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A Multilayer Framework for Urban Microclimate Analysis in Smart Sustainable City Design: The Vienna Case

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***Abstract*—This paper presents a Vienna-focused conceptual framework for urban microclimate analysis in smart sustainable city design. The study is based on a targeted review of microclimate monitoring approaches, GIS-based morphology indicators, and simulation workflows, which is used to identify recurring limitations and translate them into a multilayer structure. This framework models how morphological parameters (urban morphology and sky view factor) of urban terrain influence variability of microclimate. In more detail, the framework utilizes energy-simulation and intelligent management layers to address the problems of local weather files that lead to a climate gap, limited interaction between buildings and the surrounding microclimate, and the fragmentation between GIS layers and engineering tools. The framework enables spatially informed climate adaptation strategies as well as data-driven planning in smart sustainable cities. The proposed framework provides a transferable methodological tool for climate-responsive urban planning and design.**

Keywords*— urban microclimate, urban morphology, GIS, spatial variability, sky view factor.

I. Introduction

The concept of smart and sustainable cities is considered a contemporary challenge of the 21st century. Metropolises today face a wide range of challenges [1]. These include rapid urbanization, demographic pressure, migration flows, air pollution and socio-economic disparities [2], as well as broader geopolitical tensions. In this context, smart cities rely on information and communication technologies to support sustainable growth and improve social and economic well-being [3]. In this paper, the term 'smart city' is used consistently, following the terminology of the cited authors, although in the literature it is sometimes used interchangeably with 'intelligent city'. Smart city thinking has evolved alongside technological progress. One of the most influential frameworks is that of Giffinger et al. [4], who identify six key dimensions of a smart city (Fig. 1). According to Giffinger et al. [4], a smart city is called one that has advanced characteristics for economy, mobility, environment, people, lifestyle and management.

Fig. 1. Characteristics and factors of a smart city (Source: Adapted from Giffinger [4])

In this way, an intelligent combination of factors is created that contribute to promising development based on local

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circumstances and activities carried out by politics, business and residents [4].

Petrova-Antonova argues that “smart” cities are grounded in data and people, with technology serving as a means rather than an end [5], [6]. The emphasis falls on citizens, as a smart city should ultimately work to optimise resources for their benefit. The concept of the digital twin [7], [8] provides a basis for sustainable planning. Mapping and simulation become tools for testing design options and assessing their impact on the urban environment. Digital twins are not just 3D models, but living simulation systems that help to understand how any change will affect other urban systems. Petrova-Antonova et al. [5],[6] emphasize that by raising the hypothesis that a “smart” city is not just technological digitalization, but a significant optimization of processes to achieve correct and sustainable solutions for the benefit of citizens. Georgieva argues that smart cities should be understood not only as technological systems but also as economic and managerial transformations. Her framework is built around three pillars: smart governance, innovation systems and sustainable competitiveness [9]. According to her overall concept, a smart city is considered to be a polis that contains in its urban planning architecture effective resource management, and in this regard, technologies become a means of achieving transparent policies for and towards citizens in the process of making managerial decisions [9]. A city becomes “smarter” when it links science, business and local government into a shared innovation ecosystem, following the Triple Helix model [10]. The scientist emphasizes the importance of innovation ecosystems and the need for new models for smart governance in order to achieve urban sustainability [9]. In this context, the sustainability of innovation ecosystems depends directly on the effective management of technological obsolescence, which ensures that implemented innovations will perform their functions throughout their life cycle [11]. These perspectives by Petrova-Antonova et al. [5], [6], [8] and Georgieva et al. [9] provide the conceptual foundation for integrating governance, data and citizen-centric approaches within smart city systems.

The transition from the Triple Helix [10] to the Quintuple Helix expands the model by adding civil society and the natural environment as core components. This is a key moment that unites the concepts of intelligent (technology and people) with sustainability (environment). The role of civil society [12] as a construct is significant for the formulation and implementation of ideas in the context of innovations, which are a reflection of culture and a specific way of life. The term ‘Quintuple Helix’ is used in this study to denote the five interacting subsystems of innovation, following Carayannis and Campbell [13]. The ecological imperative, embedded in the Quintuple Helix as a critical fifth element, contributes to the highest form of the model and places the innovation system in the context of environmental protection. Focus is placed on climate change and the preservation of natural capital in the service of society, as a driver of innovation processes. Fig. 2 illustrates the systems in the context of the Quintuple Helix, which Carayannis & Campbell call nested systems [14],[15].

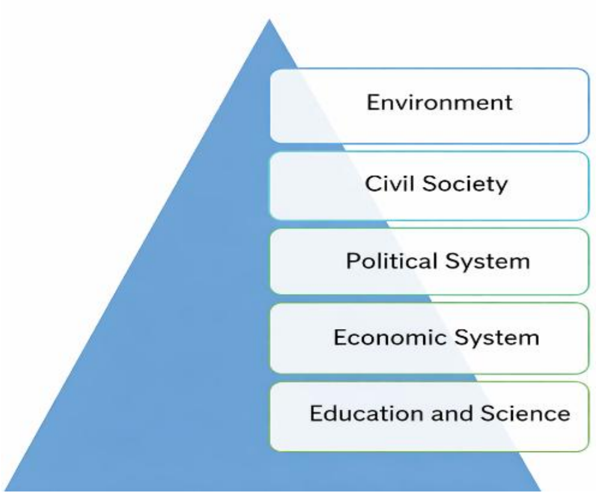

Fig. 2. Conceptual interaction model of the Quintuple Helix in a smart sustainable city

The Quintuple Helix model conceptualizes innovation as a non-hierarchical system of interacting subsystems, including academia, industry, government, civil society and the natural environment [13–15]. These components function as mutually interdependent actors within a dynamic innovation ecosystem rather than as a linear or hierarchical structure. Accordingly, Fig. 2 is reinterpreted not as a hierarchy but as a conceptual interaction model, where each subsystem contributes to and co-evolves with the others in the context of smart and sustainable urban development.

However, these subsystems should be viewed as connected, and not hierarchical. The education and research sub-system will provide the capacity for knowledge and innovation, whereas the economic sub-system will convert the knowledge into solutions. The political sub-system will guide the rules and strategy for implementation, the civil society sub-system will guarantee social involvement, and the natural environment will define the ecological boundaries for smart and sustainable cities.

There is a substantial amount of research on both urban microclimates and smart-city development, but the two fields often move in parallel rather than together. This separation creates what many planners describe as a “climate gap”, especially when simplified weather files are used in design and energy modeling. This paper outlines a multilayer framework that brings several strands of analysis into one structure: urban form, local microclimatic processes, energy performance and governance considerations. The idea is to account for spatial variability more explicitly, using indicators such as the Sky View Factor (SVF), building configuration and ventilation routes, all of which shape local thermal conditions. Vienna is used as a reference case, as it has well-developed climate monitoring practices and integrated urban planning policies, making it a suitable example for climate-responsive urban design.

II. Methodology

The methodology is structured in several steps: literature search, identification of gaps, comparison of existing approaches, framework development and pilot illustration.

A. Literature search strategy

The review relied on searches in Scopus, Web of Science and Google Scholar. Approximately 120 publications were identified through keyword combinations related to urban microclimate, UHI, SVF, energy simulation and Vienna. Applying relevance and quality criteria reduced the set to 48 studies that were examined in detail.

This study develops a multilayer conceptual framework based on a targeted review of scientific literature and policy documents on the topics of urban microclimate, UHI, urban morphology (U2O/SVF), energy simulations and smart governance, with a focus on Vienna. The paper generally takes a conceptual research method through a systematic review of scientific literature, policy documents, and planning practices. The framework put forward does not intend to be empirically checked at this stage. It rather combines fragmented analytical layers into a cohesive structure that can be used for scenario testing and pilot applications in the future.

The thematic search using keywords such as “urban microclimate”, “urban heat island”, “U2O”, “SVF”, “energy simulation”, “Vienna”, “digital twin” assisted in finding the sources, which were mainly chosen from peer-reviewed publications and official institutional materials. The various methods that had been chosen were initially categorized (e.g., monitoring/observations, GIS and morphological indicators, microclimate models, energy simulations, and management measures) and then the recurring limitations and gaps were identified (e.g. climate gap, limited building-microclimate feedback, fragmentation between GIS and engineering tools). Based on these, the gap-solution logic was followed and a multilayer framework (morphology - microclimate - energy simulation - intelligent control) was derived, intended for scenario planning and empirical testing thereafter.

B. Background on microclimate models (Vienna context)

Research analyses of the microclimate of Vienna have generally focused on the five-level framework and the urban heat island effects [16],[17] (density, materials, vegetation, comfort), and studies have shown that the above factors influence urban planning and environmentally friendly decision-making in order to improve the sustainability of the urban area and to prevent global climate change [18],[19]. Microclimatic variations in urban areas have been found to affect metropolitan areas on a local and global scale, with direct consequences for the health of people living in cities [20],[21]. Microclimatic conditions can vary significantly due to the specificities of the urban fabric. Scientists have introduced the term urban unit of observation (U2O) [22] in order to systematize the degrees of microclimatic diversity in urban areas [23] emphasizes the role of scale in microclimate studies, and for microclimate parameters to be measured correctly, the size of the sample area should not exceed a few hundred meters in radius.

Urban climatologists characterize the morphology of the city in terms of the height, width, and density of buildings, where the sky visibility factor is defined [24]. These properties affect the loss of longwave radiation at night and therefore the cooling rate, the access of sunlight during the day and thus the daily heating regime, as well as the air flow and wind speed at street level. The SVF factor for determining incoming and outgoing radiation as a heating and cooling model is shown in figure 3.

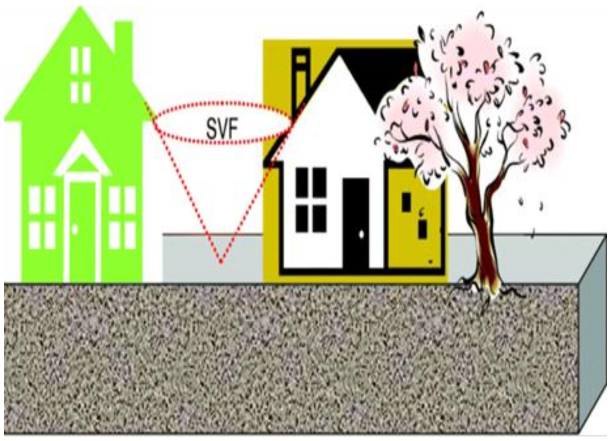

Fig. 3. SVF factor for determining incoming and outgoing radiation as a heating and cooling model [24]

The Sky View Factor (SVF) is an important parameter that influences the potential for radiative cooling and ventilation in densely built-up urban areas [25]. It forms a critical layer in the morphological analysis of U2O because it shows how effectively the urban environment can release accumulated heat through long-wave radiation. Lower SVF values are directly associated with stronger urban heat island effects. The key emphases that are placed in the development of the multilayer conceptual framework for improving architectural and landscape interventions are:

1) integrated approach – in addition to meteorological components, the strategy includes urban planning, green infrastructure and healthcare;
2) district-level measures – specific areas in Vienna are analyzed at the level of a separate observation unit in order to determine the so-called Cooling Hotspots;
3) SVF optimisation – improving sky visibility is applied as a method for natural cooling in densely built-up streets.

Vienna has an overview map of selected areas, each with one stationary meteorological station and two nearby locations for short-term mobile microclimate monitoring, attached in Fig. 4.

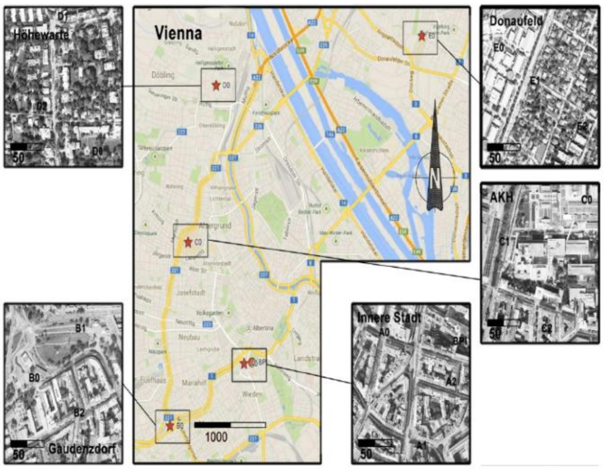

Fig. 4. Selected locations for visualization of mobile climate monitoring in Vienna in terms of air temperature, relative humidity, wind speed [27]

The results show that the temperature data from mobile monitoring stations located in the urban canyon are generally higher than the simultaneously measured data from meteorological stations [27]. Vuckovic et al.[28] conducted simulations of the thermal performance of buildings using the special EDSL TAS software due to its ability to systematically evaluate the thermal behavior of buildings while taking into account a relatively wide range of factors, such as complex building shapes, shadow effects between buildings, multi-zone building modeling, and integrated natural and forced airflow. Typical building floor plans are shown in figure 5.

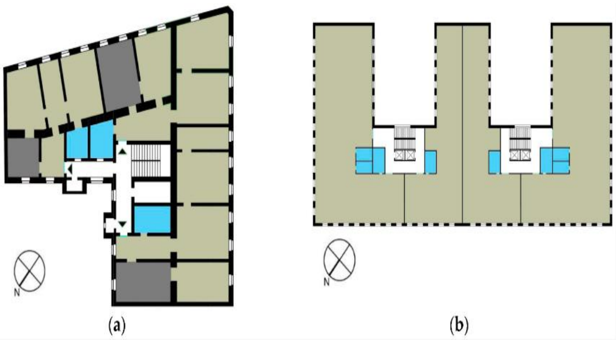

Fig. 5. Typical building floor plans [28]

According to Austrian standards, the authors of the study examined six components such as weather conditions, location specifics, ventilation, solstice.

C. Limitations and Identified Gaps

Based on the reviewed studies, an energy simulation layer is included in the proposed framework, as microclimatic conditions are closely related to building energy performance. Vuckovic et al. [28] point out that despite the ground-breaking research going on in Vienna, the problem lies mainly with the low spatial resolution of the climate data and the absence of a connection between microclimate variations and energy simulations. These limitations require the development of a multilayer conceptual framework that would overcome the fragmented approach and provide a precise interface between urban morphology and the energy efficiency of buildings

In order to build a multilayer conceptual framework, the identified gaps and limitations need to be addressed, as follows:

1) "Climate gap" – the use of averaged meteorological data from suburban stations (airports) leads to errors in energy simulations of up to 16%. Buildings in the city center are designed with inaccurate parameters for summer heat load [28].

2) Lack of dynamic feedback – energy models consider the building as a passive object, without taking into account how it itself changes the microclimate around it (heat released by facades and air conditioners) [27].

3) Static material data – GIS models of Vienna are geometrically detailed, but lack dynamic data on albedo and thermal mass of urban surfaces [26].

4) Methodological fragmentation – there is no integrated software interface that automatically connects microclimatic layers with engineering tools for building design [17].

To better position the proposed framework within the existing literature, Table I presents a simplified comparison of commonly used approaches in urban microclimate analysis.

TABLE I. COMPARISON OF COMMON APPROACHES IN URBAN MICROCLIMATE ANALYSIS (SOURCE: AUTHORS)

Approach	Main focus	Limitation
Urban morphology and GIS-based analysis [22–24]	Spatial structure and SVF	Limited interaction with dynamic microclimate processes
Microclimate studies and UHI analysis [16], [20], [27]	Local climate variability	Weak connection to building energy performance
Energy simulation models [28]	Building energy demand	Often based on generalized weather data.
Proposed multilayer conceptual framework (this study)	Integration of morphology, microclimate and energy simulation	Closes the "climate gap" by linking spatial morphology with dynamic building performance.

As shown in Table I, most existing approaches address individual aspects of urban climate analysis, while the proposed framework attempts to combine them into a unified structure.

The gaps are displayed in a Table II, which serve to build a multilayer conceptual framework (solution):

TABLE II. GAP-SOLUTION LOGIC FOR DEVELOPING THE MULTILAYER CONCEPTUAL FRAMEWORK (SOURCE: AUTHORS)

Identified gaps	Solution
Climate Gap (16% error in energy projections)	Using local U2O data instead of suburban stations

Lack of feedback (building-microclimate)	Integration of dynamic energy simulation
Static albedo/material data	Digital layer with thermal properties of surfaces
Methodological fragmentation	Multi-layer structure combining GIS and engineering

Based on the methodological analysis, the multilayer framework is proposed as a conceptual structure that follows a logical flow from data to solutions, linking static urban strategies with dynamic scientific evidence. It is designed to fill the "climate gap" by integrating GIS, microclimatic data and energy simulations. Table III presents the conceptual structure of a multilayer conceptual framework.

TABLE III. CONCEPTUAL STRUCTURE OF A MULTILAYER CONCEPTUAL FRAMEWORK (SOURCE: AUTHORS)

Analysis Layer	Key Parameters and GIS Attributes	Main Contribution to the Model
1.Urban Morphology (U2O)	Building density, Sky View Factor (SVF), building height.	Defining the territorial unit for observation using OGD data.
2.Microclimatic Variations	Temperature amplitudes, albedo, wind corridors, humidity.	Identifying local thermal anomalies relative to the urban fabric.
3.Energy Simulation	Heat load, cooling needs, energy deficit of buildings.	Overcoming the "Climate Gap" and 16% error in forecasts.
4.Intelligent Management	Blue-green infrastructure, dynamic shading, Cooling Hotspots.	Formulating sustainable adaptation strategies in real time.

D. Multilayer Framework Development

The pilot analysis focuses on representative urban typologies in Vienna, specifically inner-district street canyons (e.g., typical Gründerzeit blocks) and adjacent open urban spaces. These typologies are selected as illustrative cases rather than fixed geographic coordinates, due to the conceptual nature of the study. Thus the pilot analysis was conducted to demonstrate how the proposed multilayer framework can be operationalized by linking urban morphology - expressed through the sky view factor (SVF) - to measurable microclimatic variations within Vienna. Two very different urban units of observation (U2O) were chosen: (1) a compact perimeter-block street canyon in the inner districts, and (2) an adjacent open square with much more sky visibility. By comparing these different cases, the influence of morphological variations on local thermal behaviour is demonstrated.

Examinations of Vienna reported a great extent of elevated air temperature of residential areas in the dense street canyons as opposed to the nearby open areas. This is taken to be the result of less longwave radiative cooling and limited ventilation in these street canyons. Mobile climate monitoring in Vienna also verifies this observation as it reveals that the street canyon temperatures were consistently higher than the temperatures measured by the reference stations. As stated in the present paper, "The results show that the temperature data from mobile monitoring stations located in the urban canyon are generally higher than the simultaneously measured data from meteorological stations [29]. This corresponds to the findings of Kiesel, Vuckovic and Mahdavi, who observed significant microclimatic variability across different districts of Vienna, strongly influenced by building density, material properties and sky openness [30].

Vienna Urban Heat Island Strategy Plan (UHI-STRAT) identifies the creation of ventilation corridors and reducing heat build-up in dense areas as top priorities [31]. In alignment with these strategic objectives, this study employs the Sky View Factor (SVF) as a morphological indicator, drawing on established microclimatic research for Vienna that links low SVF to reduced ventilation and higher nocturnal heat retention [28, 30]. This scientific evidence complements the policy focus of UHI-STRAT by providing a diagnostic tool for identifying areas where cooling interventions are most needed.

For this pilot illustration, representative SVF values were derived from GIS-based morphology for the two U2Os. Dense street canyons in Vienna typically exhibit SVF values of approximately 0.25–0.35, while open squares and wider intersections reach SVF values of 0.70–0.80. Investigation of Vienna's urban climate finds that at night, the temperature can differ by several degrees Celsius between morphological types, with areas having a lower SVF (sky view factor) holding more heat after sunset [24], [30]. Such UHI patterns agree with the broader European research and also with the mobile monitoring results mentioned above.

The indicative relationship between SVF and local microclimate is summarized in Table IV. The values presented in Table IV are derived from a synthesis of reported ranges in the literature on Vienna's urban morphology and microclimate studies [24], [28], [30].

TABLE IV. INDICATIVE RELATIONSHIP BETWEEN SVF AND MICROCLIMATIC BEHAVIOUR IN TWO VIENNA U2OS (SOURCE: AUTHORS)

U2O type	Approx. SVF	Typical nocturnal air temperature behaviour
Dense street canyon	0.25–0.35	Higher nighttime temperatures; reduced longwave cooling; intensified UHI
Open square / less dense area	0.70–0.80	Lower nighttime temperatures; more effective radiative cooling; mitigated UHI

This pilot analysis operationalizes the first two layers of the proposed framework - urban morphology (U2O, SVF) and microclimatic variation - by linking a simple morphological indicator to local thermal behaviour. It also reinforces the relevance of the energy simulation layer. As noted earlier in the paper, the difference in the annual heating load between different locations in Vienna can reach 16.1 kWh/m² per year. This indicates the relevance of integrating morphology-driven microclimatic variability into building performance assessment. The pilot SVF-based analysis provides a direct bridge to the intelligent management layer. The UHI-STRAT Vienna strategy has already a leading line urban ventilation corridors, shading and blue-green infrastructures. By integrating SVF-based diagnostics within this strategic framework, it enables locating Cooling Hotspots and thus first of all the top interventions in the areas where low SVF and high night temperatures coincide.

The pilot analysis is intended as an initial application example rather than a full empirical case study. It demonstrates how the proposed framework can be used to interpret real urban conditions based on representative typologies and literature-based data. In this sense, the analysis provides an initial form of methodological validation, as the framework is applied to cases that are consistent with empirically observed microclimatic patterns reported in previous studies.

This study puts forward a multilayer conceptual framework that functions as an integrative methodological structure rather than an empirical model or software tool. Its purpose is to link four analytical dimensions—urban morphology, microclimate, energy simulation and intelligent management—into a single workflow that can support climate-responsive urban planning. Although the framework is conceptual, the individual steps are described clearly enough to allow others to follow the same logic, replicate the approach and build on it through future empirical testing.

The described workflow can be replicated in other urban contexts, provided that comparable datasets, GIS-based indicators and locally collected microclimate measurements are available. The illustrative example presented here shows how the framework can be applied to identify areas with increased heat accumulation and to support targeted, climate-responsive interventions at the district scale.

III. Discussion

The findings of the literature synthesis and pilot analysis highlight several key implications for urban climate-sensitive planning.

1) Critical influence of the local context – the microclimate varies significantly within the same city depending on the morphology (shape and density of buildings) and the materials used. Using common, standardized weather files (e.g. from the airport) for the entire city leads to serious design errors;

2) Effect on the energy efficiency of buildings – local weather conditions directly change the energy needs of buildings:

- the difference in the annual heating load between different locations in Vienna can reach 16.1 kWh/m² per year;

- a building with an identical construction will consume a different amount of energy just because of which district of Vienna it is located in.

3) Correlation between morphology and heat – strong relationships between built environment characteristics and microclimate are confirmed:

- building density – high building density is directly related to higher temperatures (intensification of UHI).

- materials – the properties of materials (albedo, thermal mass) in an urban unit influence how long heat is retained at night.

4) Need for site-specific data – for sustainable urban design, the researchers believe that site-specific meteorological data should be used, rather than average values. They propose a systematic framework for identifying the properties of the built environment (geometric and material) that influence these variations.

5) Health and comfort consequences – changes in the microclimate at the local level have immediate consequences for outdoor thermal comfort and the health of citizens, with these effects being most noticeable in densely built-up historical or industrial areas of Vienna.

The connection between the multilayer conceptual framework and the Quintuple Helix can be seen clearly when viewed through the five subsystems:

1) Educational system – the academic research of Lim et al. [27] defines the theoretical framework for the analysis of temperature variations in the urban fabric of Vienna. This allows the methodology to move from general mapping to detailed modeling of specific microclimatic units (U2O). This provides the fundamental scientific core of the proposed methodology. It not only generates the necessary empirical data on the microclimate of Vienna, but also validates the simulation models needed to overcome the spatial fragmentation in energy forecasting

2) Economic system – energy simulation directly serves the construction sector and energy management companies. Here, innovations in materials and technologies (albedo, facade insulation) are implemented in real projects, stimulating “green” business.

3) Political system – Vienna integrates this data into its official strategies, such as the UHI STRAT. This allows politicians to make evidence-based decisions on building regulations and climate measures subsidies.

4) Civil society – smart management of microclimate data reaches citizens in the form of “cool zones” and mobile apps. Public participation is critical for the adoption of measures such as traffic restrictions or increased urban vegetation.

5) Natural environment, it is the “core” of the model. Santamouris and Georgakis [17] stress that the natural environment is not only a background but also an active factor that shapes sustainability. The multilayer approach seeks to make the urban fabric coexist with ecologic limits.

The results confirm the efficiency of climate-responsive urban design strategies in enhancing thermal comfort as well as environmental performance.

IV. Conclusions

The main contribution of this study lies in structuring fragmented knowledge into a coherent multilayer framework, which supports better integration between spatial analysis, microclimate modelling and decision-making processes. The present paper proposes a multilayer conceptual framework for studying urban microclimates in the context of smart, sustainable city design with an emphasis on Vienna. The paper connects the diagnostics of urban morphology (U2O) and sky view factor (SVF) with the variability of the microclimate and extends the framework with a layer for energy simulation as well as one for intelligent management. Although the study does not include a full experimental validation, the pilot analysis demonstrates how the framework can be applied in practice.

The framework responds to the “climate gap” created when planning relies on weather files that do not reflect local conditions. It also underlines that buildings interact with the surrounding microclimate, although this interaction is only weakly represented in most existing approaches.

The framework reduces the fragmentation between GIS-based layers and engineering simulation tools and facilitates the implementation of practical actions such as the use of blue-green infrastructure, shading, and cooling hotspots.

The framework highlights the importance of spatial analysis and geographic variability for climate-responsive urban planning and district-scale interventions.

Future work can be outlined as follows:

1) empirical testing of the workflow in a pilot area of Vienna using local monitoring data and coupled simulations

2) evaluation of planning scenarios.

The framework is transferable and can support climate-responsive planning in other European cities facing similar environmental challenges.

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