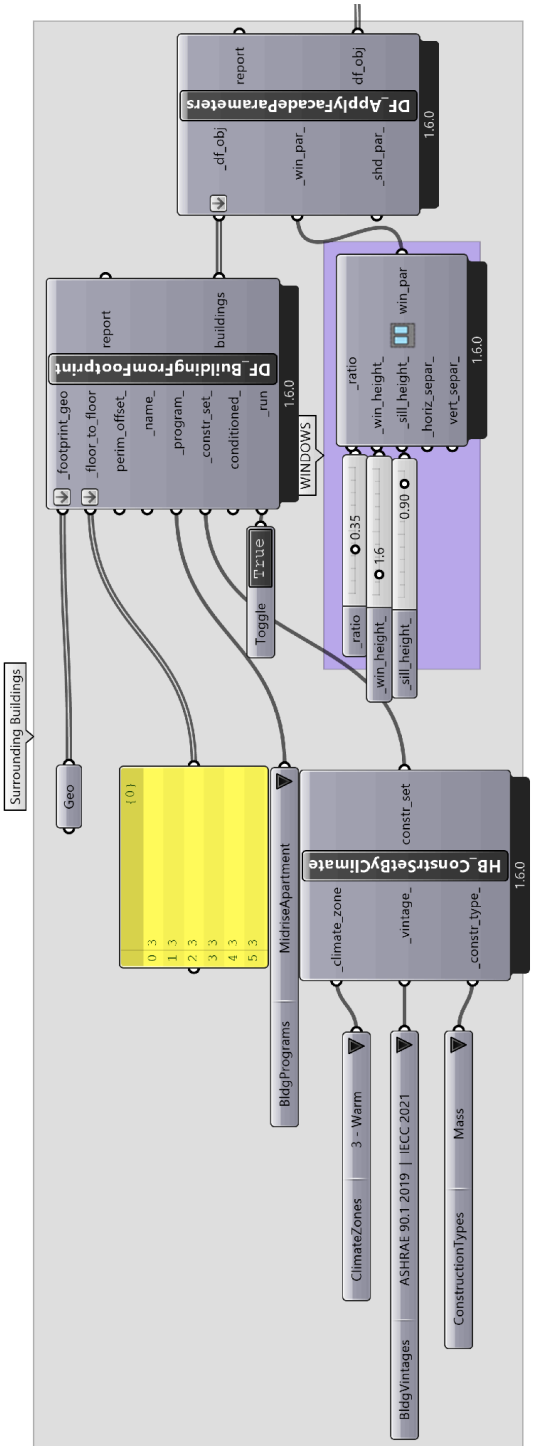

Figure A.7: Grasshopper definition to represent the surrounding of the case study building as shadow elements in the .osm model. (The “df_objects” in “DF_ApplyFacadeParameters” is connected to the DF_SurroundingBuildings in Figure A.6.)

Appendix B - Schedule Sets and Loads Used in OpenStudio Simulations

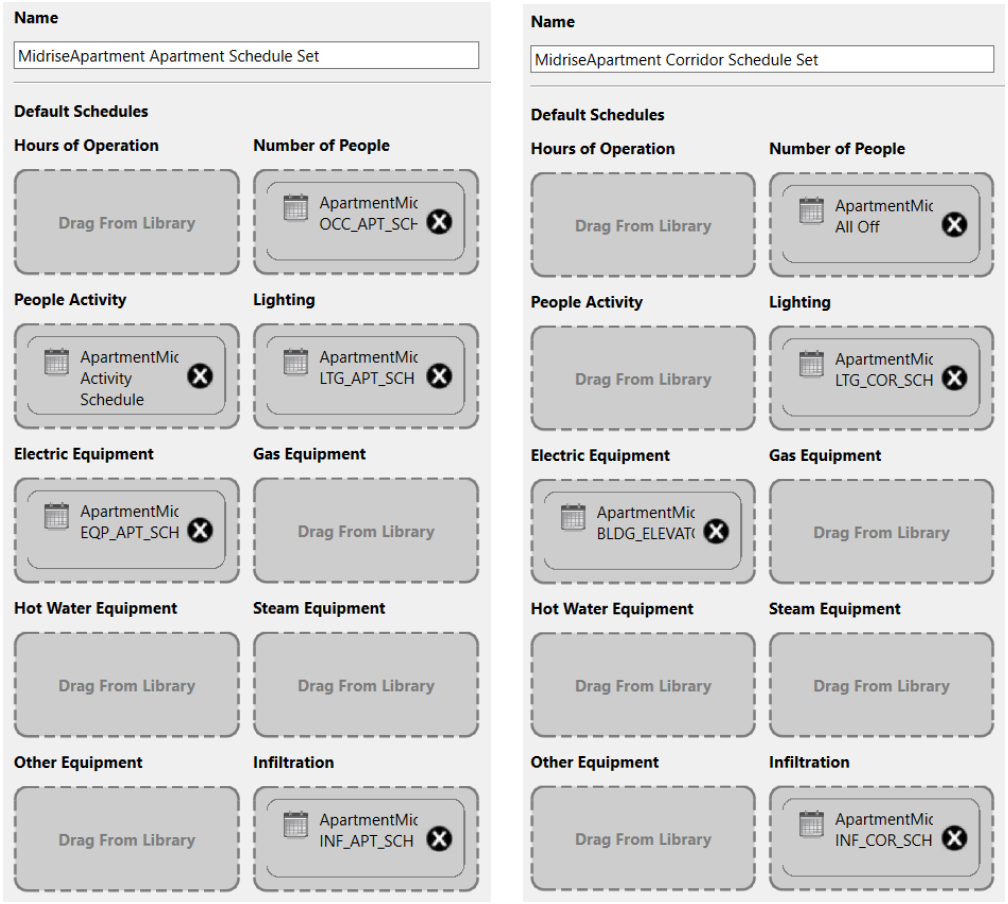

Figure B.1: Schedule sets used for the residential area (on the left) and core area (on the right).

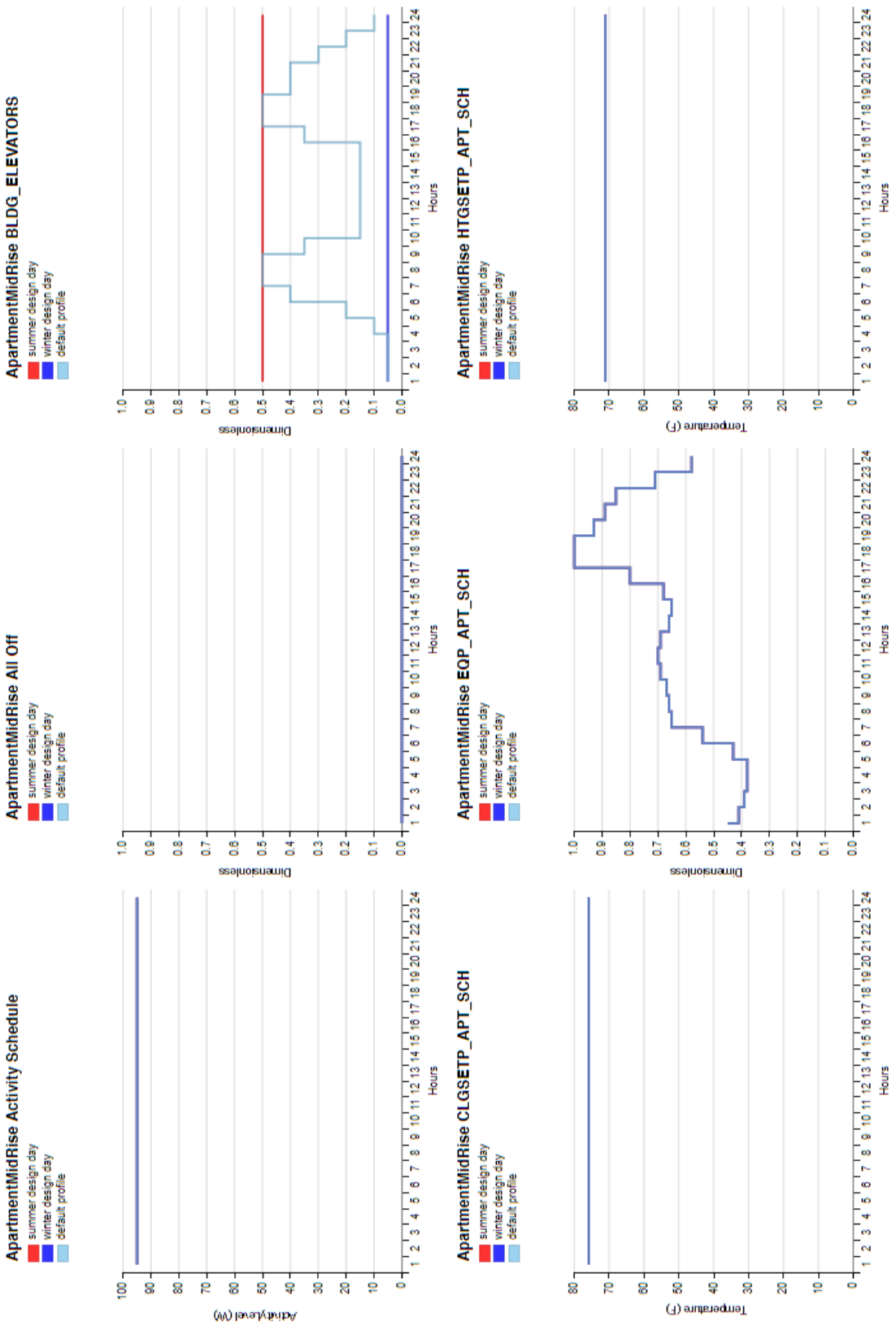

Figure B.2: Schedules overview.

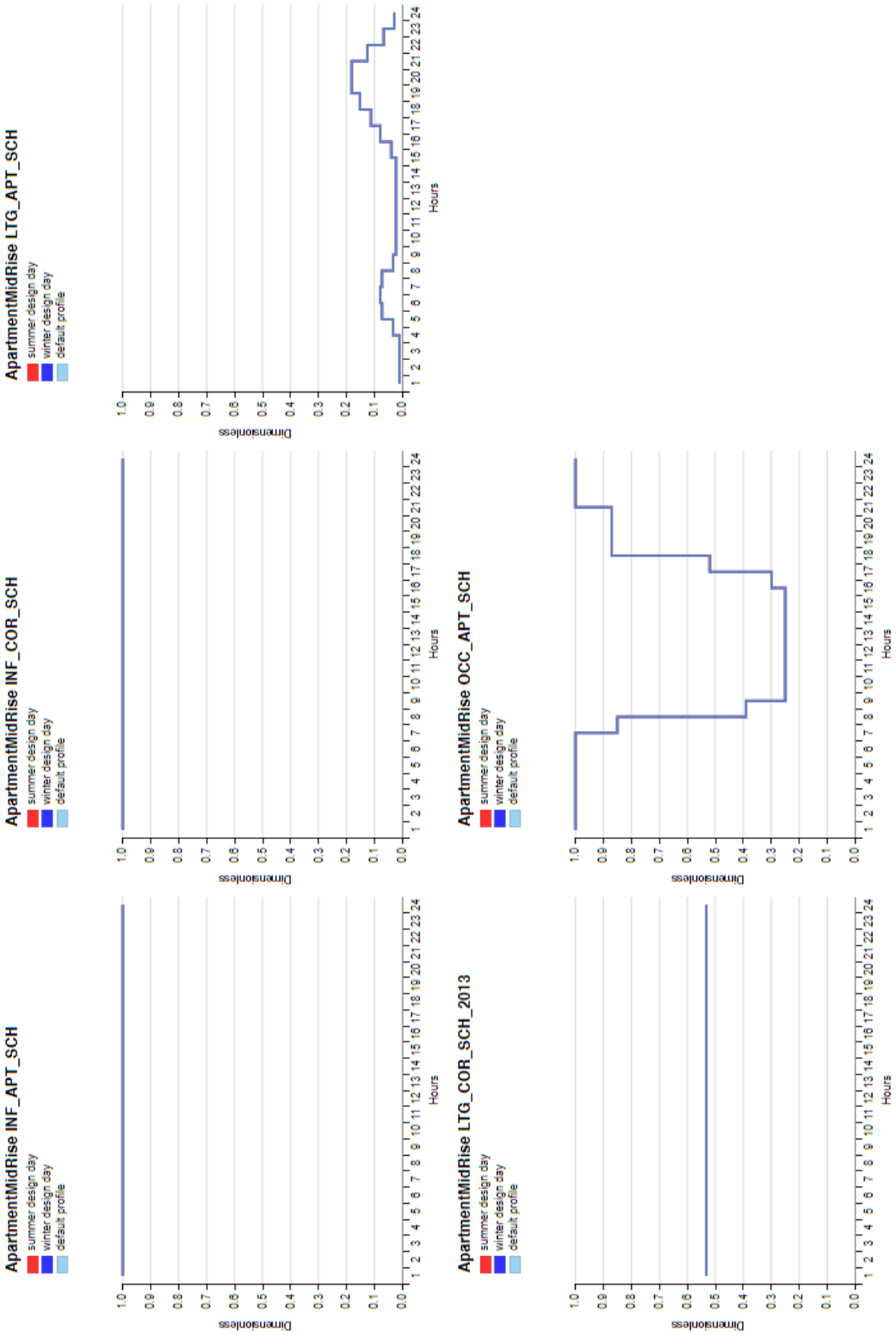

Figure B.3: Schedules overview (continued).

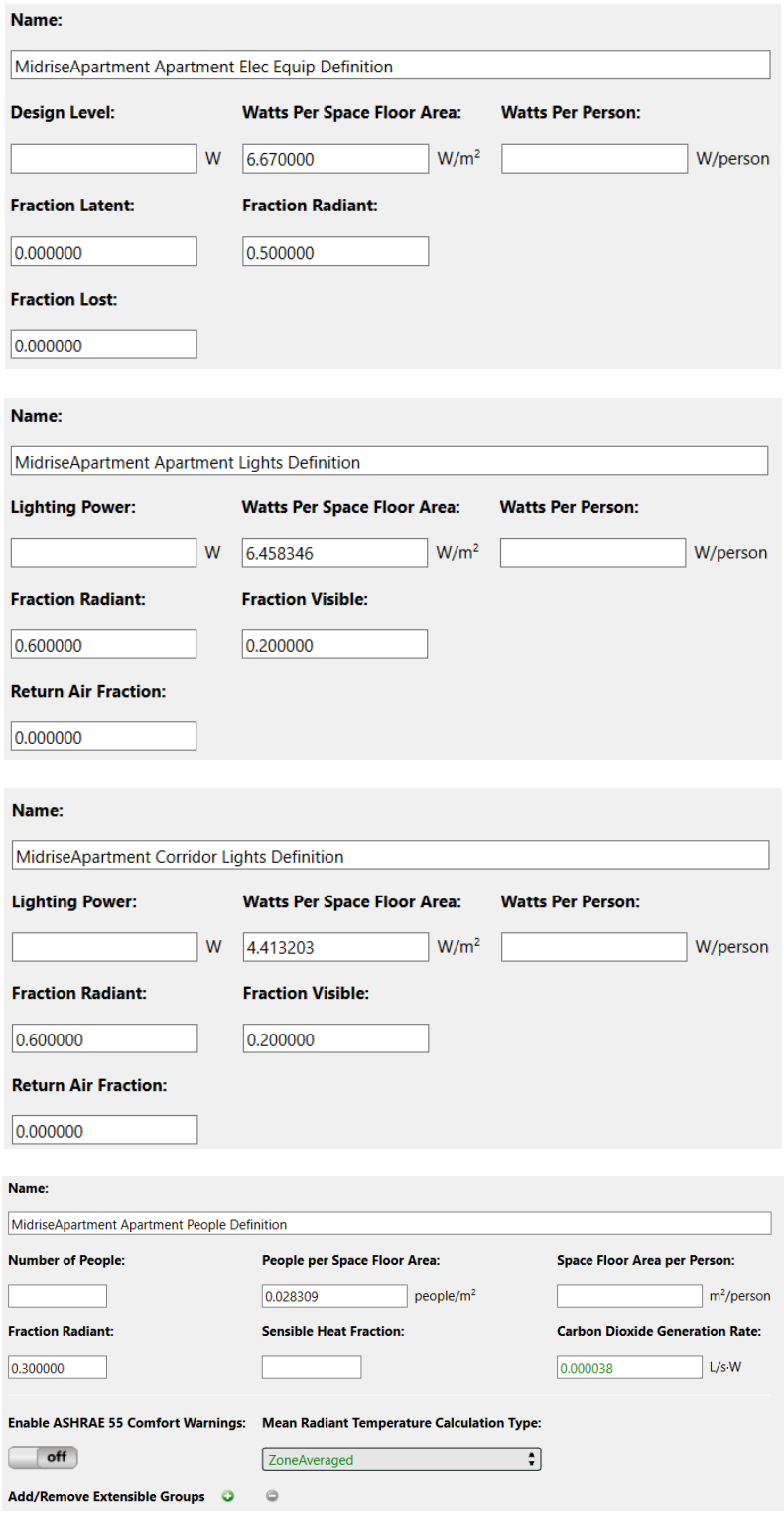

Figure B.4: Thermal load definitions.

Appendix C - The Settings of the Measure: Add Wind and Stack Open Area

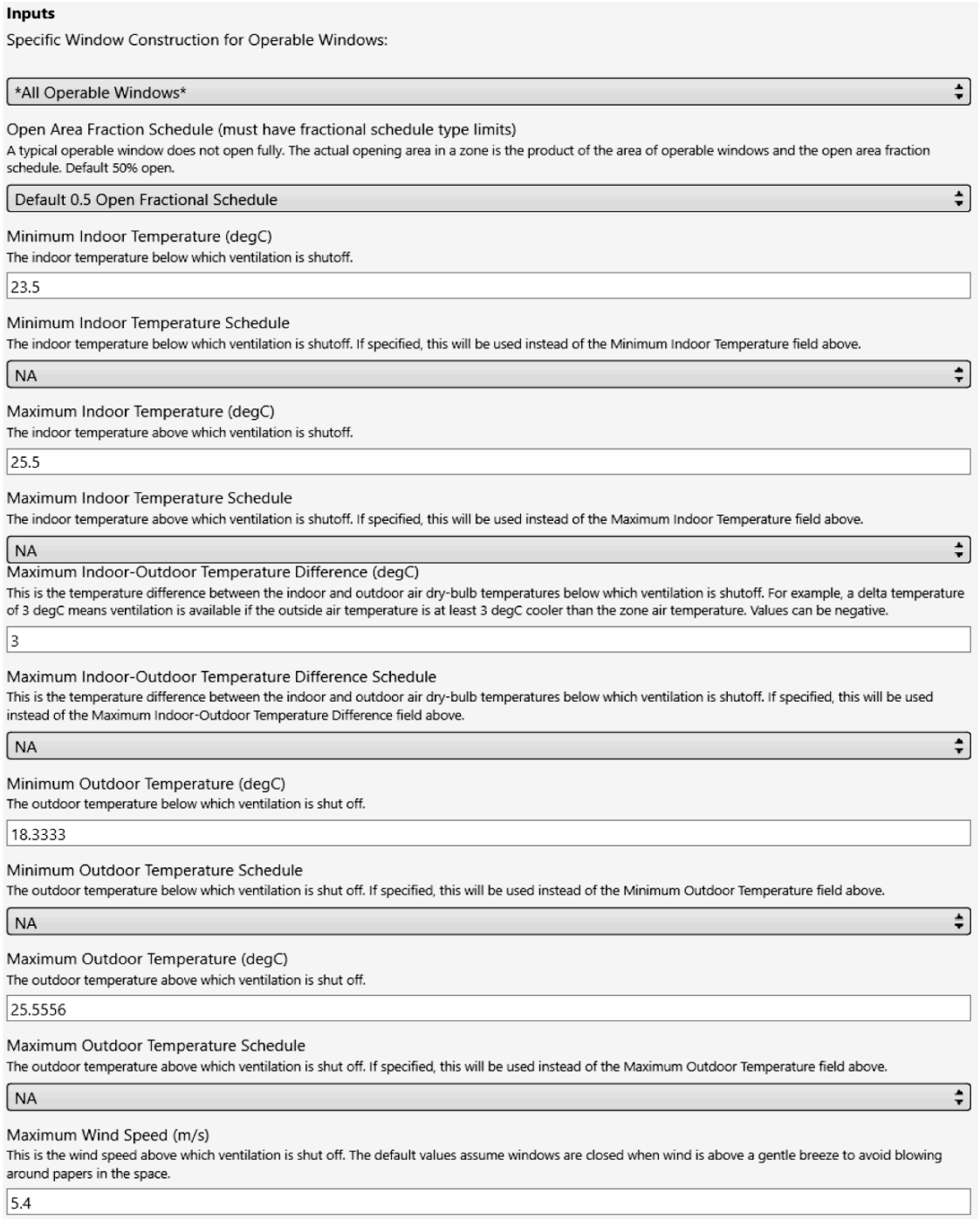

Figure C.1: The settings of the measure Add Wind and Stack Open Area.

Appendix D - Construction Set and Wall Sections Used in OpenStudio Simulations

Figure D.1: Construction set named as 90.1-2019 - MidApt - ASHRAE 169-2013-3A from OpenStudio Library.

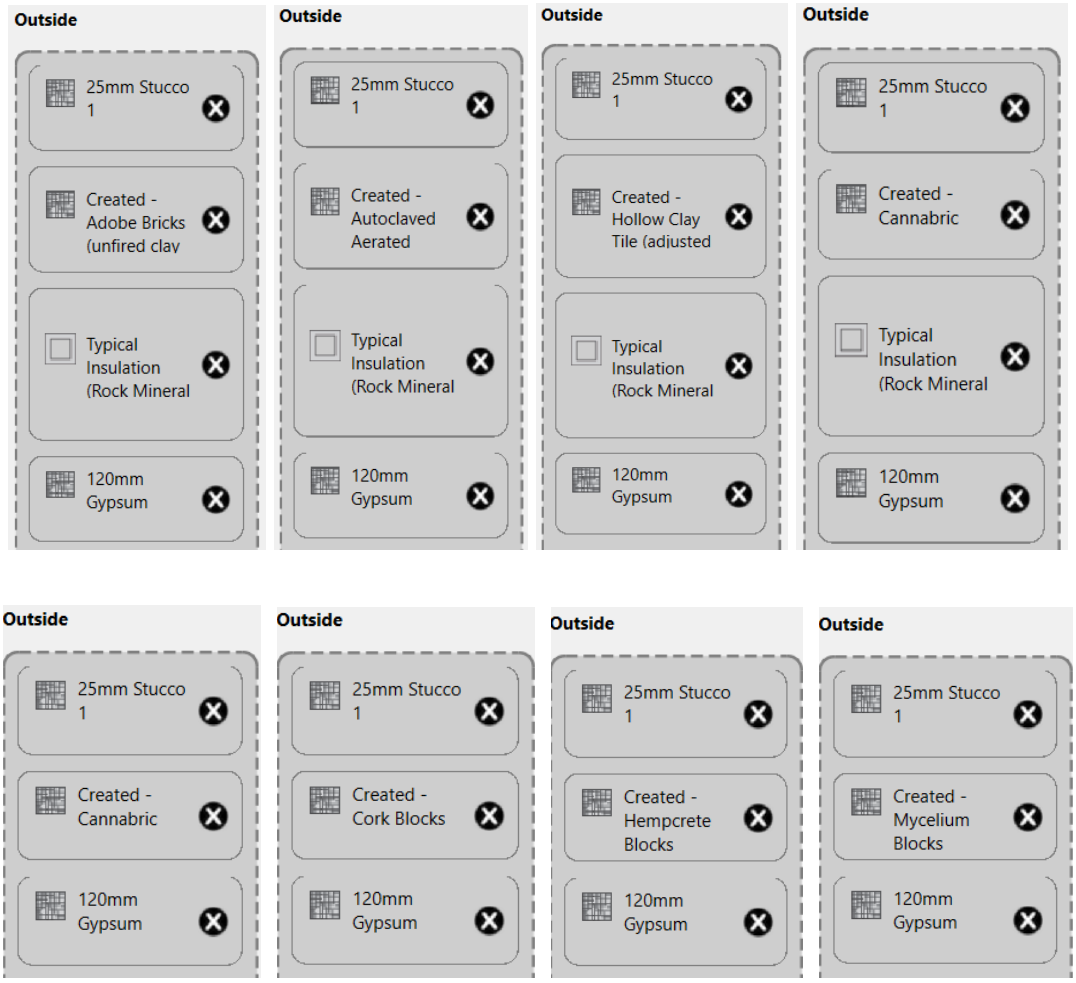

Figure D.2: Exterior wall constructions created for the simulations.

Appendix E - Grasshopper Definition to Generate Urban Weather File

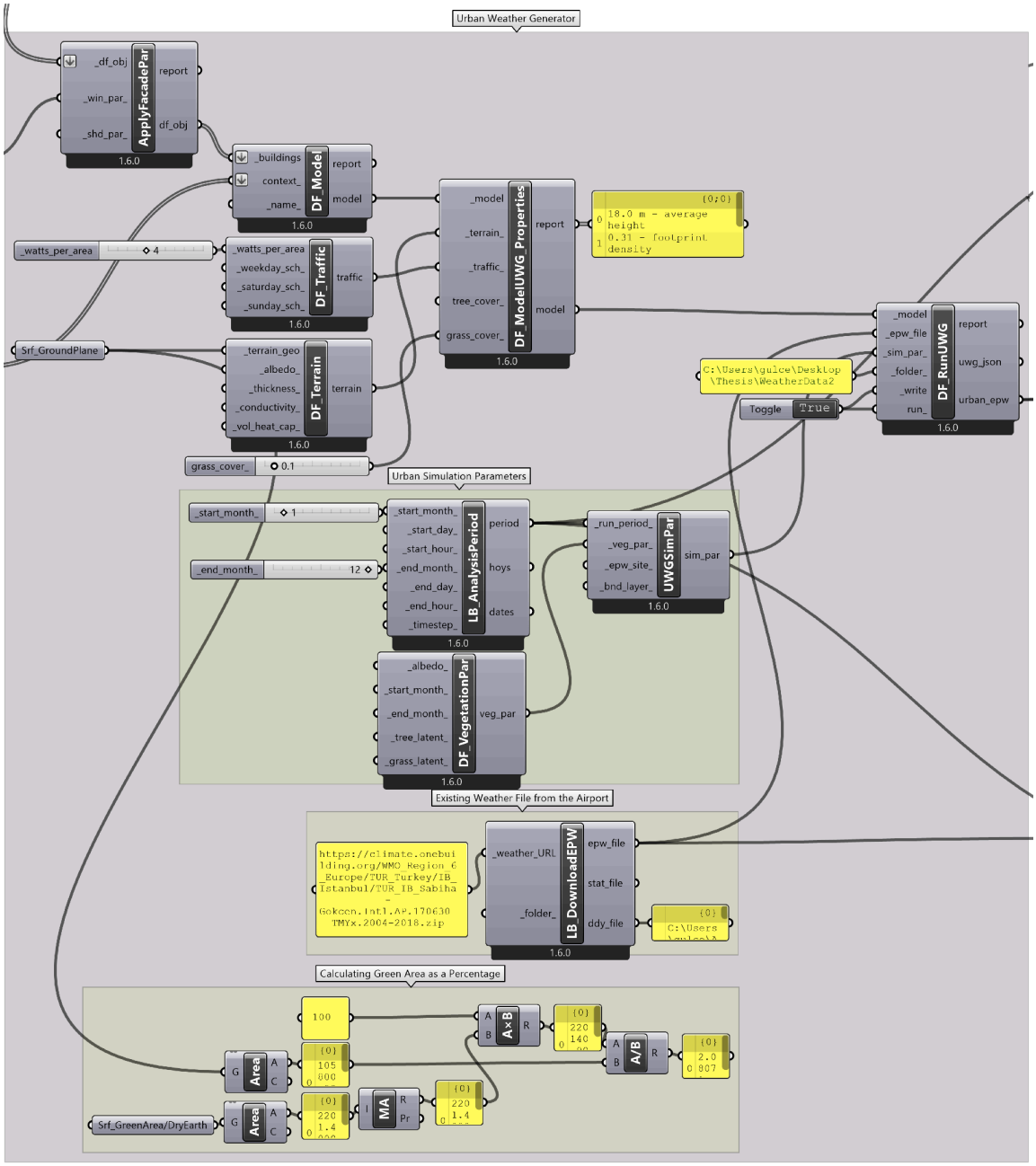

Figure E.1: Grasshopper definition to represent the selected case study area and to create the local urban weather file.

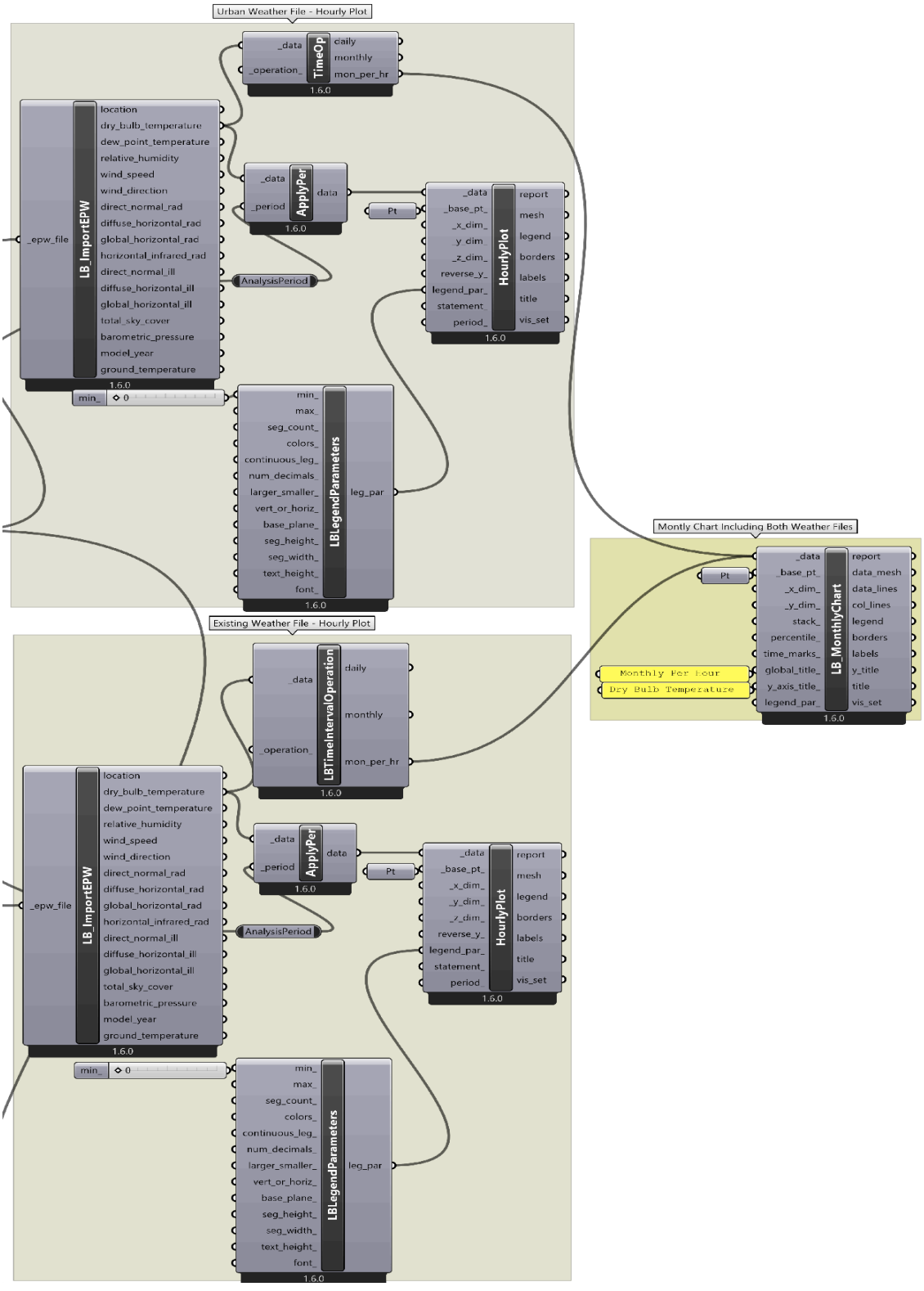

Figure E.2: Grasshopper definition to create graphs comparing the airport weather file and the local urban weather file.