TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST

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DOCTORAL THESIS- summary

THE IMPACT OF THE BUILT ENVIRONMENT ON URBAN CLIMATE

Insights on Urban Interrelationships and Thermal Environment Modelling, in our present-day challenges

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I. Introduction

The complex interrelationships that can be acknowledged in any urban environment (i) are fundamental for how we, humans, experience life and, overall, (ii) are responsible for many aspects that can lead or not to societal well-being. In this whole spectrum of interactions, different layers can be acknowledged when it comes to how humans experience life – an experience that can be seen as fundamentally linked to the idea of "climate" – which can be further understood in different ways and from different perspectives – the layers above (e.g., from the primary understanding related to the climatologic dimension to many other societal related ones).

Thus, from primary (e.g., thermal environment driven by different weather forcings which are integrated by the built environment to set a local response – which can also be associated with the primary idea of "climate") to more aspirational ones (e.g., social, economic, educational), such layers are interconnected with each other in various reciprocal ways (e.g., unfavourable climatic parameters at street level may encourage people to use cars which leads to local pollution which will further affect air quality and further discourage people from walking in the area; natural/climate-related disasters will impact societies one way or another; pending on how waste is managed will influence the environment and many aspects that can be associated to a further impact on the "local climate"; and so on).

In all these entanglements, especially when thinking of urban areas, there is one element that is in a particular relationship with all the others—and that is the altered environment—natural (e.g., parks, green spaces) or artificial (e.g., buildings, roads)—the built environment.

The form the built environment takes, the nature of its surfaces, the distribution of elements, and so on will influence climatic parameters, such as wind flow, energy transfer and storage, and so on. [283]

But, also, due to how the functions are distributed throughout the urban area influence local traffic, waste production, etc. – also further influencing the "urban climate" – with even further consequences that can be acknowledged (sometimes almost impossible to be quantified) at a societal level especially in terms of public health[308], [341] – something that also converges on the "climate" idea (e.g., a "healthy climate").

When considering the current level of concern given the Climate Change issue and the number of people living in urban areas, understanding such interrelationships becomes crucial—and given this context, understanding "urban climates" as exhaustively as possible while acknowledging the many potential interrelationships can be critical.

Preferably, this should also be the process of thought when trying to debunk the role of the built environment in this whole story—thus, understanding the built environment's impact on the "urban climate" it fundamentally influences should consider many things.

That is why, the thesis explores and discusses ideas regarding potential interactions that should be acknowledged when assessing such impacts (something that is synthesized in a Conceptual Map at the end of chapter four) – starting from (i) bare scientific branches without which a deep understanding of the many processes and occurrences within the urban world would not be possible; (ii) and up to the tools that can be employed to get a comprehensive picture on various issues that can be related, one way or another, to a specific urban climate; (iii) also, since the importance of the climatologic perspective in the whole urban setup and understanding of urban climate(s) is acknowledged, towards the end, the focus is placed on the "thermal environment subject to a specific weather forcing during the hot season" problem – something of high concern nowadays – this part is meant to assess and discuss how different changes to the built environment may drive local response differently when subjected to the same weather forcing – something done in two application examples.

As a summary, the thesis begins with an "Introduction" chapter – this part attempts to place things into context and direct further discussions. It briefly explores some general ideas, such as the ones already discussed previously, on how people are constantly surrounded by and interact with the built environment, from homes to urban landscapes, and how this interaction influences aspects of human life – from comfort to behaviour, and choices – in a reciprocal spectrum of interrelationships. The text discusses the fundamental role of physiological needs and sensory experiences in defining the relationship with the surroundings. It proposes in this sense that, as already advocated, the urban climate problem should be seen extensively starting from problems such as thermal comfort, air quality, acoustics[75], and visual aspects – while acknowledging the many societal aspects linked to these.

Apart from this, from the beginning, the implications of climate change on urban living are brought forth – it is not only about understanding the current status (which is essential nevertheless) but also about being able to predict how things will evolve and how different changes might affect the outcome – i.e., in our case, the urban climate. Therefore, from the introductory chapter, the initial discussions emphasise the critical need for both a coupled human-centric-climate-aware approach in urban development – while acknowledging and highlighting the importance of the climatic perspective in the whole compendium of ideas surrounding urban climates – therefore, it emphasises the urgency of integrating climate considerations into urban planning to foster environments that support human health, comfort, and wellbeing, especially given the challenges posed by climate change.

While primarily discussing topics such as the ones already mentioned, this first chapter sets the stage for a deeper investigation into how the built environment drives urban climates and inherently human lives (humans who, themselves, drive the built environment—acknowledging thus the complex interrelationships at play).

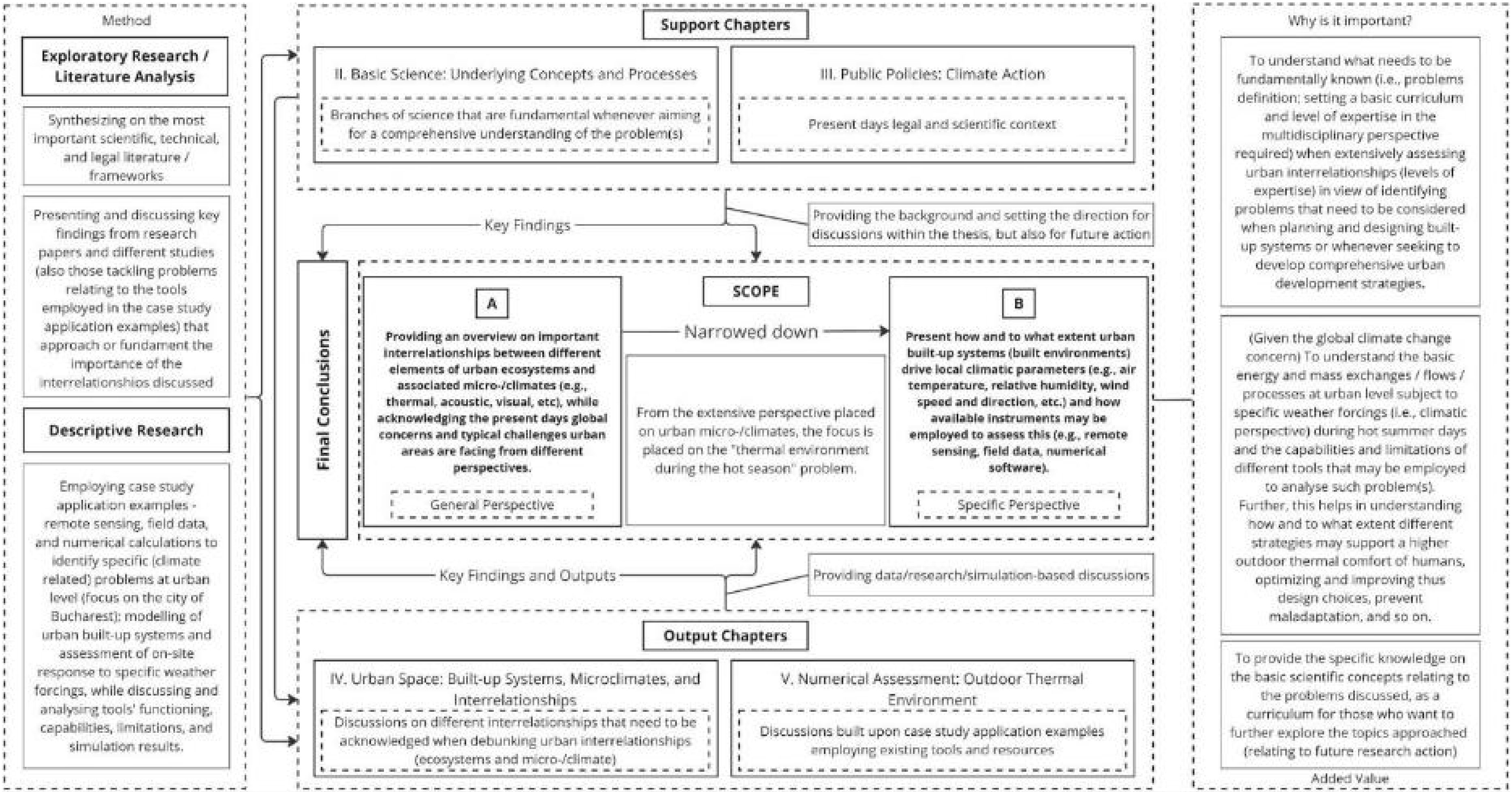

Figure 1 – Overview of the Scope, Method, Content, and Relevance of the Thesis

II. Basic Science: Underlying Concepts and Processes

This chapter focuses on the basic scientific ideas that form the foundation for further understanding the interplay between the built environment, urban climates, and humans. It serves as a bridge to better understanding the many aspects of urban climates.

Thus, this chapter evokes some of the most important branches of science and puts together and briefly highlights some key pieces of basic, well-established scientific knowledge they bring forth. Such elements should be acknowledged both to gain a general perspective on issues as those underlined earlier but also to set a direction on the type of expertise and understanding needed when exploring the urban climates problem extensively – i.e., first steps, as a prerequisite necessary to understand the more complex phenomena governing urban interrelationships as the ones already mentioned earlier.

It briefly tackles basic scientific ideas related to (i) Physical Sciences (i.e., Thermodynamics[3], Fluid Mechanics[24], [38], [42], [47], Rheology[58], Acoustics[75], Chemistry); (ii) Life Sciences – with specific discussions on Metabolism, Carbon Sequestration, Evapotranspiration, Biogenic Volatile Organic Compounds (BVOCs), etc.; (iii) Social Sciences; while also approaching problems related to the key methods in which (iv) Modelling (with special focus on the Scientific Method) of different Phenomena can be done – from basic depictions to numerical approaches – while highlighting some limitations due to (v) Complexity. Also, it explores fundamental concepts and knowledge regarding Earth's climate[198], [208], [235], [277], which is a key element of study when trying to understand the climatic context of urban areas and the fundamental processes at play.

Overall, this chapter emphasises the critical importance of basic scientific frameworks in comprehending how urban-built environments interact and drive local climates. It underscores the necessity of grounding urban planning and design in solid scientific principles to address the multifaceted challenges related to air quality, thermal comfort, acoustics, and visual environments in urban areas – as (proposed) critical descriptors of local climates.

Therefore, this part of the thesis attempts to facilitate a better understanding of what to consider when assessing the built environments' impact on human well-being or when attempting to design sustainable (regenerative) and resilient urban spaces.

Thus, the notions brought forth may serve to better understand many issues related to climatology, environmental science, urban ecology, and public health. This part relates to the preparation process of Thesis. It is meant to further support and equip readers with a comprehensive view of the scientific basis that can guide science-based approaches when developing strategies to improve urban climates / enhance urban liveability.

Moreover, this chapter strongly emphasises the interdisciplinary nature of addressing urban climate challenges. It argues for a holistic approach that combines insights from different scientific disciplines to develop comprehensive solutions that account for the complex interactions between physical, biological, and social systems in urban areas. This interdisciplinary perspective is crucial for developing strategies that effectively mitigate climate impacts and support public health and well-being – all of these, together, leading under different pathways, leading to specific urban climates.

In conclusion, this second chapter of the Thesis provides some insights on the foundation for further understanding the complex dynamics between the built environment, urban climates, and human experiences. It underscores the importance of an extensive science-based approach in urban planning and design, arguing, therefore, for interdisciplinary research and collaboration between professionals with different types of expertise to address the multifaceted challenges of creating sustainable, resilient, and liveable urban spaces – especially in the face of the current climate change crisis.

III. Public Policies: Climate Action

International efforts and policy initiatives are vital to addressing the challenges of climate change, particularly within the urban context. Understanding the international context can be fundamental for many reasons when tackling any subject in general, not to mention when it comes to one that is relevant worldwide. Thus, it was important to have a chapter that explores the evolution of climate policies and actions while highlighting the contributions of global organisations, scientific bodies, and legislative frameworks that have shaped the collective understanding and response to the climate change problem.

In this context, this third chapter explores the history and role of The Intergovernmental Panel on Climate Change (IPCC), the leading body in shaping the global climate action landscape worldwide. The chapter outlines the IPCC's beginning, underscoring its critical role in synthesising and disseminating scientific knowledge on climate change to policymakers and the general public. It explores the periodic IPCC assessment reports and highlights some general ideas on key issues tackled by each report – the information brought forth is very important for understanding the general context but also to acknowledge some of the most important climate change implications for urban areas around the world.

Also, some brief insights on the IPCC's Special/Methodology Reports attempt to further contribute to better help readers explore the problem of climate change – e.g., the general approach in such reports allows a better understanding of the urban climate issues. From analyses of specific sectors like aviation and land use to examinations of broader issues like renewable energy sources and climate change mitigation, these reports serve as critical resources for informing policy and guiding international and local action. The chapter emphasises how these reports provide a nuanced understanding of the diverse aspects of climate change, including vulnerability assessments, adaptation strategies, and mitigation pathways, which are essential for developing effective urban climate policies.

The chapter covers various aspects of climate action, including the actors and initiatives that complement the work of the IPCC. It emphasises the importance of collaborative efforts in tackling climate change, highlighting the contributions of entities such as the European Environment Agency (EEA), the European Space Agency (ESA), and various Earth observation programs like Copernicus. These entities are crucial in monitoring, researching, and sustaining science-based climate action.

It gives examples of initiatives from around the world that can be linked to climate change mitigation efforts and/or the built environment/urban climates.

Also, statistics that are introduced in the Thesis, as the one presented in the next two figures, highlight why climate-related action and initiatives are critical.

	Belgium	Bulgaria	Croatia	Cyprus	Czechia	Denmark	Estonia	Finland	France	Germany	Greece	Hungary	Ireland	Italy
Drought	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Flood	67	82	4	0	100	0	0	0	324	258	123	310	5	1134
Earthquake	2	131	9	42	0	0	0	0	58	1	1273	0	0	115610
Extreme weather	101	3	3	3	18	27	0	0	467	231	128	60	41	322
Extreme temperature	5380	1353	1571	162	759	252	178	225	32400	17597	4221	1354	26	38183
Volcanic activity	0	0	0	0	0	0	0	0	0	0	0	0	0	735
Landslide	0	11	0	0	0	0	0	0	297	5	0	0	0	2604
Wildfire	0	10	13	4	0	0	0	0	112	0	237	0	0	21
Glacial lake outburst	0	0	0	0	0	0	0	0	0	0	0	0	0	11
Dry mass movement	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fog	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 2 – Recorded deaths from natural disasters 1900-2023 (European Union) – per type of disaster (1) [276]

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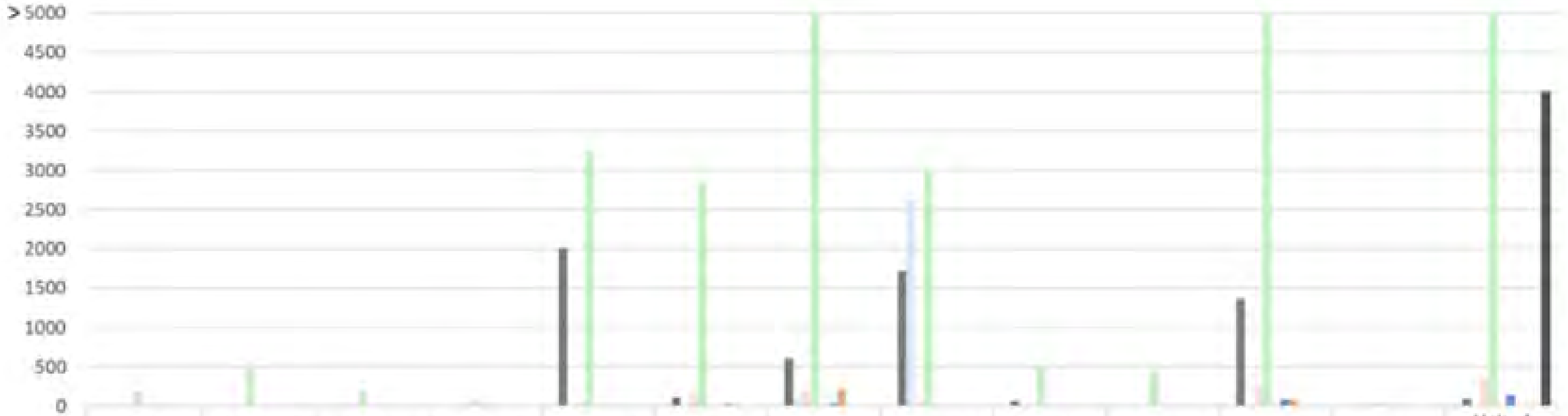

	Latvia	Lithuania	Luxembourg	Malta	Netherlands	Poland	Portugal	Romania	Slovakia	Slovenia	Spain	Sweden	United Kingdom
Drought	0	0	0	0	0	0	0	0	0	0	0	0	0
Flood	0	4	0	0	2001	115	597	1719	67	3	1366	11	94
Earthquake	0	0	0	0	0	0	111	2630	0	1	21	0	0
Extreme weather	6	8	0	0	43	154	200	61	3	8	251	19	366
Extreme temperature	191	473	214	76	3235	2848	5411	2986	493	444	26964	40	7270
Volcanic activity	0	0	0	0	0	0	0	0	0	0	1	0	0
Landslide	0	0	0	0	0	0	29	0	0	0	84	13	140
Wildfire	0	0	0	0	0	35	210	0	6	0	74	0	0
Glacial lake outburst	0	0	0	0	0	0	0	0	0	0	0	0	0
Dry mass movement	0	0	0	0	0	0	0	0	0	0	0	0	0
Fog	0	0	0	0	0	0	0	0	0	0	0	0	4000

Drought ■ Flood Earthquake Extreme weather Extreme temperature Volcanic activity
■ Landslide ■ Wildfire ■ Glacial lake outburst ■ Dry mass movement ■ Fog

Figure 3 – Recorded deaths from natural disasters 1900-2023 (European Union) – per type of disaster (2) [276]

IV. Urban Space: Built-up Systems, Microclimates, and Interrelationships

A detailed understanding of the complex interrelationship between urban spaces and various aspects that can be understood through their associated climate – while focusing on the primary dimension of the concept – can be critical in many aspects related to urban development.

Thus, the chapter explores how architectural designs, infrastructure, different sectors, and the spatial organisation of cities influence the creation of distinct microclimates while discussing how the elements that may fall under the idea of urban dynamics may be affecting various societal aspects (e.g., public health) and environmental sustainability – highlighting the complex entanglement of cause-effect relationships between various factors, with the focus, of course, on the built environment and anthropogenic activities. It points out important elements that should be considered when exploring the different climates (with a focus on the microclimate problem) that can be acknowledged at the urban level – for which, at the end of the chapter, after the various discussions carried out, a conceptual map is provided to incorporate the main lines of thought when it comes to assessing urban climates in an extensive as possible manner.

IV.1 Urban Dynamics

The exploration into the ecosystems that make up urban spaces, the complex interactions that can be acknowledged between the different components of urban ecosystems, and the collective influence of various factors on urban climates is essential for many reasons – having a deep understanding of such issues can be a critical thing in any process that leads to a change in the built environment.

This part of the thesis (more or less briefly) delves into the main components of urban ecosystems, including the atmosphere, biosphere, hydrosphere, pedo-/lithosphere, built environment, and human population. This section emphasises the interrelationships between these components, highlighting how human activities and the built environment significantly shape urban climates and local ecosystems.

The discussion on buildings within urban spaces presents a foundational understanding of how architecture and infrastructure contribute to the dynamic urban landscape. It categorises buildings based on their functions – e.g., residential, commercial, industrial, recreational, and cultural – underscoring that each can define local climates and ecosystems differently. This acknowledges, on the one hand, the direct impacts of the built environment on urban climates, such as their influence on solar radiation distribution, wind flow patterns, and local thermal environments, but also its indirect role when it comes to the Climate System, through the greenhouse gas GHG emissions it leads to. Further, the discussion focuses on examining the different types of urban infrastructure while acknowledging their importance in the urban landscape – also given the role of the various infrastructures in sustaining urban metabolisms – another problem discussed in this subchapter.

The subchapter also addresses urban morphology and its fundamental role in shaping local climate conditions. It (i) briefly touches upon the reciprocal relationship between urban form evolution and local climate dynamics and (ii) discusses how urban morphology directly affects the urban thermal environment, atmospheric circulation, etc. – something related to the influence of building geometry and spatial arrangements, as well as surface and material properties.

Urban metabolism is another brief focus of this subchapter – and this relates to the fact that urban ecosystems are complex systems that undergo various processes that involve the transformation of energy and mass at different levels – something that can be essential to be understood when aiming to have a comprehensive picture on the different climates that may be perceived at urban level. Proper data and a well-tailored urban metabolism framework can aid in monitoring and visualising problems related to resource dependency, energy efficiency, emissions or waste, cars and industry, etc.

To evaluate the built environment's impact on urban climate, it is important to understand the specific urban metabolism and the factors that drive it. This can help identify risks, predict changes, and find appropriate mitigation and adaptation measures. Emissions by type and source are critical considerations in this process, and urban metabolism should be acknowledged accordingly as a tool to assess the built environment's direct and indirect impact on the urban climate.

Urban areas face various challenges, including biodiversity loss and a furthering from natural environments. This is critical for how the local climates "look like". Technology can help us gather insights on how to address these issues. However, nature itself can also play a significant role in solving many of these problems. That is why a brief discussion is carried out on the role of (and associated challenges related to) Nature Based Solutions (NBS) and of Blue Green Infrastructures (BGSs) roles in "restoring" urban areas[296], [300] – while emphasising that urban areas seeking a robust approach towards becoming more sustainable and resilient when faced with all sorts of challenges should understand and embrace BGI's full potential.

To conclude, this subchapter thoroughly explores the various processes and interactions between the different components of urban ecosystems. Overall, it attempts to put as much as possible a comprehensive perspective on the different key elements of the built environment that should be acknowledged at the urban level when assessing the various urban climates. Through its exploration of some important ideas behind urban ecosystems, buildings, infrastructure, morphology, metabolism, and restoration, this subchapter provides valuable insights into some of the most important components of the urban world that should be considered in any practice seeking to foster a comprehensive understanding of urban climates and (based on that) a climate-aware, human-centric, evolution of urban landscapes.

IV.2 Energy Sector

The subchapter tackles the problems of Energy Demand and Production while discussing the overall role of the Energy Sector in driving local climates (and vice versa) and impacting the global climate system, acknowledging a certain reciprocity.

First, local climate conditions are important in driving energy demand for buildings. Especially in climates where buildings need heating during cold seasons and cooling during hot seasons, implementing energy efficiency principles and technologies can help reduce energy demand. This inherently leads to less GHG emissions and, if done correctly, to more comfortable indoor conditions. For instance, incorporating high solar gains during cold seasons, low solar loads during hot seasons, limiting unwanted convective heat exchanges, using heat pumps, mechanical ventilation with heat recovery, smart facades with phase-changing materials, and nanotechnology can play (now or in the future – as some cutting-edge technologies may not be affordable yet/applicable at large scale) a crucial role in reducing energy demand.

However, it is emphasised that if the idea of sustainability prevails, special attention should be given to different things – e.g., the production, transportation, installation, and lifespan of materials meant to reduce energy consumption (and GHG emissions) should not lead to an environmental impact greater than their contribution. Also, sustainability does not relate only to lowering energy consumption and

GHGs – other societal components should be considered in any decision-making process – and this is something else highlighted in this part of the thesis.

Another key aspect pointed out in this chapter is that it is essential to acknowledge that energy efficiency and demand in buildings are somehow related to human health – they go hand in hand (e.g., reducing thermal bridges reduces risks for cold surfaces and respectively mould apparition, etc.). The compliance of buildings with building thermos-technics principles can be vital for occupants' health, as nonconformities in design and construction, accompanied by bad exploitation practices could lead to problems such as "the sick building syndrome" [301]. Such issues can significantly impact human health and society, making them crucial for urban climates and their interrelationships. Apart from this, it is emphasised that aspects such as acoustics, structural safety, lighting, and aesthetics[313], [373] should also be considered in this context – highlighting that, in some case, special care should be shown at design level to avoid any clashes (e.g., energy efficiency and structural strength[302].

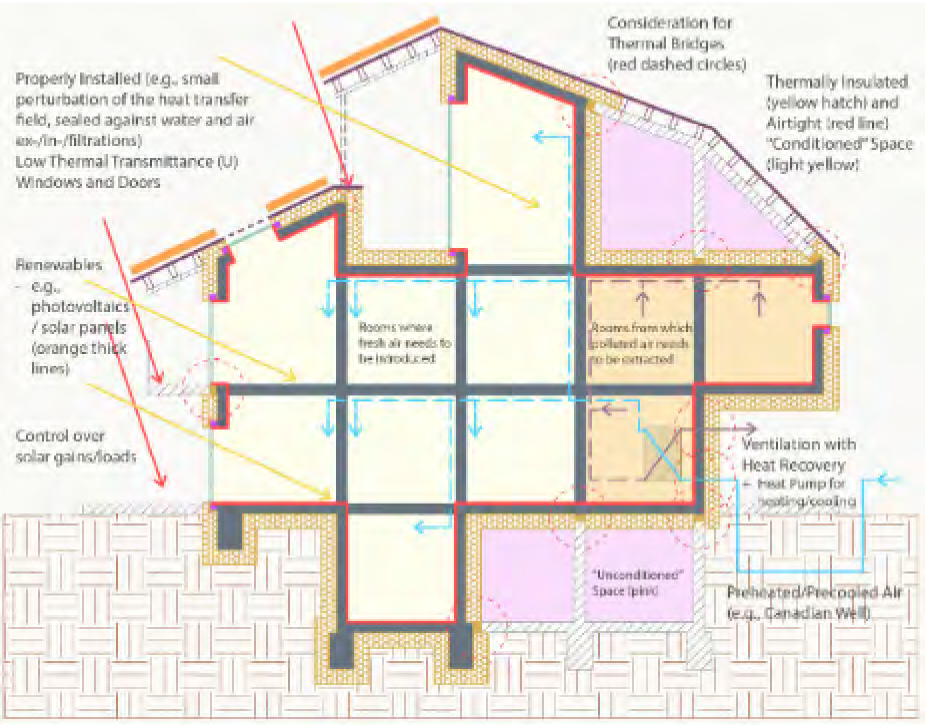

Figure 4 – Concepts for reducing Energy Demand in Buildings

On the other hand, as said, the problem of Energy Production is discussed – and here, the discussion is directed towards the idea that reducing energy demand and transferring energy production closer to where it is needed while using renewable energy sources are important factors to consider given the extensive ramifications that can be acknowledged. When energy demand is low, smaller energy production equipment is required, leading to a smaller impact on the environment, reduced financial costs of installing or maintaining the units, and more. However, renewable energy production, especially solar and wind, depends on local climate conditions. Therefore, deciding where to place and integrate such equipment is important. Having relevant field data and properly modelling the built environment and simulating local microclimate conditions can help identify suitable locations for various technologies. Of course, this part also highlights that risks related to strong winds, hail, and other weather conditions should also be considered when placing various equipment (e.g., photovoltaics), for example, on buildings.

Apart from these, some various discussion on how lowering energy demand may be possible – an example is given: instead of consuming energy to cool data centres, heat pumps can transfer heat and use it for district heating or hot water production – also, renewable energy can be used to power such data centres alongside solutions employing geothermal energy – while, of course, not neglecting the environmental concerns that could emerge.

IV.3 Transport Sector

This part mainly reflects on how the problem of mobility and concepts like walkability (i.e., how friendly a city is for pedestrians) and bikeability (i.e., how friendly a city is for cyclists) relate to the built environment and urban climate.

There are different types of buildings within urban areas with different functions, and people need to travel between them. They also need to travel outside of the urban area. Goods must also be transported from one place to another, whether within or outside the urban area. Considering the built environment, all the infrastructure necessary for these transfers, including vehicles, boats, aeroplanes, and other technologies, falls under the transport sector. Specific infrastructures like roads, rails, walkways, bicycle lanes, train stations, ports, and airports are needed for different types of transport. The way the transport sector takes form fundamentally defines and shapes the physical landscape, enables different transit options, and influences local microclimate conditions. Various factors, such as the distribution of buildings, the needs of the human population, the natural environment, and climate and weather conditions influence how it takes form. It plays an important role in influencing transport choices, urban surfaces, air pollution, and many other aspects that directly or indirectly relate to the urban climate. To minimise the impact on local climate conditions and facilitate less harmful choices of transport, the transport system needs to be viewed as a whole, but at the same time, approached carefully at a small scale (e.g., looking into the microclimate problem of walkways).

Urban transport aims to provide efficient, safe, and diverse options for people to travel within cities. The impact of each transport option on the local climate and environment should be understood to assess how the built environment relates to the local urban climate. High mobility with a high level of accessibility is essential for achieving sustainability goals and addressing social inclusion issues. Responsible urban mobility management is necessary to address climate change concerns [312], but also to create a healthier local climate. Transport choices can affect decision-making, and diverse options are crucial to finding ways to respond to travel needs with minimum impact on the local climate. Various aspects regarding this topic are further discussed within the Thesis – especially about how beneficial a high level of walkability and bike-ability could be for a city and how the built environment and the whole setup may encourage (or discourage) people pursuing such eco-friendly means of transport.

IV.4 Water Sector

This chapter approaches the issue of urban hydrology and discusses its profound impact on the urban climate, sustainability, and resilience. This section focuses on the vital role of water management in urban areas, not just as a resource essential for life and daily activities but also as a key element in shaping urban microclimates and contributing to the overall health of urban ecosystems.

Various components of urban water systems are mapped out, including freshwater supply, sewage, and stormwater management – while discussing how the built environment and anthropogenic activities relate to this fundamental component of any urban ecosystem. Thus, this subchapter highlights the interplay between these systems and the built environment, underscoring how urban development patterns influence water distribution, usage, and quality. The discussion points out the challenges urban areas face in managing water sustainably, especially in the context of climate change – i.e., the intensification of things such as water scarcity and flooding, critical aspects in many parts of the world.

Another discussion relates to urban hydrology and how water interacts with the different elements that may be found within urban ecosystems. It highlights the importance of shaping the built environment to facilitate managing water runoffs and reducing flooding risks.

Water management practices within urban settings are presented as critical determinants of local climate conditions. Properly designed and managed, these practices can help mitigate the urban heat island effect (UHI), improve air quality, and provide recreational and aesthetic benefits to humans. Conversely, inadequate water management can lead to adverse environmental and climatic effects, highlighting the need for integrated, sustainable approaches to urban water planning as another component vital for nurturing a pleasant and sustainable urban climate.

IV.5 Waste Sector

The complex problems related to urban waste management are yet another thing that should be considered when exploring how the built environment leads to different specific micro-/climates. This part acknowledges that waste generation is an inevitable byproduct of urban metabolism, emphasising the critical need for effective management strategies that mitigate environmental impacts. This chapter underlines the multifaceted nature of urban waste, ranging from household to industrial and construction debris, each contributing differently to the urban climate (e.g., bad air quality, GHG, public health).

A significant focus is placed on pollution, detailing how improperly managed waste can contaminate air, water, and soil. Such pollution not only degrades the urban environment but can also adversely affects public health and local microclimates, exacerbating the urban heat island effect and contributing to GHG emissions. The need for a shift towards recovery and recycling as a means to reduce the waste sector's environmental footprint is also emphasised alongside circular economy principles – e.g., reduce, reuse, recycle. However, some barriers are also pointed out and briefly discussed (e.g., various societal aspects).

The "Waste Sector" subchapter presents a concise yet comprehensive overview of how urban waste management can relate to local (urban) climates. It highlights the importance of an integrated approach that considers waste not as an endpoint but as part of a broader urban system – with direct consequences on the quality of air, soil, and/or water – but also on many other aspects of the human experience of urban areas.

IV.6 Comfort and Health

This part intricately explores the intersections between urban environments and microclimates and their profound impacts on human well-being. It addresses the multifaceted ways in which urban design and climatic conditions converge to influence people's physical comfort and health outcomes, highlighting the importance of creating liveable urban spaces that are favourable to physical and mental health.

The discussion focuses on the Urban Heat Island (UHI) effect, a prevalent issue in urban climatology that exacerbates thermal discomfort in densely built-up areas, especially during the hot season.

The UHI effect, characterised by elevated temperatures in urban areas compared to their rural counterparts, is attributed to the modification of land surfaces and the abundance of heat-absorbing materials in cities. This phenomenon significantly impacts the thermal environment, affecting residents' comfort levels and potentially leading to heat-related illnesses during peak temperatures.

Further, the discussion expands to encompass the broader implications of urban climates on public health. It underscores the direct health risks associated with extreme temperatures and air quality, such as heat strokes and cardiovascular and respiratory conditions. Air quality thus emerges as another critical aspect of urban comfort and health discussed in this subchapter. The concentration of pollutants, including particulate matter, nitrogen oxides, and volatile organic compounds, is closely linked to urban infrastructure, transportation systems, and other anthropogenic activities – fundamental elements of/linked to the built environment.

Urban acoustics is yet another significant concern in the broader urban climate perspective (proposed in the thesis from the beginning). Urban streets impact sound propagation, which is generated from many different sources distributed throughout the urban space. Urban sound[78] can convey positive emotions; however, it can also be bothersome, leading to urban noise that can impact human sleep, productivity, and more.

Apart from this, some additional concerns regarding the problem of electromagnetic smog and radon emissions are also brought up in the chapter: within urban areas, a variety of activities contribute to the formation of a specific local climate from other perspectives apart from those that may be considered central. Urban areas are home to various equipment such as radio towers, power lines, transformers, and vehicles that generate radio frequency radiation (RFR) and electromagnetic fields (EMFs) – and this can be seen as something that could potentially interfere with the local climate – and thus, worth being explored in more depth. Also, it is essential to consider specific exposure safety measures for certain activities within urban areas.

Apart from the electromagnetic field-EMF concern, other elements, such as radon, pose a different threat to living organisms as it exposes them to α-radiation. Radon is a noble gas present in the atmosphere as it is being released from soil and rocks and can be present indoors or outdoors (from the ground or even from construction materials).

Beyond the general thermal environment, air quality, urban sound, visuals, and aesthetics concerns brought up primarily, this part of the thesis also emphasises the idea that, when discussing (urban) climate-related problems, it is essential to consider the radiation problem, as, if not properly managed, it may have a serious impact on the human population and on the biosphere.

So, the problems discussed around the comfort and health problems associated with urban climates given urban dynamics are covered as exhaustively as possible – even if key issues are touched upon only briefly. This means that the problem of “urban climate” is explored beyond the usual "climatologic" perspective. Nevertheless, this is still a primary, critical, and fundamental component of the whole setup, and that is why it receives special attention throughout the discussions in the Thesis.

IV.7 Assessment Tools

To handle the many issues urban areas are faced with, it is important to be aware of and employ the most powerful assessment tools out there – and this refers to satellite imagery, big data, AI, various numerical models, and so on. This section underscores the critical role of these tools in supporting “climate-aware” and “human-centric” urban planning and design processes, enabling stakeholders to make data-driven decisions that enhance urban resilience and overall life experience for the entirety of the human population. Central to the discussion is the categorisation of various assessment tools, which range from simple observational methods to sophisticated modelling software and sensor networks.

These tools are instrumental in quantifying the multifaceted elements of urban environments, from air quality and outdoor thermal comfort to energy efficiency. Thus, they can support a comprehensive understanding of urban ecosystems' current states and can help predict potential future scenarios.

This part of the thesis highlights the importance of Geographic Information Systems (GIS), emphasising its capacity to integrate and analyse different types of data from diverse sources and for different scopes (many of which, in the end, can be integrated to assess different dimensions of local climates – from the many perspectives thought of when looking at it extensively). GIS applications facilitate the mapping and visualisation of urban heat islands, green space coverage, pollution levels, and many other types of information that can be relevant for many reasons – especially in the urban planning and design perspective. Thus, GIS technologies may be offering valuable insights into spatial patterns and identifying areas of concern that require intervention. Also, they can be coupled with remote sensing data and field measurements – other topics of discussion under this subchapter.

Furthermore, the subchapter focuses on the problem of the available modelling and simulation software solutions that can be employed to understand and predict the outcomes of urban design strategies on urban micro-/climates. These models allow planners and architects to evaluate the effectiveness of proposed solutions in mitigating adverse climatic effects, such as heat islands and poor air circulation. By simulating various scenarios, stakeholders can assess the impacts of different design choices on urban comfort and environmental quality, guiding the development of more sustainable urban spaces – something dealt with when exemplifying such approaches in two application examples under the fifth chapter of the thesis (i.e., Numerical Assessment: Outdoor Thermal Environment).

The discussion also touches on the emerging role of smart technologies and the Internet of Things (IoT) in assessing urban climates. For example, sensor networks deployed across urban areas collect real-time data on many things of interest (e.g., climatic parameters).

Such data can be used in many applications, e.g., by providing access to a high level of detail and accuracy that can be used to test and validate models and simulations and for real-time analysis of various problems.

To complete the picture of digital tools that can be employed to assess various aspects converging on the problem of urban climates, different solutions are briefly referenced/presented. These technologies are available on the market and can be employed from the already mentioned problem of assessing / simulating urban micro-/climates (e.g., ENVI-met – https://www.envi-met.com/, OrbitalStack https://orbitalstack.com/), but also for looking into additional sides to the story of urban climates: the urban sound problem (e.g., SoundPLAN – https://www.soundplan.eu/, Predictor-LimA – https://dgmrsoftware.com/products/predictor/), urban traffic (e.g., PTV VISSIM – https://www.ptvgroup.com/en/products/ptv-vissim, Eclipse SUMO – https://projects.eclipse.org/projects/automotive.sumo), urban flooding risks (e.g., HEC-RAS – https://www.hec.usace.army.mil/software/hec-ras/, SWMM – https://www.epa.gov/water-research/storm-water-management-model-swmm), various urban vulnerabilities (e.g., Orbital Insight – https://orbitalinsight.com/, EpiModel – https://www.epimodel.org/), but also for complex system modelling (e.g., Anylogic – https://www.anylogic.com/, Vensim – https://vensim.com/).

Apart from this, the subchapter discusses advantages and limitations related to various Laboratory Experiments/Activities that can be employed to assess urban climates (e.g., having physical simulations in wind tunnels), but also the importance of Social Feedback in the whole problem of understanding urban climates extensively – while also providing some examples of projects employing such practices (e.g., DivAirCity – https://divaircity.eu/, RESTORE – https://www.eurestore.eu/).

Finally, some important Indices and Rating Systems that can be used to assess different urban areas are presented, alongside some discussions regarding the Whole Life Cycle Assessment problem.

In conclusion, the "Assessment Tools" subchapter emphasises the usefulness of advanced tools and technologies in studying and managing various factors that influence urban climates. By employing these tools, urban planners, designers, and policymakers can gain deeper insights into the environmental challenges facing urban areas and devise more effective strategies for creating healthy, comfortable, and sustainable urban climates.

IV.7 Conceptual Map: How are things connected?

As said, the key (categories of) ideas discussed in the first four chapters are centralised in a scheme meant to assist those interested in exploring different interrelationships. This mapping can be further (detailed and) used to develop specific methodologies for assessing urban areas and employed in any strategic approach towards more sustainable urban climates.

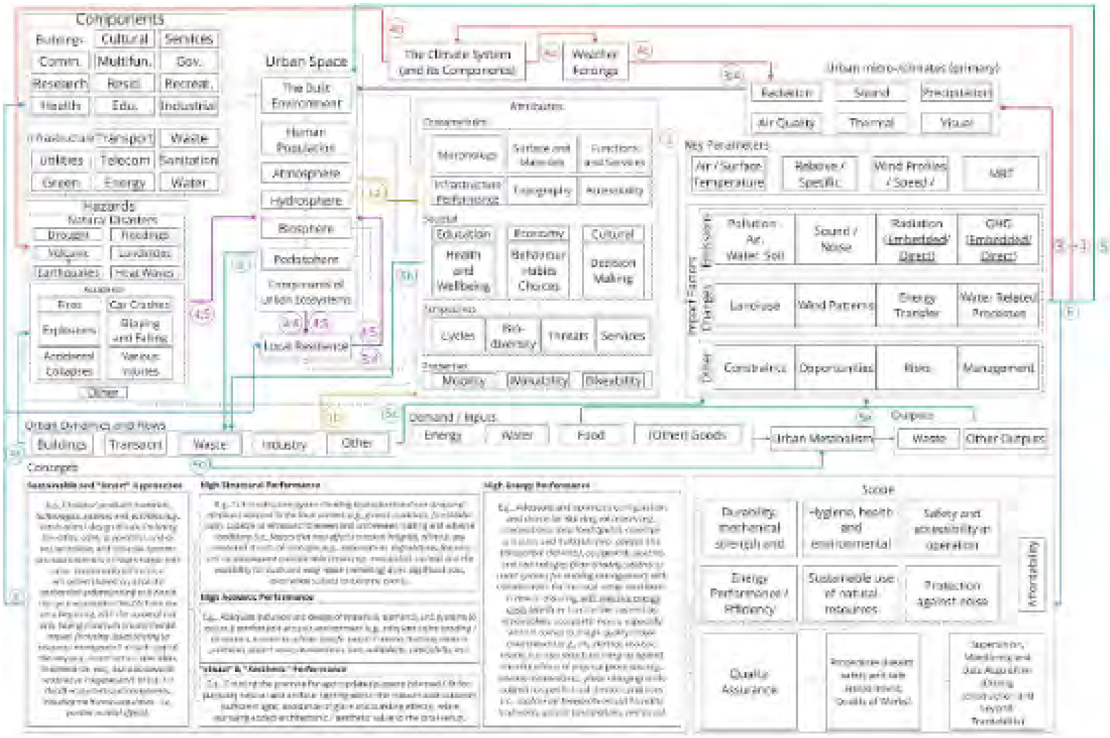

Figure 5 – Conceptual Map: Visualising Interrelationships

V. Numerical Assessment: Outdoor Thermal Environment

When looking at the problem more broadly, the built environment and the associated anthropogenic activities it is fundamentally related to in a certain degree of reciprocity greatly influence all other components of urban ecosystems. Therefore, it is responsible for creating a unique urban climate that can be viewed from various perspectives, all within frameworks characterised by complex interrelationships.

Given this significant role of the built environment in driving specific urban climates and the climate change context, understanding how different configurations of the built environment will lead to different climatic parameters becomes critical.

This also relates to the major concerns of our time and inherent discussions related to climate change and the overheating of cities during the summer months.

That is why this part of the Thesis aims to explore how present-day capabilities and tools can be employed to assess how a specific urban area responds to particular weather forcings in terms of thermal environment and human comfort, particularly during the hot season. To do this, the city of Bucharest is selected as a study area to further develop specific application examples.

First, satellite imagery is used to identify hot areas within the city. Also, by analysing how air temperature and a custom comfort indicator have evolved in the past years – this relates to assessing data acquired from https://meteoblue.com – via the History+ services, based on NEMS (high resolution), a multiscale model (from global down to local domains), which stands for NOAA Environment Monitoring System: https://docs.meteoblue.com/en/meteo/data-sources/datasets#nems –, a representative day for the peak of the season is determined and used to simulate how different variants of the built environment will influence the local climatic response.

Further, as said, two application examples are developed. One examines a larger part of the city (i.e., a neighbourhood-sized area), while the other focuses on a smaller scale (i.e., street level).

As said, the main objective of these two applications is to provide a numerical estimation of how various parameters of interest change when the urban setup changes (i.e., different surfaces, vegetation, etc.).

V.1 Software and Method

If thinking of the methodology employed, this can be understood via four steps:

Step 1: Problem Definition – understanding the impact of built-up systems on local climatic response during hot weather conditions, with two key aims: (i) to explore how changes in materials, surfaces, and vegetation coverage can affect local climatic response during hot weather, and (ii) to identify the key tools that can be used to study these changes.

Step 2: Finding the right Software – to address the problem(s) in Step 1, first, suitable GIS and Simulation tools had to be identified – QGIS (to integrate Land Surface Temperature – LST satellite imagery) and ENVI-met (for modelling and simulation purposes) were considered the best option for the task.

Step 3: Models and Simulations – As said, ENVI-met was used for this task – the software allows the creation of 3D models, the simulation of specific weather forcings, and the assessment of how different scenarios will lead to different climatic parameters – the functioning of the software is discussed in an extensive manner within the Thesis.

Step 4: Conclusions—Based on the simulation results from Application I and II and certain simulations done on some "Test Spaces" to explore the functioning of the software, this step relates to how different changes to a setup may affect climatic parameters. It focuses mainly on energy and mass transfer processes while considering atmospheric parameters, different surfaces, human comfort, etc. Apart from this, some limitations and things to be aware of when employing such numerical assessments are highlighted.

V.2 Application I (ENVI-met): Neighbourhood

The first step was to use an LST satellite image to identify some problematic areas. Out of these, one (1) was selected for simulation purposes (the neighbourhood-scale simulation).

This refers to the area between Iuliu Maniu Bd (N), Timișoara Bd (S), Paul Teodorescu General Bd. (E), and Lujerului Str. (W)—an area characterised by shopping malls, parking spaces, “black” asphalt roads, and dense building areas.

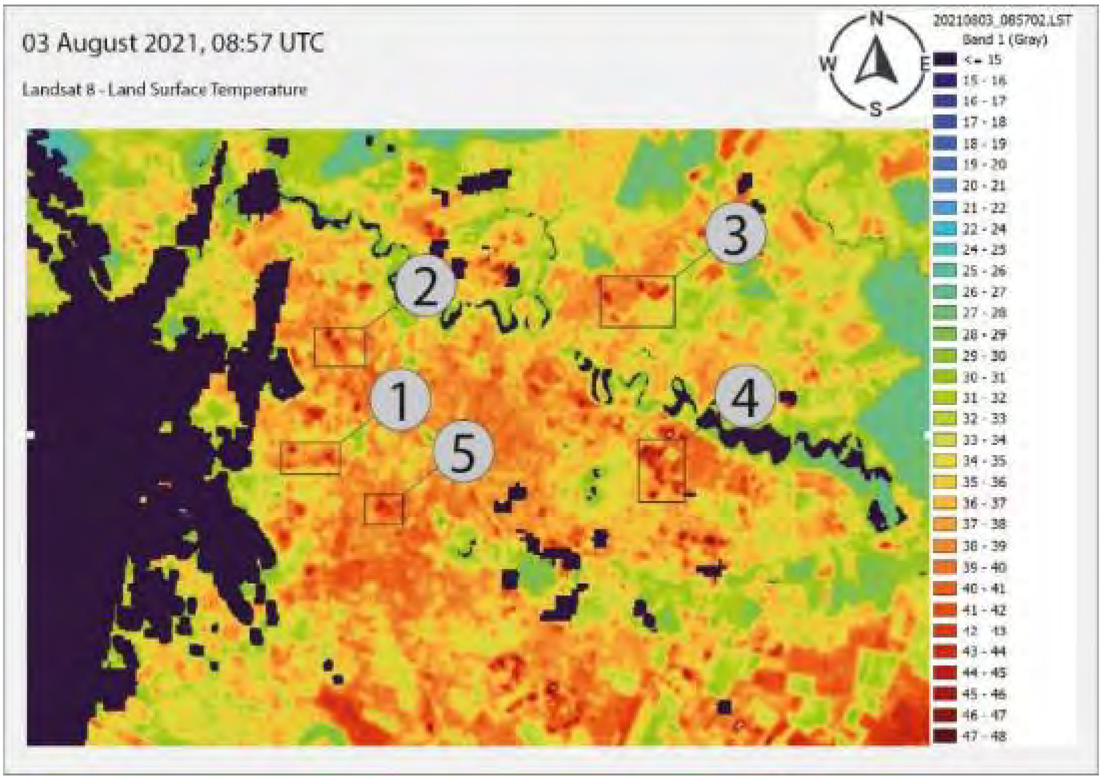

Figure 6 – Landsat 8 Image showing Land Surface Temperature (LST) for Bucharest, 03 August 2021, 08:57 UTC (11:57 Local Time) – this allows the identification of hot spots around the city and the identification of a study area.

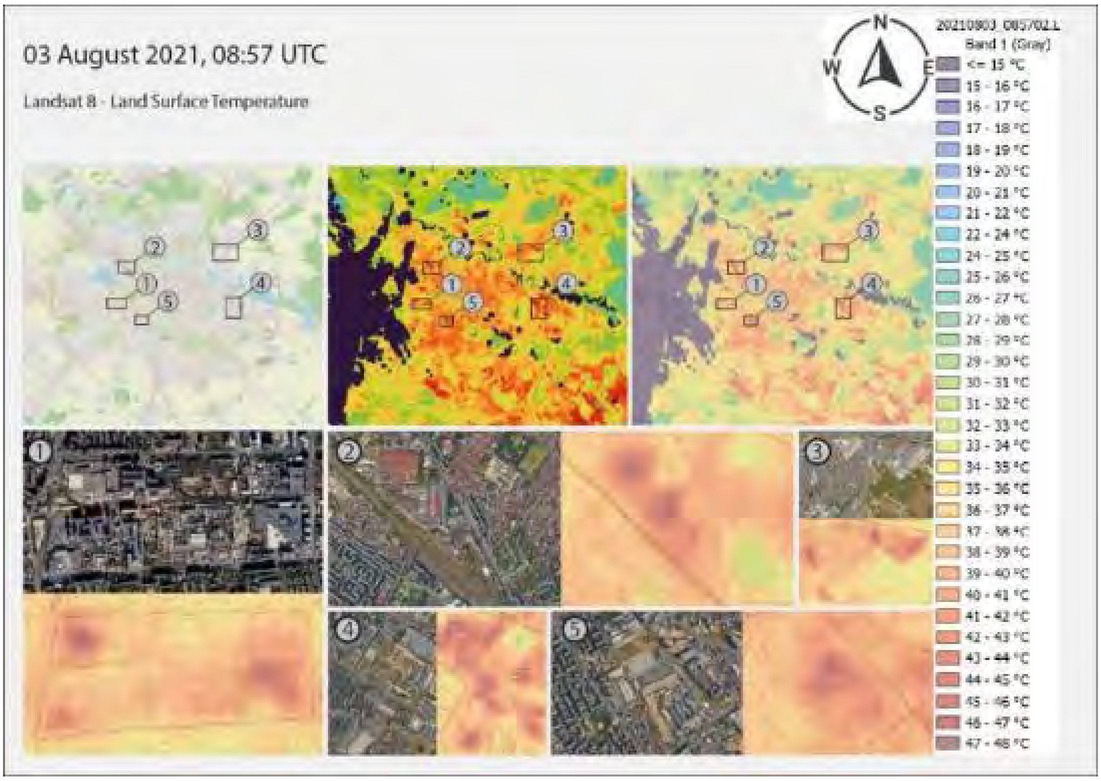

Figure 7 – Landsat 8 Images showing LST for different areas in Bucharest, 03 August 2021, 08:57 UTC (11:57 Local Time)

Figure 8 – Google Earth Image - Example 1 (Imagery Dated 19 October 2022)

Apart from finding the urban space to model, another task was to find a "representative day" for the peak of the hot season. Therefore, 15 years of hourly data (2008 to 2022) has been assessed and used to identify such a day while employing two indicators (air temperature and ITU – comfort index).

$$\mathrm{ITU} = (\mathrm{T} * 1.8 + 32) - (0.55 - 0.0055 * \mathrm{RH})[(\mathrm{T} * 1.8 + 32) - 58]$$

where T is the air temperature, and RH is the relative humidity

In the chosen timeframe,

2% of the hours were with air temperatures above 34.68°C,

and

2% of them had ITU above 79.75.

The 2% was considered representative of the "peak" of the season.

Subsequently, the analysis continued by looking at the number of hours with air temperatures above 34.68°C and ITU above 79.75.

$\mathrm{N}_{\mathrm{temp}}^{\mathrm{day,x}} = \sum_{1}^{24} \mathrm{t_i}$, where the hourly temperature $\mathrm{t_i} > 34.68^{\circ}\mathrm{C}$;

$\mathrm{N}_{\mathrm{ITU}}^{\mathrm{day,x}} = \sum_{1}^{24} \mathrm{ITU_i}$, where the hourly $\mathrm{ITU} > 79.75$

This allows insight into "how much" the temperatures surpassed 34.68°C, and respectively, "how much" the ITU values surpassed 79.75.

From the total number of days with hours surpassing the above values, 10% cumulatively surpassed the 34.68°C threshold by at least 19.5 cumulative °C and the 79.75 threshold by at least 17.6 cumulative ITU units. Out of these, one was randomly chosen to be used for the simulation – and that is August 5, 2021.

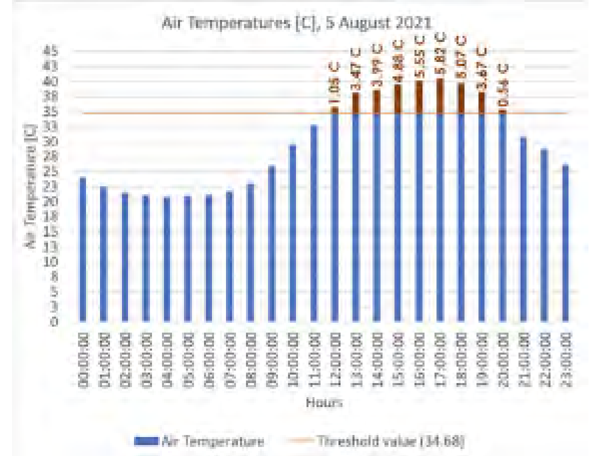

Figure 9 – Degree hours above 34.68°C for August 5, 2021

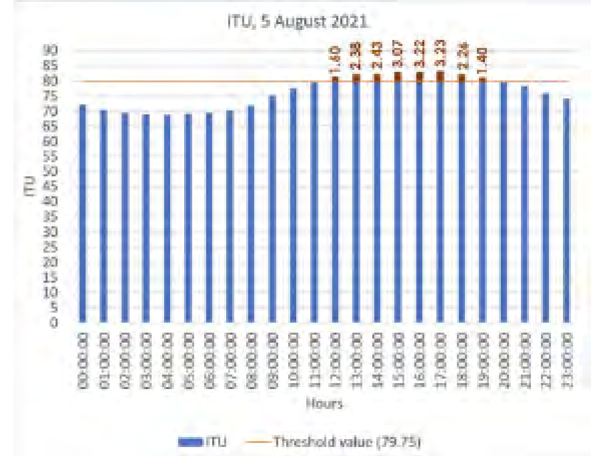

Figure 10 – ITU units above 79.75 for August 5, 2021

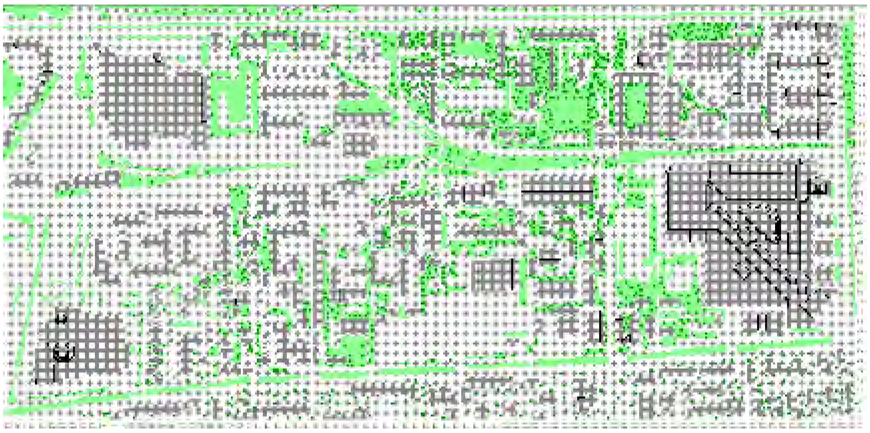

Figure 11 – Model 1, Layout (approximation of existing setup)

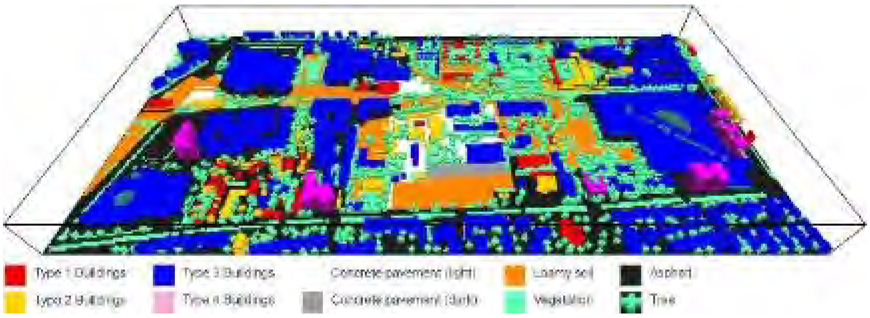

Figure 12 – Model 1, 3D (approximation of existing setup)

Figure 13 – Model 2, Layout (modified setup)

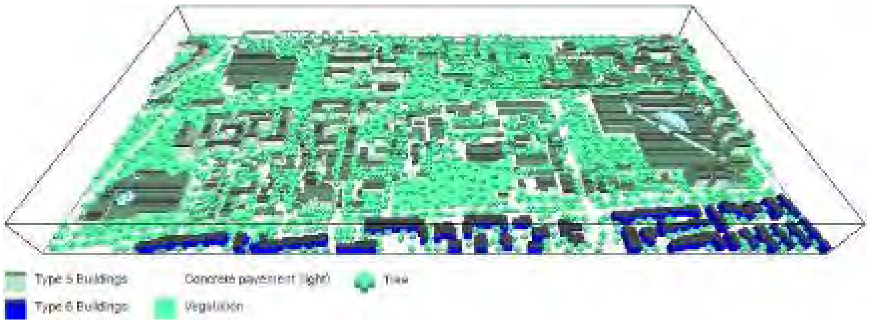

Figure 14 – Model 2, 3D (modified setup)

In the next extract from the simulation results, slightly smaller air temperatures can be observed in the second simulation (model) when compared to the first one – however, in this example (at this time and in this view plane), given the extreme forcing (peak of the season), the difference is only limited and can be accounted more if a higher resolution model is employed – nonetheless, in scenarios with such forcings, something that is also highlighted in the thesis is that the discussion is not about “comfort”, but rather about limiting severe health risks – the same can be concluded when looking at the PMV extract as well.

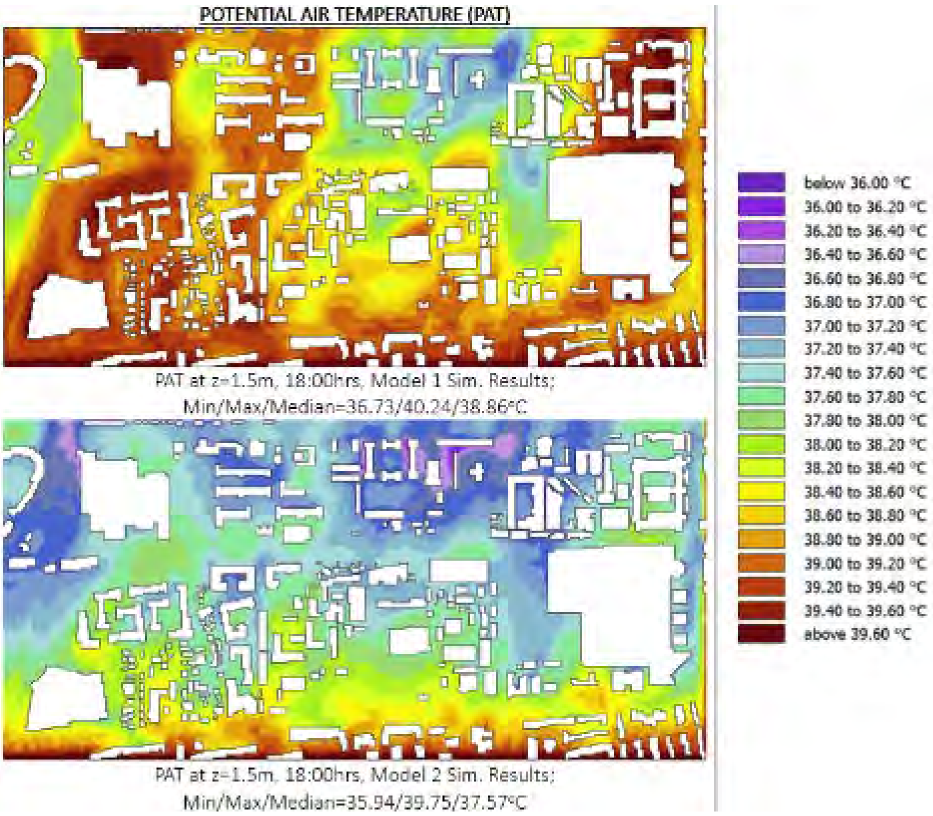

Figure 15 – Data output: Layout showing estimated Air Temperatures for the two different models, subject to the same weather forcing at a given time and within a given view plane

The PMV indicator shows how a certain person, as defined in the model, is expected to experience the thermal environment – values should be interpreted as follows:-4-> Very Cold,-3-> Cold,-2-> Cool,-1-> Slightly Cool, 0-> Neutral, +1-> Slightly Warm, +2-> Warm, +3-> Hot, +4-> Very Hot.

In this layout, the localised effects of the greening added can be observed. However, since the second model introduced higher reflectivity surfaces, the Mean Radiant Temperature increased, negatively compensating for the cooling effect of the vegetation – the thesis provides some more in-depth discussion on this matter.

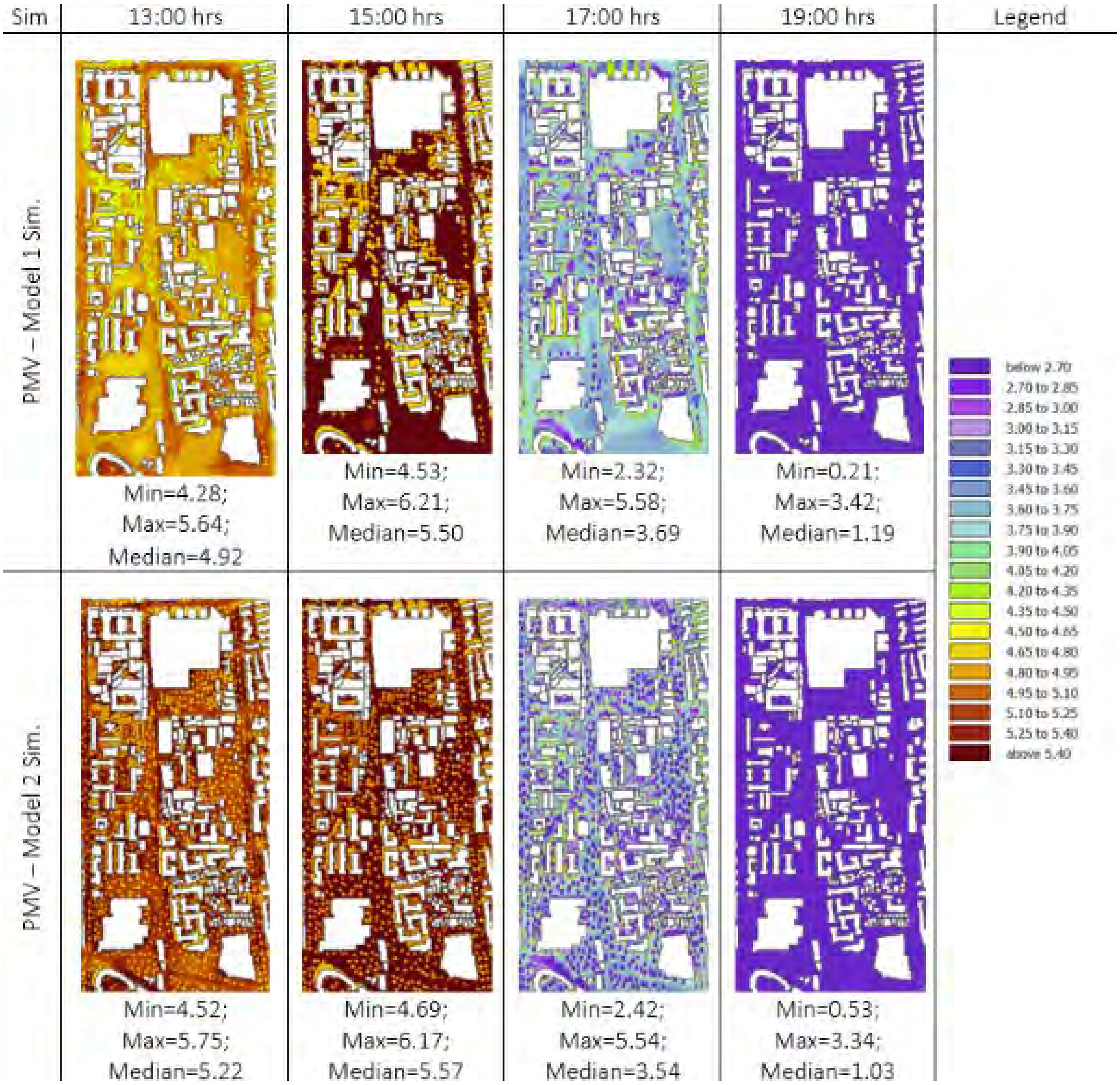

Figure 16 – Data output: Layout showing estimated PMV comfort levels for the two different models, subject to the same weather forcing at different moments

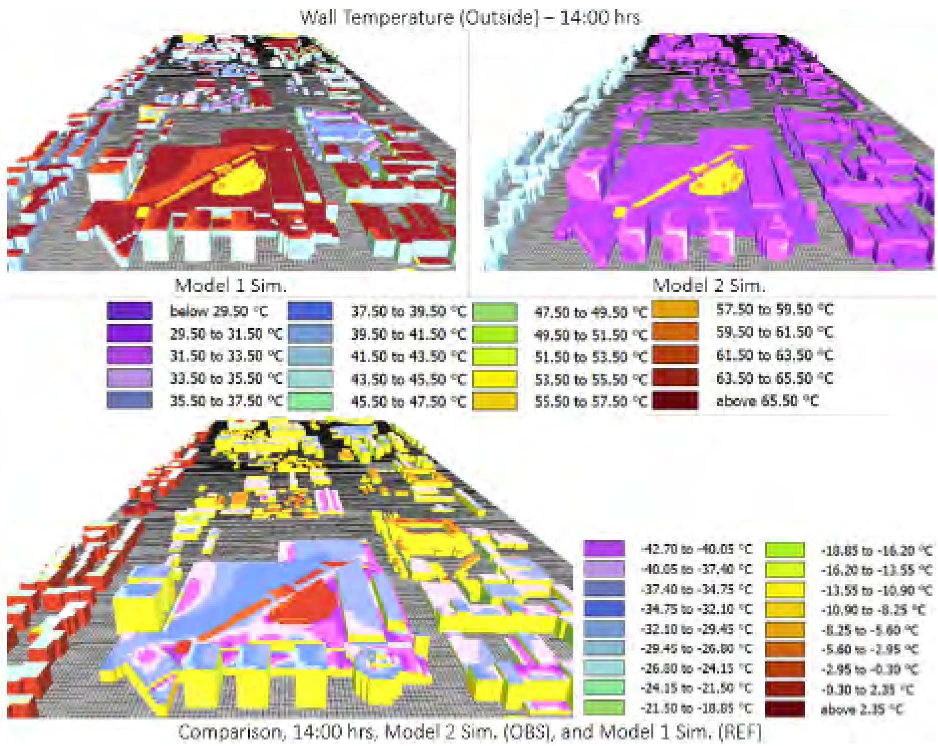

Figure 17 – Data output: Surface temperature of buildings for two different Models (with a comparison between them) subject to the same weather forcing at a given time, in 3D view

When it comes to the buildings, one thing that can be underlined and shown in the figure above is that the changes brought to the first model led to different surface temperatures (for example, greenings applied on buildings—e.g., "magenta" in the second model; or high reflectivity surfaces on rooftops—e.g., "left-hand side where rooftops are no longer red, but rather light blue").

V.3 Application II (ENVI-met): Street Profile

Again, the ENVI-met software is employed to analyse how specific urban design elements impact the thermal environment and human comfort along a (permissive) street profile that can be encountered in many places within the city of Bucharest. By applying a set of weather conditions that can be seen as characteristic of the hot season (however, with a linear variation that would allow more control and understanding of how variables change), the study explores three setups for the same space, including changes in surface materials, vegetation coverage, and water bodies. It also tackles a bit of the car pollution problem and initiates some discussion in this regard.

Figure 18 – Street Profile considered when building up the second application model (approximation)

Key findings underscore the significant role of street-level design in shaping microclimatic conditions, highlighting the effectiveness of dense vegetation and carefully placed reflective surfaces in improving outdoor comfort. The application exemplifies the potential of targeted design interventions at the street level (e.g., strategic placement of trees and water bodies) in creating cooler, more comfortable urban spaces during hot periods of the year. While exploring how each setup resulted in a different thermal environment, this part highlights the critical importance of incorporating micro-/climatic considerations into street-level urban design to promote more sustainable and liveable urban environments.

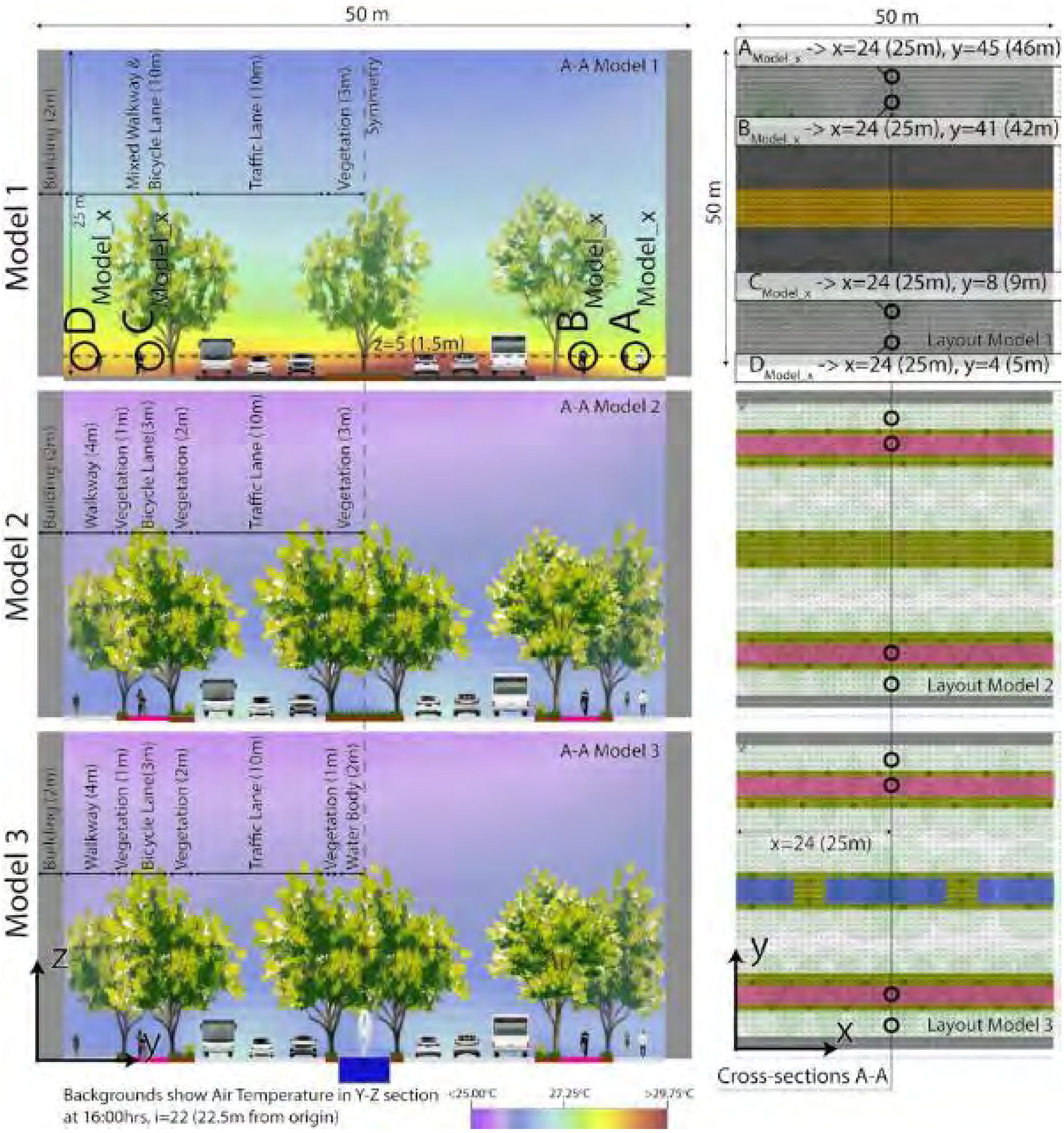

Figure 19 – Models cross sections (left) and layouts (right) – Model 1: Approximation of existing setup, with less vegetation and black asphalt; Model 2: Improved setup, with more vegetation and reflective surfaces; Model 3: Second model slightly changed -> trees slightly moved, water bodies and a fountain added on the central area that separates car traffic

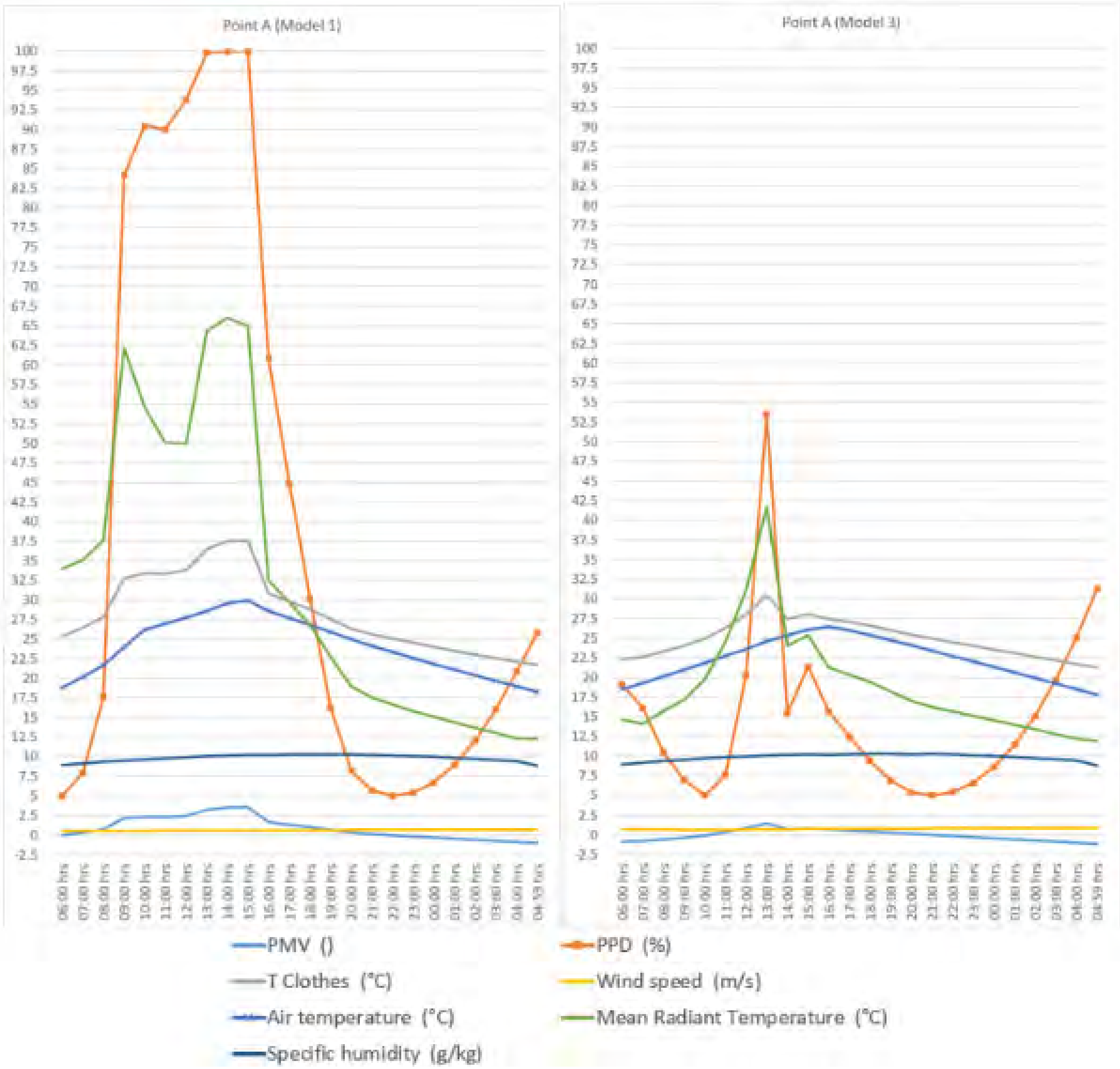

Figure 20 – Comparison between comfort parameters evolution in Point A (Model 1 versus Model 3) – a considerable drop in the Predicted Percentage of Dissatisfied (PPD) can be observed, highlighting the effect of high-density tree canopy introduced in the second model

VI. Final Conclusions

The Thesis advocates for an interdisciplinary approach, integrating Physical, Life, and Social Sciences with Earth's Climate to explore the built environment's impact on urban climates comprehensively. It emphasizes a dual "human-centred" – "climate-aware" approach when exploring urban climates and in urban design in general – i.e., an approach that focuses both on basic human physiological needs for comfort (e.g., thermal/acoustic/visual comfort) and broader societal aspirations while considering global and regional climate contexts and other urban ecosystem components and the overall interrelationships that lead to one urban climate or another.

It begins with an exploration of the global climatic situation, emphasizing the scientific efforts to understand Climate Change, the role of the IPCC, and the impact of natural disasters on human mortality. This helps place things into context.

Then, it discusses the dynamics of the urban world and how things like urban morphology/metabolism and anthropogenic activities are defining specific urban climates.

Further, it details how various urban sectors like energy (including energy demand and inherently the energy efficiency problem, transport, and waste management contribute to and are affected by urban climatic conditions.

These discussions are concluded with a brief reference to the digital (or not) tools that can be employed to assess urban climates – e.g., mapping, remote sensing, and numerical simulations, highlighting their importance in urban climate studies.

Ideas regarding urban interrelationships – which are identified and discussed extensively in the Thesis – are captured in a Conceptual Map that is specially developed to illustrate the most important interconnections among various elements that influence urban climates. This Map may be extremely valuable in terms of aiding anyone interested in having an overview/gaining a comprehensive understanding of these complex systems.

Two application examples given as case studies using ENVI-met software – a numerical tool extensively used to assess urban microclimates which underwent various validation studies [390], [394] – show how changes in vegetation and surface properties can alter microclimates at neighbourhood and street levels. Both application examples focus on the hot season.

Overall, as a synthesis on the general conclusions, the following key ideas can be noted:

- Understanding software limitations is essential for interpreting microclimate simulation results correctly.
- Strategic vegetation placement may significantly improve local microclimates, reducing peak temperature/solar radiation effects and enhancing human comfort – but with certain limitations in case of strong heat waves (when it can no longer be discussed about "comfort" but rather in terms of limiting "severe health risks" – both for humans and the various components of the local biosphere [403]).
- Using highly reflective surfaces can increase mean radiant temperature – MRT, potentially worsening discomfort during hot seasons. That is why such high reflective surfaces should be carefully placed.
- Conducting simulations with model settings that are as detailed as possible and at various scales while considering the actual phenomena is crucial for microclimate assessment.
- Water bodies and spraying can play an important role, but as also different studies suggest, the efficiency of such means depends on the local wind currents and inherently on the urban design and planning to consider this aspect [426].
- Simulations, as the ones given as examples in this Thesis, aid in optimal urban design and in any applications where the configuration of the outdoor environment is at stake, by assessing the impact of various factors, like vegetation and surface properties, on the outdoor thermal environment – but in other directions as well (e.g., estimating leaf temperatures can be important to assess risks for vegetation, buildings' walls temperatures can help us better estimate energy demand, etc.).

VI. References

selection

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