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Contrasting the features and functionalities of urban microclimate simulation tools

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ABSTRACT

The impact of human activities on climate change has become increasingly evident, with cities being particularly vulnerable to its effects. Anthropogenic emissions, such as heat and greenhouse gases, are projected to intensify climate-induced phenomena, which can lead to negative health outcomes. To understand how human health would be affected by such climate-exacerbated phenomena, computational models that consider the local microclimate are essential to better regulate cities to respond to these phenomena. Many simulation tools have been created and enhanced over the years. Therefore, this study systematically reviews the currently available urban microclimate simulation tools and compares their features and capabilities. The review suggests that these models can effectively assist in investigating urban health and testing adaptation strategies, but it is important to acknowledge their limitations due to assumptions made. Nonetheless, with proper interpretation and utilization, these models can provide valuable insights and contribute to informed decision-making processes.

1. Introduction

Population growth and urbanization have increased dramatically in recent decades. By the end of the century, it is expected that about half of the world's population will live in urban areas [1]. According to the 2022 Revision of World Population Prospect's projections provided by the United Nations (UN), by 2030, the population will reach 8.5 billion people; by 2050, the number of people could grow to around 9.7 billion, and by 2100, it will be around 10.4 billion [2]. Strongly related to the growth of the world's population, migration from non-urbanized regions to towns and cities has been the driving force behind the expansion of urban areas [3–5]. In 2007, for the first time, the population in urbanized areas exceeded that in rural areas [6]. This increasing urbanization leads to structural changes in the characteristics of the land and the replacement of natural and green surfaces with roads and artificial, dry, and impermeable surfaces [7].

Furthermore, cities use up to 75% of the global primary energy, producing about 50-60% of global greenhouse gases. This number increases to 80% if indirect emissions produced by people living in the cities are also considered [8]. Consequently, urban areas contribute significantly to many environmental problems, affecting global and local scales [9,10]. It has been widely demonstrated that the profound changes characterizing the global environment come mainly from human actions and greenhouse gas emissions, which manifest with increased frequency, magnitude, and duration of extreme events such as heat waves, frost waves, floods, and forest fires. The Intergovernmental Panel on Climate Change (IPCC) states that more frequent and intense extreme events due to human activities and human-induced climate change have caused damage and widespread impact on ecosystems, people, settlements, and infrastructures [11]. Specifically, it was proved that climate-induced phenomena lead to a rise in human mortality rate [12]. In this context, cities facilitate the generation and interaction of anthropogenic heat and pollution[6], which cause compound effects on human health. While cities are commonly described as urban heat islands, they should be seen and treated as combined urban heat, pollution, and noise islands [13,14]. However, cities are complex systems that respond to external stressors (i.e., anthropogenic actions), similar to how living organisms react to an altered surrounding environment. It is, hence, essential to have conceptual models that can represent this complex interaction between different urban and environmental items. Available models derive from thermodynamics and compute mass and energy flows. From this perspective, the world is an extensive network of cities with dense people and infrastructure that draw resources from global hinterlands. The strength of thermodynamics lies in its ability to describe aggregate properties at the macroscale that emerge from complex microscale processes [15]. The city, therefore, can be considered as a complex adaptive system that, from a

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Nomenclature

Acronyms

ASCII	American Standard Code for Information Interchange
BIM	Building Information Modeling
CFD	Computer Fluid Dynamics
CIMO	Context, Intervention, Mechanism, and Outcome
CSV	Comma-Separated Values
EPW	EnergyPlus Weather (File format)
gbXML	Green Building Extensible Markup Language
GIS	Geographic Information System
HTML	HyperText Markup Language
PM	Particle matter
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
UHI	Urban Heat Island
ULI	Urban Lighting Island
UPI	Urban Pollution Island

thermodynamic point of view, is equivalent to an open system far from equilibrium, which continuously imports energy, matter, and information and dissipates heat as a result of energy transformations that take place within the boundaries of the system [16–19]. Most of the resources on which the urban ecosystem relies, such as fuel, water, and materials, affect the atmosphere and play a major role in the urban climate [20]. Indeed, human actions exploit these resources and re-emit them into the environment in a degraded manner [21,22]. Since the city can be conceived as a complex thermodynamic system in which different phenomena and new events can continually arise depending on collective and spontaneous behaviors and on the variable relationships between the parts that make up the system, the term 'urban metabolism [20,23–25] was introduced to highlight the analogy with living organisms.

Marchettini et al. [18] describe the cities' structure as a physical system in contact with different sources and sinks, crossed by matter and energy flows, leading to increased entropy. From a biophysical point of view, cities' survival is entirely based on their compliance with the physical limits of the planet and the preservation of the surrounding ecological environment and their ecosystem services. Therefore, thermodynamics does not predict the infinite growth of a finite system with a finite regenerative capacity, such as the Earth. Thus, it is necessary to understand and model the natural and anthropogenic flows that govern the city and its surroundings because the level of exploitation of natural resources, together with the capacity of ecosystems to absorb anthropogenic emissions, has already exceeded the Earth's carrying capacity.

In Figure 1, we have summarized and graphically represented the built environment's main mass and energy flows. Along with the flows, we have also represented the main effects of anthropogenic actions, distinguishing the various areas according to the land use type.

In Figure 1, the rural areas are characterized by a very low population density, with a predominance of natural surfaces. An increasing population density and a larger presence of buildings and artificial surfaces characterize suburban residential areas. Concentrations of factories characterize industrial areas. Commercial areas, located commonly between the suburban residential area and the downtown, host all commercial activities and are characterized by an increasing percentage of artificial surfaces and large buildings. Urban residential zones have more buildings than suburban ones, with average greater heights and more artificial surfaces. Downtowns are characterized by tall buildings and narrow streets, which generate the so-called urban canyons; consequently, the size of outdoor urban spaces becomes smaller and darker. The features of the built environment, such as the presence of more artificial and darker (i.e., absorptive) surfaces, the smaller size of urban canyons, and the greater height of buildings, cause several phenomena within cities. Regional winds, for instance, moving from open areas to more densely built-up areas, find even more obstacles along the way, and this results in (i) increased turbulence between buildings, (ii) generalized reduction of wind speed at the street level because of the presence of the obstacles impeding natural flow, and (iii) increased wind speed in given urban canyons due to the channeling of prevailing winds. Solar radiation is another crucial aspect that must be taken into account. While in rural or sparsely dense areas, radiation is largely reflected, within urbanized areas, due to (i) the presence of dark, dry and impermeable surfaces, (ii) the increased density of buildings,

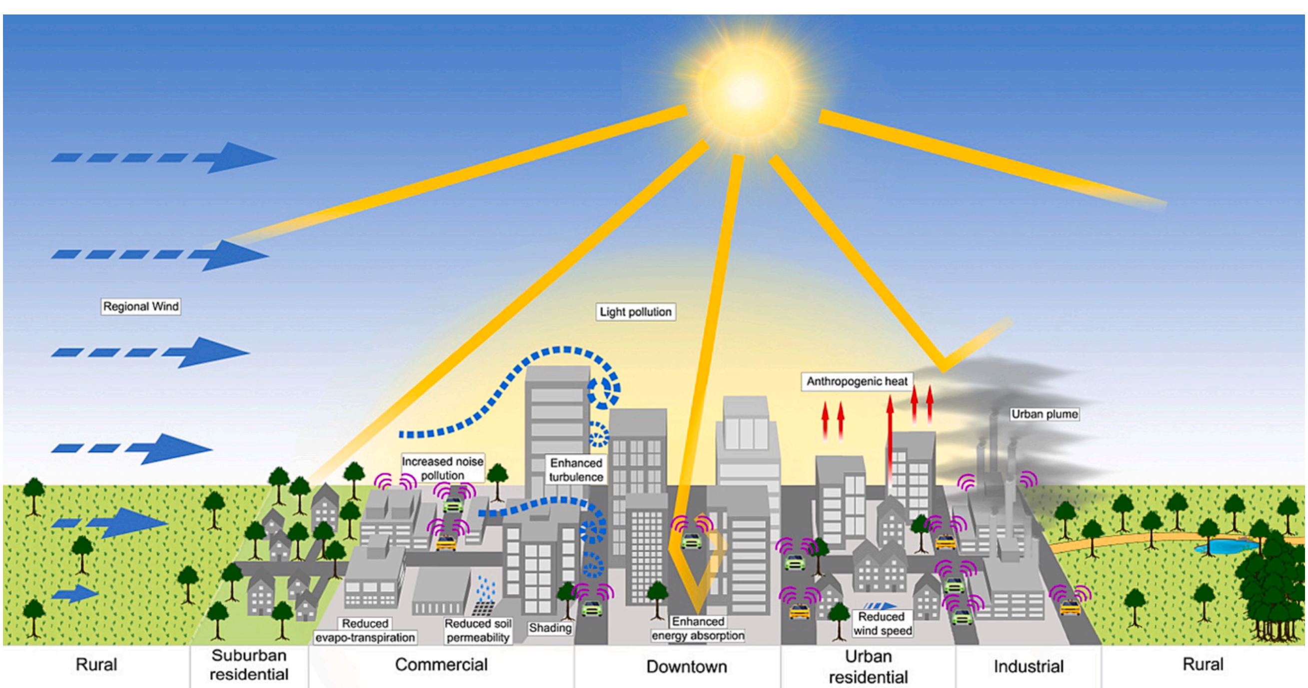


Figure 1. Identification of the energy fluxes within the urban area. Modified from Ref. [26]

and (iii) the presence of very tall buildings and very narrow streets; the radiation is trapped causing amplified energy absorption that increases the internal energy on the urban systems resulting in higher ambient and mean radiant temperatures. Also, it is essential to mention the anthropogenic heat caused by human actions, such as air conditioning and heating, vehicle emissions, and other means of transport, which are also significant sources of noise pollution. Furthermore, human actions also cause an increase in air and water pollution especially generated in industrial areas. Finally, due to the many light sources installed for fostering night vision, urban areas cause lighting pollution, which affects biological rhythms, daily activity, and the reproduction of wildlife [27]. In this background, cities must exploit their fertile ground for smart design, innovation, and experimentation through multi-sectorial collaborations and codesign to develop solutions to mitigate and adapt to climate change. For instance, nature-based solutions provide many promising outcomes in terms of benefits and reduction of climate risks, while some key challenges need to be addressed. In particular, the capacity to learn from different fields to produce collaborative data and actionable knowledge, the ability to use and leverage, in a systematic way, multiple types of collected data, and the identification of the roles of the participants at the different scales of application. Research-based tools may help bridge between theory and application [28]. In this age of game-changing technologies and worldwide interconnectedness, we are witnessing new levels of knowledge and a shift "from a rural world into an urban world, from a world of highly local interactions to a world of global interactions, from a world based on physical technologies to a world based on information technologies." [29] With these tools, what is made of flows becomes visible, reflecting physical and human flows. Visualizing these flows is an excellent opportunity to understand the dynamics of complex urban systems, and their quantification provides a perfect chance to find systematic relations between microclimate, urban environment, urban health, and human activities [30]. Over the years, various calculation models and software tools for microclimatic analyses have been developed to study these phenomena. They are, thus, fundamental to providing information on the behavior of the built environment solicited by various climate-induced factors or anthropogenic actions. In addition, given the built environment's importance and its substantial contribution to the global emissions that cause climate change, it is necessary to pay special attention to the design and shape of the cities. This significant role has been stressed by the United Nations' 2030 Agenda for Sustainable Development. One of the main Sustainable Development Goals, goal number 11, "Sustainable cities and communities [31]," explicitly addresses the need to make cities more inclusive, sustainable, and resilient. In particular, the targets under this goal include by 2030, to (i) "enhance inclusive and sustainable urbanization and capacity for participatory, integrated, and sustainable human settlement planning and management in all countries," (ii) "significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to the global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations," and (iii) "reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management" [32]. Hence, sustainable design plays a key role in ensuring that the well-being of current generations does not compromise the well-being of future generations and the environment on which we all rely. However, sustainable design requires communication between the various parties in action and simultaneously requires balancing between multiple and sometimes even opposing goals with limited resources available [33]. The availability of limited resources requires adopting an integrated design, which consists of exploring nature-based solutions to improve public health, safety, and the livability of spaces, especially restoring hydrological and ecological processes. Given the limited resources available, however, it is questionable how cost-effective it might be for a city to invest in nature-based solutions and what benefits can be expected. Keeler et al. [33] state that there are three significant limitations to the adoption of urban ecosystem services, which relate to (i) the adoption of a limited number of nature-based solutions, most often street trees, (ii) the context is often overlooked in valuing or not valuing a particular solution, thus not providing information on the generalizability of the approach taken, and (iii) there is no comparison between nature-based solutions and alternative solutions that can go a long way toward improving well-being by reducing exposure to other factors such as air or water pollution.

It is appropriate to try to move beyond the often incomplete and imperfect "perfect rationality" by aiming for "bounded rationality," which recognizes that perfectly rational solutions are typically not applicable in practice because the complexity of the decisions exceeds the time and intellectual power that humans can devote to these decisions [34]. In this view, as already mentioned, the thoughts and actions of human beings extend beyond the concept of perfect rationality by being shaped by various factors such as context, emotions, and experiences. These deviations from perfect rationality can cause a cognitive bias and, in some way, hinder sustainability development. Therefore, the only functional approach has to be holistic, acting simultaneously on different aspects, thus creating a multidisciplinary and interconnected field of analysis and discussion. Hence, the objective of this paper is twofold: first, it aims to identify the tools available in the literature; second, it provides a comparison of the features of these tools to identify their peculiarities, strengths and weaknesses, and possible fields of application. To achieve these aims, we initially conducted a bibliographic analysis through a systematic literature review to gain information about the topic landscape, and then, we built an evaluation framework to analyze and compare the tools. Lastly, we developed critical discussions of the results obtained based on the previous comparison.

In the next section, the research methods to conduct the literature review and the bibliographic analysis are provided. Section 3 provides a description of the framework used to analyze and compare the microclimate tools. Finally, Section 4 tries to summarize the findings from the previous sections and define future outlooks and directions of work that should be investigated.

2. Methodology

2.1. Research methods

Surface energy balance determines near-surface thermal microclimates of the urban environment controlled by the blended forcings (i.e., anthropogenic actions) in combination with the mix of radiative, aerodynamic, thermal, and moisture properties of the surfaces. As a result, the urban environment is affected by some phenomena like urban heat islands or pollution domes. In addition, cities are considered hotspots of energy consumption, anthropogenic emissions, and air pollution, straining society from local to global scales. Thus, it is essential to identify tools to study these flows and describe the complex interaction between urban and environmental elements. When it comes to studying and evaluating energy performance in the built environment and its impact on the city as a complex system, various tools are available. However, it is essential to identify those who can describe as many fluxes as possible to gain a comprehensive understanding of the city's energy performance.

For this reason, it is pivotal to investigate which models that can simulate the urban microclimate are available in the literature and what their features and capabilities are. Therefore, a comprehensive screening of the existing literature on modeling the urban microclimate has been conducted, producing a systematic literature review. To conduct the literature review, the Preferred Reporting Items for Systematic and Meta-Analyses (PRISMA) methodology [35] was employed. Also, the research question was structured utilizing the CIMO logic (Context-Intervention-Mechanism-Output).

The first step in the systematic literature review consists of precisely framing the problem under investigation by constructing a straightforward research question. The CIMO logic [36] is used in this study, and the identified research question is: "*How can we study (M) the impact of climate (I) on public health (O) in the urban environment (C)?*". Based on previous knowledge and direct literature searches, a set of keywords was identified for each element of the CIMO logic. These keywords were linked together using the Boolean operators "AND" and "OR" to create a search query. The "OR" operator connects the various keywords within each CIMO array, while the "AND" operator connects the keywords across different CIMO arrays. When formulating the search query, it is crucial how keywords may end to accommodate grammatical variations, spelling differences (such as British or American English), and specific technical terms. To enhance accessibility and facilitate the replication of the literature search, we report the search query that was enquired in the Scopus database:

"TITLE-ABS-KEY(("Built environment" OR "Urban spaces" OR "Urban environment" OR "Urban areas" OR "Outdoor environment" OR "Urban climate" OR "Urban microclimate" OR "Urban micro-climate")AND ("Urban heat island" OR UHI OR "Urban noise island" OR UNI OR "Urban pollution Island" OR UPI OR "Anthropogenic heat" OR "Air pollution" OR "Noise pollution" OR "Thermal stress" OR "Extreme temperature" OR "Heat wave" OR Heatwave OR "Heat island" OR "Climate change" OR "Heat stress" OR "Planning" OR "Design" OR "Adaptation strategies" OR "Light pollution" OR "Urban light island" OR "Over-illumination" OR "Over illumination")AND("Numerical model" OR "Simulation tool*" OR "Microclimate model" OR "Micro-climate model" OR "Microclimate tool" OR "Micro-climate tool" OR "Microclimate software" OR "Micro-climate software" OR "Microclimate simulation*" OR "Micro-climate simulation*" OR "Microscale model*" OR "Micro-scale model*" OR "Computational tool*")AND(Well-being OR Wellbeing OR "Life quality" OR "Human health" OR "Outdoor thermal comfort" OR "Human comfort" OR "Mean radiant temperature" OR "Universal Thermal Climate Index" OR "Physiological equivalent temperature" OR "Standard effective temperature" OR "Noise level" OR "Acoustic level" OR "Air quality" OR "Outdoor visual comfort" OR "Visual comfort"))".*

After reading several documents, we realized that different authors used different semantic constructs to describe, in particular, the outcomes of their studies. We decided to cluster the contributions of the identified documents according to the four domains that, it is commonly accepted, characterize indoor and outdoor environmental quality.

Next, exclusion criteria were identified and applied to limit the results to all written in English, whether articles, conference papers, reviews, book chapters, or books. The search query was executed in the Scopus database (accessed on 22/01/2024). So, all documents identified by the search query were collected and screened. Initially, the screening process focused only on the title, abstract, and keywords. Several documents were excluded because they were irrelevant to the research question. Subsequently, the full text of the remaining articles was analyzed, and those that were not pertinent to the research topic or whose full text was not available were removed.

As Fig.2 shows, the number of records collected through the Scopus database has been extended by adding additional documents obtained via 'other sources.' These documents have been collected adopting the snowball approach, following the indications provided by Wholin [37]. Finally, from all the identified, screened, and included documents in the

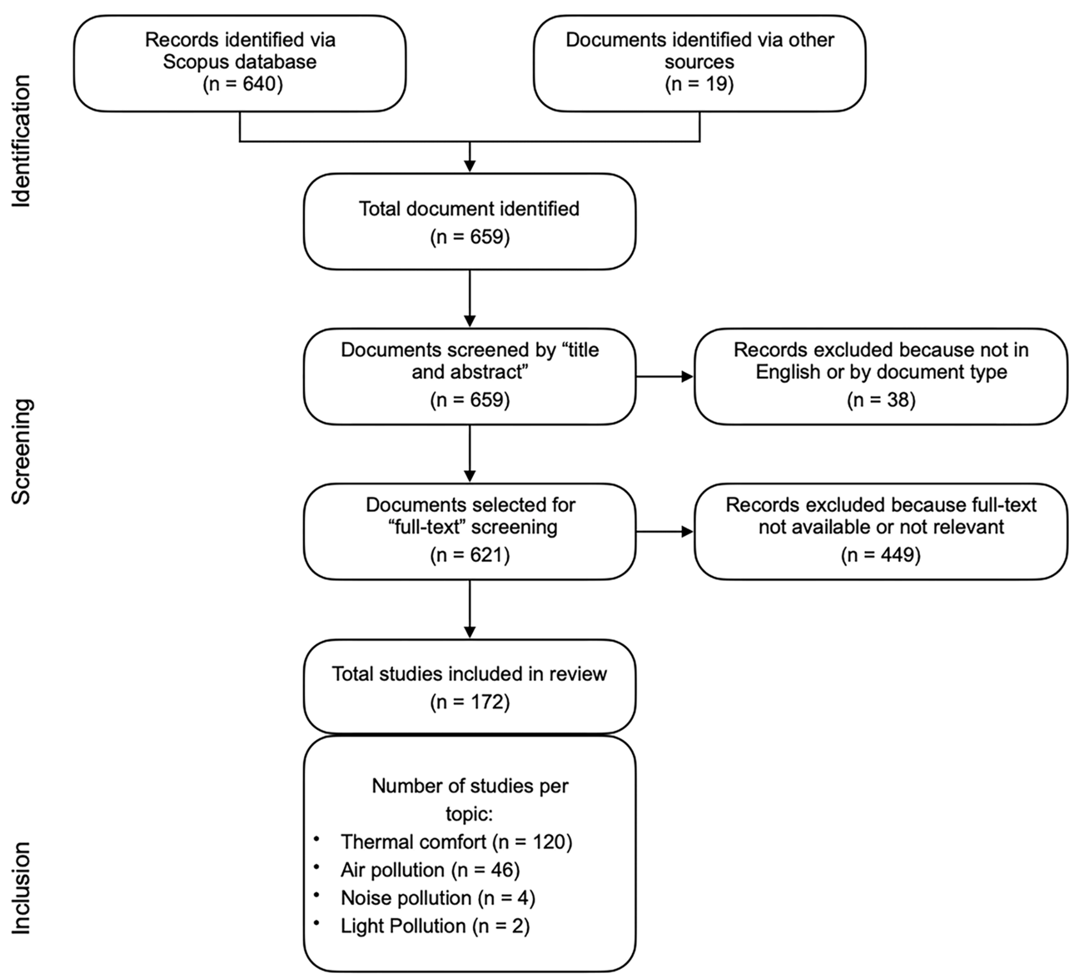


Figure 2. Literature screening. The Process according to the PRISMA methodology.

review pool, several microclimate computational tools were identified and compared to determine their capabilities, basic principles, and possible fields of application. For this purpose, we introduced an evaluation framework that compares, analyzes, and evaluates different aspects of the identified microclimate simulation tools.

2.2. Bibliographic analysis

Once the identification, screening, and inclusion processes were concluded, the resulting bibliographic database comprised 172 studies (accessed on 22/01/2024). A bibliometric analysis of the final database was conducted by executing the Bibliometrix tool. Bibliometrix is an open-source tool developed in R for carrying out comprehensive science mapping analysis of scientific literature [38].

First, the publication period of the studies was considered. This way, it was possible to understand how much interest there has been so far in the research field and how it has evolved. As shown in Figure 3, all the documents are pretty recent and were published between 2005 and 2023. In addition, the most significant number of publications occurred in 2022.

Subsequently, the database was analyzed to understand which topics are most discussed within the documents included in the database. For this purpose, the occurrence of keywords belonging to each CIMO field was examined, identifying the most frequently used words in the various documents' titles, abstracts, and keywords. The results of this analysis are shown in the following charts. For the folder Context (Figure 4), the most used keyword is "Urban canyon," adopted 37 times, followed by "Built environment," used 31 times, and "Urban environment," which appears 29 times. The occurrence of the keyword for the Intervention folder (Figure 4) shows that the most frequently used word is "Adaptation strategies" 46 times, followed by "Air pollution" 41 and "Urban heat island" 30. Interestingly, there are no documents that use words such as "Urban noise island," "Urban pollution island," or "Urban light island." For the Mechanism folder (Figure 4), "Numerical models" is the most frequently used word, found 62 times, followed by "Simulation tool" and "Microclimate tool" with 32 and 26 occurrences, respectively. Finally, for the Outcome folder (Figure 4), "Outdoor thermal comfort" is the most adopted word, cited 78 times, followed by "Mean radiant temperature" and "Air quality," equally adopted 35 times.

The occurrence analysis of the keywords previously described has helped define the relevance of research topics. In this regard, we have plotted a thematic map (Figure 5) that shows the importance of different themes based on their density and centrality, as described in Cobo et al. [39]. The centrality of a theme is defined as the level of its interaction with others terms. The density represents how much and how well that theme is developed. Combining the two terms, a four-quadrant matrix is determined. Each quadrant collects different themes based on their values of centrality and density. Themes in the upper-left quadrant (low centrality and high density) have well-established internal connections, but their link with other external themes is poor, resulting in marginal importance. These themes are very specific and peripheral, so they are called "Niche themes." Themes in the upper-right quadrant (high centrality and high density) define a research field. These themes are known as "Motor Themes" given their strong centrality and development degree. In addition, unlike niche themes, themes in this quadrant show their external relation with concepts that can be applied to other themes that are conceptually related. In the lower right quadrant (high centrality and low density), there are "Basic themes," which are essential for the research but are of general interest. So, this quadrant groups general, transversal, and basic themes. Finally, themes in the lower-left quadrant (high centrality and low density) are considered emerging or declining according to their density and centrality.

Finally, we plotted a co-occurrence network map to understand the scientific landscape and the correlation between each research topic within the bibliographic database (Figure 6). This map helps understand research trends and how themes are interconnected. The co-occurrence

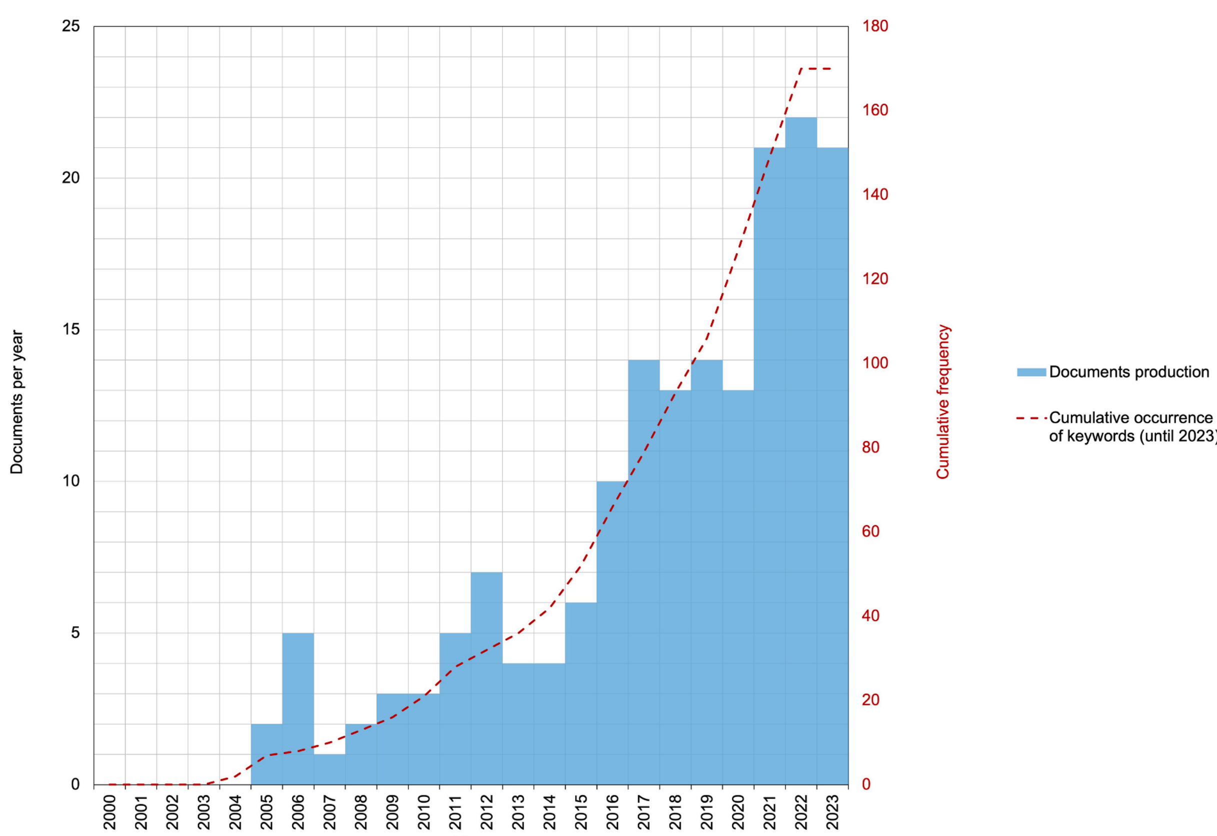
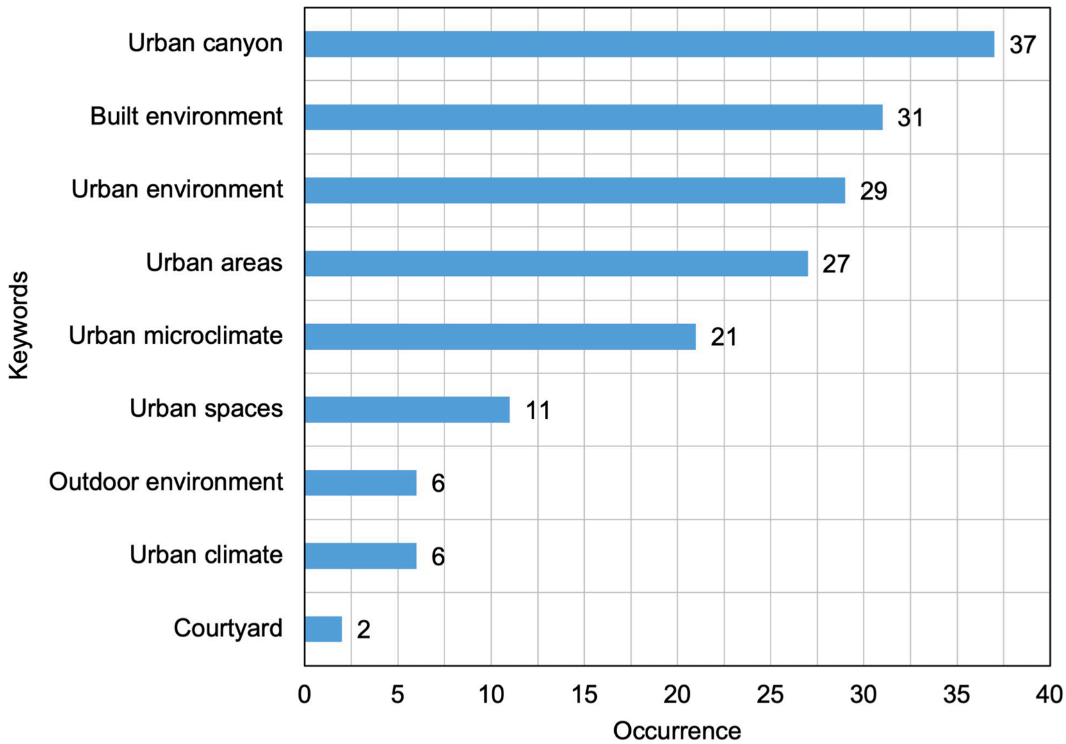


Figure 3. Annual scientific production.



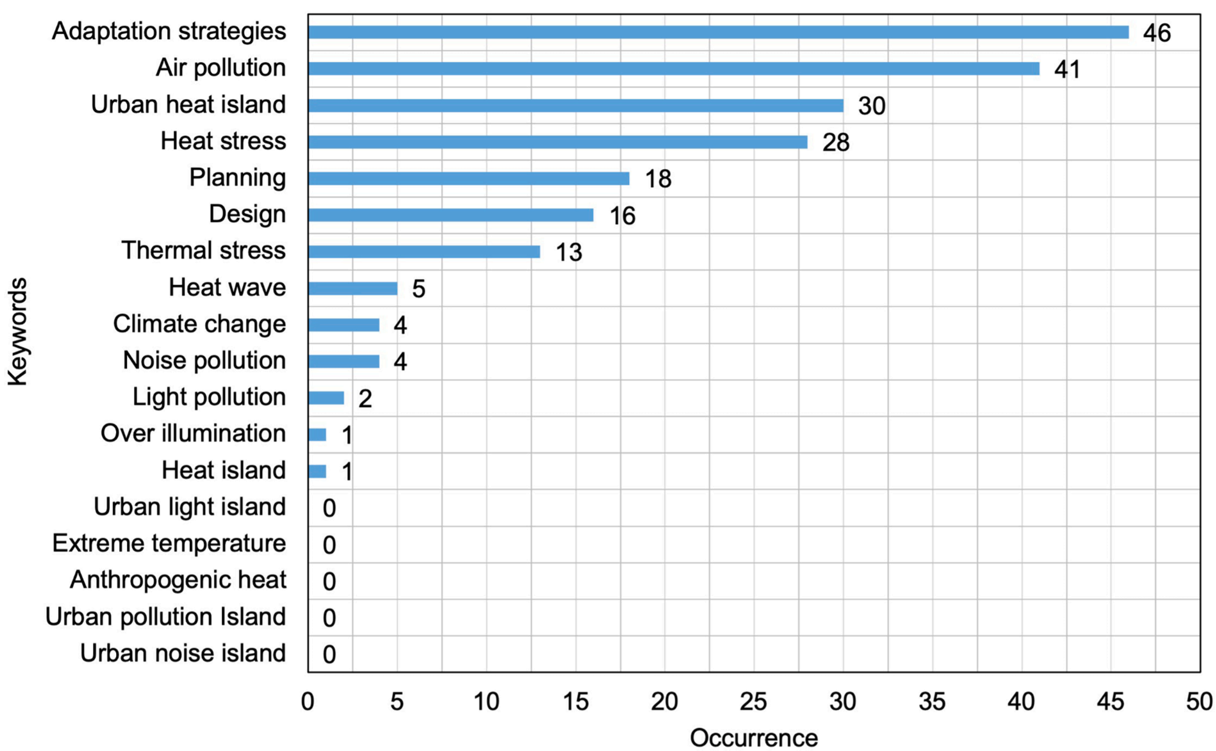
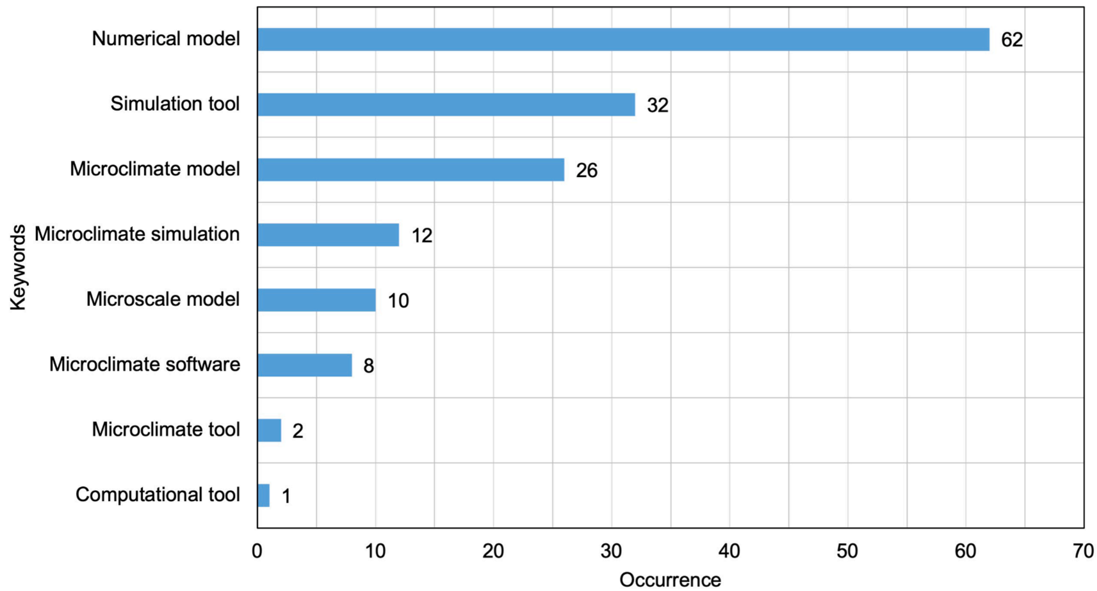


Figure 4. Occurrence of the keywords in each folder of the CIMO logic. At the top left-hand side, there is Context; at the top right-hand side, there is Intervention; at the bottom left side, there is Mechanism; at the bottom right side, there is Outcome.

network shows the linkages and the relations between the different keywords previously identified through the occurrence analysis. In this regard, the plot shows the relationship between various themes forming the clusters. The wider the theme, the larger the diameter of the cluster. Furthermore, the more relationships a theme has with others, the thicker the link between them will be. To define the clusters, we adopted the Walktrap algorithm assuming a node count of 50 and normalizing the relationships to the strength of the association as described in the Bibliometrix guidelines [38].

In particular, from the database analysis, the co-occurrence network



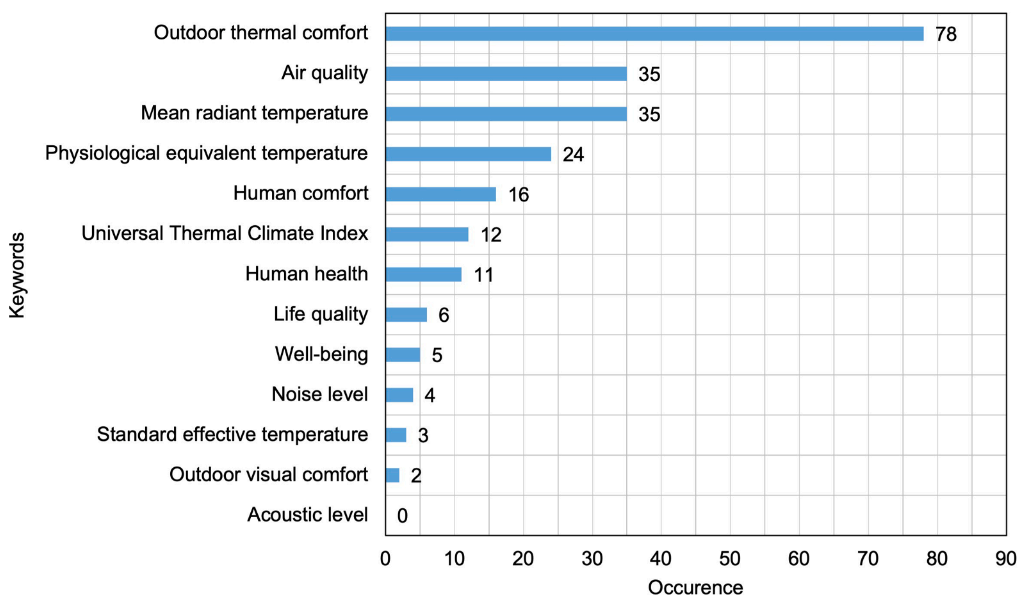


Figure 4. (*continued*).

shows the formation of three clusters. The green one, on the top left side of the picture, mainly focuses on the theme of air quality and air pollution. At the same time, the cluster includes the aspect of thermal comfort, highlighting the link with air pollution and stressing its importance in the urban environment. The second cluster, on the bottom left side, in red, emphasizes the relationship between outdoor thermal comfort and the urban microclimate and how it can be studied by exploiting the capabilities of numerical modeling, particularly computational fluid dynamics. Finally, the third cluster, on the right side, shows a strong connection between the urban environment, climate dynamics, and the application of the numerical simulation.

Overall, the three clusters are interested in the numerical simulation and modeling of the atmosphere dynamics, paying attention to the air quality and the thermal comfort in the urban environment. Urban planning becomes, therefore, a key element by linking these aspects and requiring integrated approaches to address sustainable urbanization and face climate change challenges.

With this background, seeing the keyword 'envi-met' at the center of the picture is unsurprising. ENVI-met is not only the most used microclimate simulation tool but also the one that tries to pursue the holistic approach necessary to model more than one domain characterizing the urban environment.

A final remark regarding the link between thermal comfort and air quality should be provided. Figure 6 shows a thin link between these two topics, indicating that those keywords recurred together a few times. Nevertheless, we expanded the research and found that several studies analyze the intricate interplay between outdoor and indoor thermal comfort and air pollution in diverse urban contexts. For instance, in Dortmund Marten, Germany, during a heatwave, aggravated health risks near unshaded roads revealed the challenges of local heat stress and air quality [40]. Similarly, in Erzurum City, Turkey, positive correlations emerged between ozone (O_3) concentration and the Physiological Equivalent Temperature (PET), affecting human health and thermal comfort [41]. The temporal variation of the urban aerosol

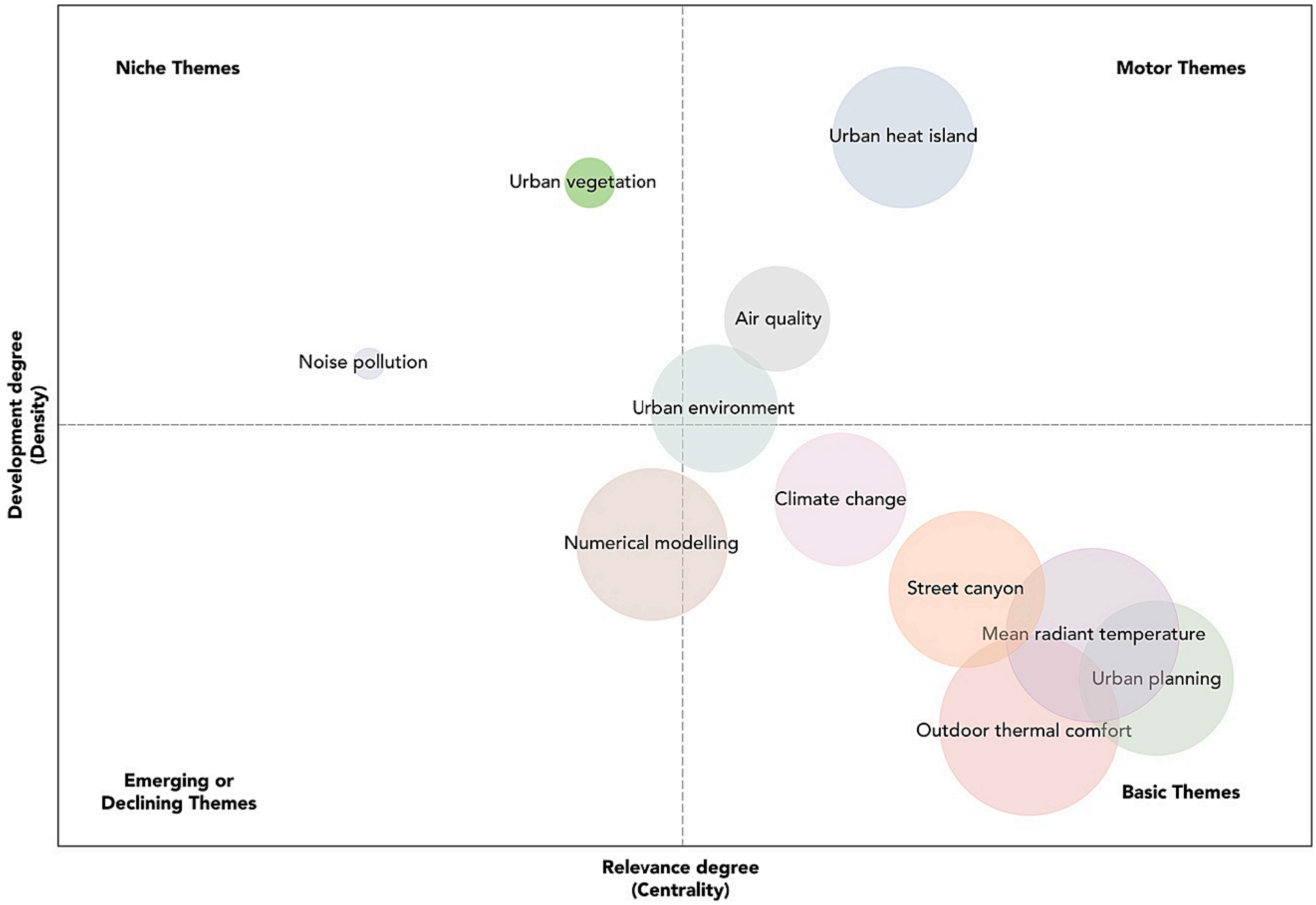


Figure 5. Relevance of the research themes.

pollution island (UAPI) in Berlin revealed slight relationships between PM_{10} concentrations and urban-rural disparities, emphasizing the need to comprehend the temporal dynamics of air pollution and its links to urban heat island effects [42].

Meanwhile, a study in Chinese cities introduced the Meteorology and Environment Comfort (MEC) index, exposing the significant impact of air pollution on reducing comfort levels during extreme temperatures [43]. Birmingham, UK, experienced amplified pollutant levels, mainly ozone, during heatwaves, urging additional air pollution reduction measures during forecasted hot spells [44]. The interaction between urban heat island (UHI) and urban pollution island (UPI) in Berlin revealed spatial consistencies, underlining the interplay of surface UHI and atmospheric UPI [45]. Additionally, research in Wuhan, China, identified synergistic effects between particulate matter (PM_{10}) and high temperatures on daily mortality, emphasizing the critical role of air quality during extreme heat [46]. Studies in Shenyang, China, explored vertical synergies, uncovering correlations between outdoor and indoor thermal comfort and air pollutant levels at different heights in an urban street canyon [47]. Lastly, computational modeling assessed how indoor-outdoor temperature differences impact building ventilation and pollutant dispersion in urban communities, offering insights into optimizing natural ventilation strategies to reduce indoor and outdoor air pollution exposures [48].

3. A framework for comparing microclimate tools

To consider the holistic approach and to keep it at the heart of this study, we thoroughly compared different microclimate tools. The aim of this analysis is to provide a guidance that allow designers, researchers, and other stakeholders to identify the solutions that best meet their specific and local needs. Also, we should highlight any possible gaps that may push new development lines for newer software or seamless interoperability between the existing ones. Therefore, the motivation behind this work is twofold. On the one hand, considering the city as a complex system requires identifying tools that can describe as many fluxes as possible affecting the urban climate. Identifying such tools will be crucial from a holistic point of view.

On the other hand, many works [49–52] have already addressed the problem of studying and evaluating some forms of energy performance within the city through computational tools. However, these works exclusively focused on the computational capacities in modeling energy flows. The fundamental work by Crawley et al. [53] is the one that most details a range of computational software for building energy simulations covering more aspects than those closely related to the sole energy performance of building performance simulation software. Similarly, this article aims to contrast the features and functionalities of computational tools developed to evaluate urban microclimate (Table 1). They were identified through a systematic search of the scientific literature. The characteristics of the detected simulation tools were compared to identify their fundamental principles, capabilities, and possible fields of application. Thus, we introduced an evaluation framework that compares, analyzes, and evaluates different aspects of those tools. The studies identified were collected in a bibliographic database that was then analyzed. Through the support of a bibliographic tool, analyses were conducted that showed that: (1) most of the works have been produced recently, (2) the studies focus mainly on the analysis of heat fluxes within the urban environment, so much so that the concept of Urban Heat Island (UHI) is already well established, (3) air quality and pollution within the urban environment is a very recent topic but has already produced a considerable amount of works, (4) there is no trace

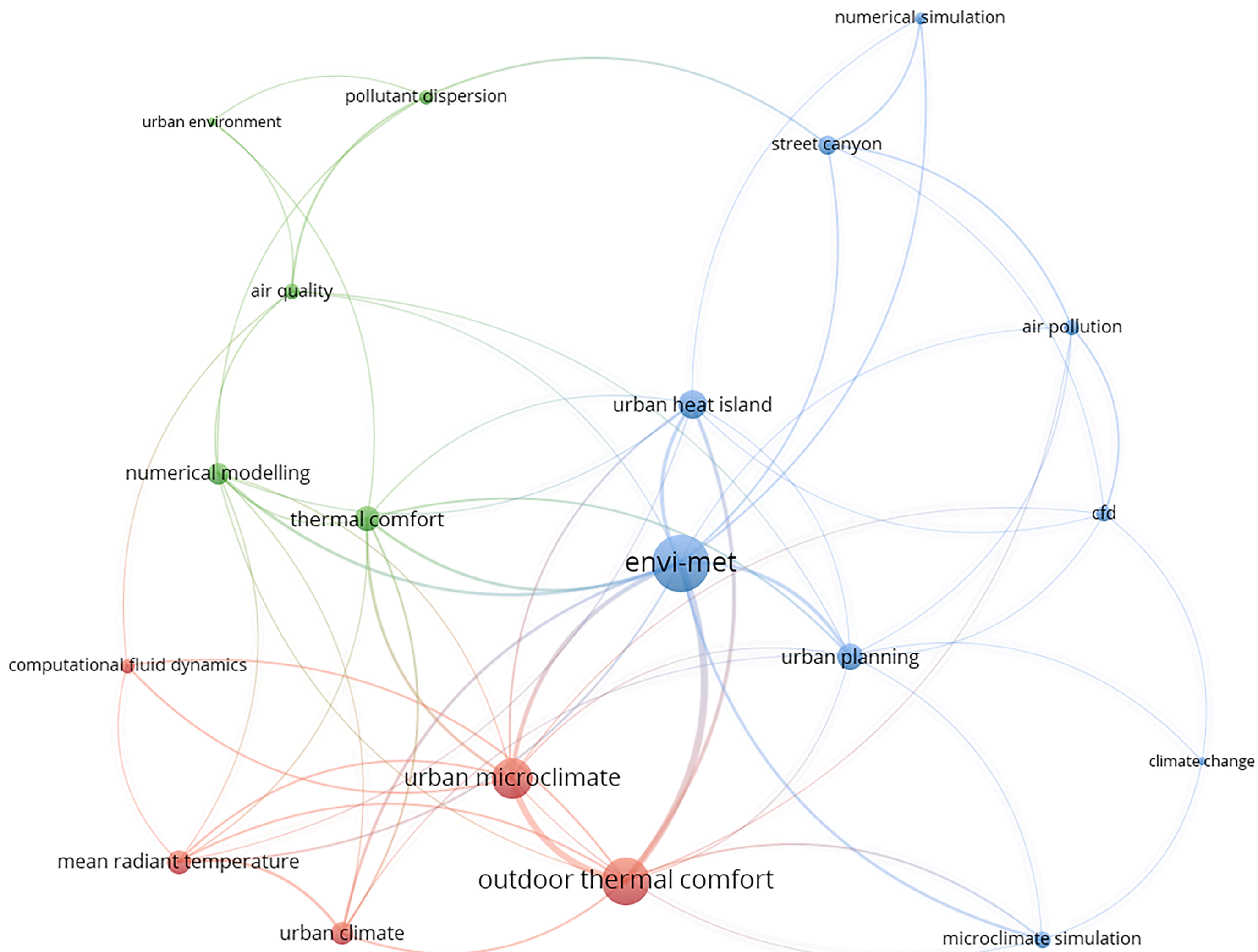


Figure 6. Co-occurrence network showing the aggregation of the keywords of the CIMO logic in specific clusters.

or almost no work aimed at the investigation of noise and light pollution.

Further details on the tools retrieved and compared, their description and the comparison tables of the evaluative framework, have been included in the supplementary information available at the end of this paper.

3.1. Microclimate simulation tools

After identifying the relevant documents, their screening, and their final inclusion in the review pool, 25 microclimate simulation tools were selected and included in the study. They were then analyzed using an evaluative framework to univocally identify their main functionalities and capabilities and provide a transparent, coherent, and thorough comparison.

The information necessary to evaluate the functionalities and capabilities has been extracted (i) from informative primary sources, such as technical manuals, user guides, and brochures, (ii) from secondary sources like scientific articles, and (iii) from querying support services to clarify inconsistencies and completing the data required by the comparative framework.

Some tools, such as UMEP and UWG, were not included in the assessment. Instead, we focused on SOLWEIG and SUEWS individually, both of which are components of UMEP. This decision was made due to the standalone capability of SOLWEIG and SUEWS. Additionally, UMEP consists of a set of tools categorized by their functions: pre-processing, processing, or post-processing. Furthermore, UMEP is available as a QGIS plugin. As for UWG, it has been recognized as part of the LadyBug tools suite.

Comparing tools' features and capabilities, we found that CFD tools are the prevalent typology, with 10 out of 25. Other tools, such as RayMan, SOLWEIG, and SUEWS, belong to the Surface Energy Balance (SEB) category. TAS is a Building Energy Model (BEM). While ADMS Temperature and Humidity model is air quality-oriented, Ladybug tools are a collection of software that aims to support environmental design. The collection includes CFD, BEM, and object-oriented models. CFD-based tools can simulate most of the flows that characterize the constructed environment. Among the CFD tools, there are substantial differences depending on the user needs and research scope: *general-purpose CFD tools* (such as OpenFoam, Fluent, and Autodesk CFD) offer a high level of customization of the simulation (e.g., CFD model selection, parameter setting) and more detailed geometrical modeling features (e.g., meshing tools) but require the modeler to create all items without offering pre-set urban item libraries; these tools provide the possibility for more accurate and physically grounded simulations but require solid theoretical knowledge on fluid mechanics and computational methods and advanced specific competences in CFD modeling.

On the contrary, specialized microclimate tools, such as ENVI-met, Ladybug DragonFly, and UrbaWind, are developed explicitly for microclimate simulations and offer very useful pre-set urban item libraries, but reduce the set of options available. For example, regarding

Table 1
Identification of the keywords according to the CIMO logic.

Context	Intervention	Mechanism	Outcomes
Where? In which context is the intervention embedded?	*What? Which is the main topic?*	*How? Which is the medium?*	*To get what? What is the wanted information?*
Built environment	Urban heat island	Numerical model	Well-being
Urban spaces	Urban noise island	Simulation tool	Life quality
Urban areas	Urban pollution island	Microclimate model	Human health
Outdoor environment	Urban light island	Microclimate tool	Outdoor thermal comfort
Urban climate	Anthropogenic heat	Microclimate software	Human comfort
Urban microclimate	Air pollution	Microclimate simulation	Mean radiant temperature
	Noise pollution	Microscale model	Universal thermal climate index
	Thermal stress	Computational tool	Physiological equivalent temperature
	Extreme temperature		Standard effective temperature
	Heatwave		Noise level
	Heat island		Acoustic level
	Climate change		Air quality
	Heat stress		Outdoor visual comfort
	Planning		
	Design		
	Adaptation strategies		
	Light pollution		
	Over illumination		

the CFD model selection, the parameter setting, or the geometrical modeling tools. Most of these tools show well-developed interoperability features, importing data and information from various drawing or 3D modeling software. In addition, some (like ADMS, Ladybug tools, UrbaWind, OpenFOAM, RayMan, and SOLWEIG) also support importing files from GIS programs with their geolocation, and others (AKL FlowDesigner, Autodesk CFD, DIALux evo, and scSTREAM) offer the possibility of importing IFC files, which are necessary to enable interoperability with other BIM tools.

The most adopted geometry modeling approach is mesh modeling, especially among CFD tools (AKL FlowDesigner, Fluent, Autodesk CFD, UrbaWind, OpenFOAM, PHOENICS, scSTREAM, and STAR-CCM+). Still, some tools use 3D (ENVI-met, TAS, TownScope, and UMI) or parametric modeling (Ladybug Tools).

When it comes to modeling the urban context and the various elements that characterize it, CFD tools allow great versatility and the possibility of defining most of the variables necessary to determine the thermal characteristics of the surfaces. Vegetation and water bodies are more detailed elements that only a few models consider, such as ENVI-met, UrbaWind, or TownScope.

As far as the meteorological variables are concerned, almost all the tools analyzed allow the import of weather files in different formats, the most frequent being the EnergyPlus (EPW) format.

Regarding the numerical solutions adopted to solve the equations that govern the various energy and mass flows, the analysis first addressed atmospheric modeling and all the equations and mathematical models adopted to solve turbulence, wind flow, and thermal fluxes. Next, the models adopted to describe the soil, vegetation, and water bodies were considered. Finally, models for air quality and noise were also scrutinized.

As for the analysis of atmospheric modeling, the study of built environment modeling has followed the same approach. Firstly, all the models that describe the surface energy balance of walls and roofs were considered. Next, the capability of considering the indoor air temperature was analyzed. Lastly, the analysis deals with methods and algorithms for assessing daylighting and light transport. CFD approach is one of the most flexible and thorough approaches that can model most atmospheric phenomena and their interaction with the soil and the built items.

Furthermore, several CFD tools can also model vegetation, water bodies, and soil. However, equations or sub-models describing their physical processes must be coupled with the starting model [54,55]. Other tools (RayMan, SOLWEIG) only deal with solar radiation assessment and average radiant temperature calculation, so they do not solve the buildings' surface energy balance or the atmospheric flows.

Among all analyzed microclimate tools, ENVI-met offers the possibility of modeling most aspects related to both the urban environment and the buildings. However, it adopts simplifications and presents limitations regarding the type of numerical schemes available to solve the governing equations of heat conduction, convection, and radiation (Table 6 and Table 7).

It is also important to note that not all tools analyzed could assess air quality, lighting and noise pollution. Only recently, in 2022 and 2023, five studies were published assessing noise propagation and one study used a tool for lighting calculations.

As far as the simulation settings and the modalities of representation of the results, it is necessary to emphasize that for the generic CFD, it is necessary that the analyst can choose a timestep and length of the simulation period tailored to the complexity of the analyzed model and the number of variables taken in consideration. Therefore, these parameters are user-defined. Other more straightforward tools (RayMan) adopt a fixed daily simulation period. Regarding spatial resolution, it is editable only in CFD tools, and, in ENVI-met, it spans between 0.5 and 10 meters.

Considering the visualization of the output of a simulation, all the analyzed tools offer different reporting tools and options, both numerical, textual, or graphical. The most common output files are text files, comma-separated value files, and ASCII files. Some tools (ENVI-met, STAR-CCM+) also create elaborate simulation outputs and compile standardized reports in HTML and CSV format.

The last comparison field is their capability to quantify environmental emissions and, in particular, which pollutants can be modeled and simulated. There are few microclimatic tools, apart from those specific for evaluating air quality, that implement a thorough and insightful analysis of environmental emissions. Among these tools, ENVI-met offers the possibility to model hourly areal pollutant generation (nitrogen oxide, NO; nitrogen dioxide, NO_2; ozone, O_3; and particulate matter, PM_{10} and $PM_{2.5}$) mostly for addressing traffic emissions.

3.2. Distribution features

Microclimatic simulation tools offer different accessibility modalities, installation options, supporting documentation, training opportunities, and after-sale support. A thorough overview of the distribution features of all identified microclimatic simulation tools, presented in Table 2, can be identified in the supplementary information in the Description of Tools.

To indicate the legacy of a tool and its updates, the *Release dates* are reported, if available, to display the date of the software's last version release. Then, the main websites are added to provide instant access to the most updated information and support each software house offers.

In the section *Documentation*, all the valuable documents related to each tool are listed, and they are classified into: (1) *Requirement documentation*, which outlines the features and the operation of the specific tool; (2) *User guide*, which describes the main components of the tool like interface and software engine(s); (3) *Technical references*, which explain in detail the models and equations that are run to solve the model and the user-defined parameters and physical and numerical assumptions adopted;

Table 2
Tools retrieved from the review.

Tool	Open Source	Commercial	Operative system	Support Training
ADMS Temperature and Humidity model		X	Windows	X
AKL FlowDesigner		X	Windows	X
ANSYS Fluent		X	Windows	X
Autodesk CFD		X	Windows	X
CadnaA		X	Windows	X
DIALux evo		X	Windows	X
ENVI-met		X	Windows	X
iNoise		X	Windows	X
Ladybug Tools	X		Windows/ Mac OS	X
MITHRA-SIG		X	Windows	X
MUKLIMO_3	X	X	Windows/ Linux	
NOISEMAP Five		X	Windows	X
OpenFOAM	X		Windows/ Mac OS	X
PALM-4U	X		Linux	X
PHOENICS		X	Windows	X
RayMan	X		Windows	X
scSTREAM		X	Windows	X
SOLWEIG	X		Windows	X
SoundPLAN		X	Windows	X
STAR-CCM+		X	Windows	X
SUEWS	X		Windows	X
TAS		X	Windows	X
Townscope		X	Windows	X
UMI	X		Windows	X
UrbaWind (Meteodyn)		X	Windows	X

The Support section gathers all the alternatives available to the user to solve or fix issues (e.g., Helpdesk, Forums, FAQs, Blog, troubleshooting service, and Scientific references).

In the same way, the *Training* section collects all the different sources available to develop skills about the use of the tool (such as Training courses, Workshops, Online learning hubs, Video tutorials, Webinars, Online academies, and Lectures).

Due to the computationally expensive nature of microclimatic simulation, we have included the *Operational requirements* section by identifying compatible *operative systems* and *minimum system requirements* necessary to run each tool as mentioned by each software house.

The *distribution modalities* (Public domain, Permissive and open-source software (FOSS), Copyleft FOSS, Freeware/Shareware/Freemium, Proprietary license, Subscription, and Full version) of the tools have also been specified, listing the different types of licenses for each tool makes available and the related limitations, if any. Finally, price information is reported when available (updated on 22/01/2024)

As shown in Table 3, it has been possible for each tool to retrieve different information about the different sections that make up the table. For instance, most tools provide documentation like a user guide or technical references. On the contrary, only some tools come with user training services. Regarding the operational requirements, most of the tools considered are designed to run on Windows-based machines. Some are computationally demanding and require a significant amount of free disk space.

Distribution modalities, Installation types, and Price sections try to cover the commercial side of the tools' distribution. Almost all the tools are distributed under proprietary licenses, meaning users must purchase a license to run the tool. Very few tools are distributed as freeware, and others provide the possibility to choose between free and licensed versions. Thus, the installation type will also change according to the license type. Most tools with proprietary licenses have a double installation type: Trial and Full versions. Finally, the prices change according to the type of license selected and the services provided with the license (e.g., customized customer support, technical documentation, or constant maintenance of the tool).

3.3. Interoperability and user interface

When choosing a simulation tool, a few communication aspects can inform the selection process. For research or holistic assessment purposes, often, simulation tools need to be integrated into process automation workflows by connecting different simulation or statistical tools for complex analysis. To establish such processes, it is crucial to choose tools that can communicate with the other automation managers or simulation engines. Also, it is essential to know which are the interoperability features of a tool to learn which the available import and export data formats either to take advantage of prior available inputs (e.g., maps, geometrical models, topographical models) or to use simulation outputs to inform other data processors or simulation engines. Finally, it is helpful to know whether a tool is provided for a textual interface that can be easily programmed using other software or called using batch or routines written in programming languages. Focusing on microclimatic simulation tools, in this study, we gathered information on native interoperability with geographical information systems (GIS) and other simulation programs. The possibility of importing maps from GIS programs is valuable since the knowledge of topography is a fundamental aspect of microclimate studies.

Besides native interoperability options, data import and export formats are listed for each tool. Import data formats are further classified concerning the type of information in the tool, focusing on the file formats available to be imported concerning the design, the mesh, the topography, and building information.

Tools are scrutinized about the *User Interface* to determine whether they are equipped with a graphical user interface or need textual input.

Table 4 highlights the tools' diverse procedural methodologies and interoperability aspects, showing distinct functionalities and input/output procedures. The table underscores the importance of the visualization tools and the Graphical User Interface (GUI), which enhances user experience and facilitates the manipulation of the elements to be modeled. The interoperability aspect is another interesting outcome of the table, showing how different tools are open to import/export thanks to the seamless import/export options they can provide. The presence of tools that can work with files developed with BIM tools is auspicious with a view to the interoperability and the multifaceted topic of urban microclimate. At the same time, many tools can already work with/through the GIS, indicating that the direction to be followed to assess urban environment-related problems is by exploiting georeferenced and source-crowded data. Those tools are more academic research-oriented, like SOLWEIG, SUEWS, or, in particular, PALM-4U privileged text-based files for their operations.

Nonetheless, PALM-4U, for instance, only works with netCDF format files. This file type is compact, meaning it uses storage space efficiently and requires very little additional overhead to store metadata that goes with the primary dataset. This way, the stored information is always accompanied by the context and details.

3.4. Microclimate computational modeling

Microclimate simulation tools are computer-based, multidisciplinary, and problem-oriented mathematical models. They are adopted to study the complex interactions between buildings, infrastructures, natural elements, the surrounding atmosphere, and the ground, relying on fundamental physical principles and engineering models.

They usually adopt numerical methods that provide a simplified and approximate solution to the investigated phenomena. To this end, microclimate simulation software needs to offer tools for reconstructing selected geometrical attributes of a site and the relevant natural and built elements located on it, defining the simulation domain, assigning initial and boundary conditions to it, assigning thermophysical and optical properties to the materials within the given simulation scene,

Table 3
Distribution features.

	ADMS Temperature and Humidity Model	AKL FlowDesigner	ANSYS FLUENT	Autodesk CFD	CadnaA	DIALux evo	ENVI-met	iNoise	LadyBug + HoneyBee	MITHRA-SIG	MUKLIMO-3 Basic/Thermodynamic	NOISEMAP Five	OpenFOAM	PALM-4U	PHOENICS	RayMan	scSTREAM	SOLWEIG	SoundPLAN	STAR-CCM+	SUEWS	TAS	TownScope	UMI	UrbaWind (Meteodyn)
Release date																									
First release date	1993		Late '80s				1998		January 2013				2004		2018			2008		October 2004	2011			May 2013	September 2009
Latest release date	February 2022	2021	July 2023	December 2022	August 2023	January 2024	June 2023	September 2023	October 2023	January 2024	April 2000	October 2010	December 2023	October 2018	December 2023	End of 2006	June 2022	December 2022	January 2023	February 2023	May 2020	September 2023	2014	November 2014	October 2021
Web site	X[1]	X[4]	X[7]	X[10]	X[13]	X[16]	X[18]	X[21]	X[25]	X[26]	X[30]	X[35]	X[40]	X[41]	X[42]	X[46]	X[48]	X[53]	X[54]	X[57]	X[61]	X[62]	X[65]	X[69]	X[70]
Documentation		X[5]																							
Requirements documentation	X		X	X	X	X	X		X	X	X	X[36]	X	X	X		X[49]		X	X					X
User guide	X		X	X	X	X	X		X	X	X[31]	X	X	X	X	X	X[49]	X	X		X	X		X	X
Technical references	X		X	X	X	X	X		X	X	X[31]	X[36]	X	X	X	X	X[49]	X	X		X	X		X	X
Support		X[5]						X[22]				X[37]	X						X[55]			X			
Helpdesk	X			X	X	X				X		X			X	X	X[49]	X		X					X
Forums			X	X			X		X							X	X[49]								
FAQs					X	X	X	X	X			X		X	X		X[49]	X					X		
Blog						X	X										X[49]					X			
Troubleshooting				X		X								X							X				
Training		X[5]					X						X		X						X	X			X
Training courses	X		X			X				X					X		X[49]	X							
Workshops																									
Online learning hubs			X																			X			
Video tutorials		X		X		X	X	X	X			X				X								X	X
Webinar					X												X[49]								
Online academy					X				X								X[49]								
Lectures					X																				
Operational requirements																									
Operative systems	Windows 8, Windows 10	Windows 8, Windows 10	Windows 10	Windows 10	Windows	Windows 10/11 (64 bit)	Windows	Windows 7/8/10 (64-bit)	All Operative Systems	Windows (64-bit)	X[32]	Windows 7 or above (32 or 64 bit)	All Operative Systems	Linux OS	Windows 10	Windows	Windows 10, 11 (64 bit), Linux (RedHat 7, 8)	Windows	Windows (64 bit)	Windows 10	Windows	Windows	Windows 32/64 bits from NT up to Windows 7, MAC OS X 10.4 or higher	Windows	Windows 10
Minimum system requirements	Fast CPU recommended, RAM - at least 2GB, fast RAM recommended	CPU better than Intel i3/i5/i7, RAM - 4 GB, FREE DISK SPACE - 20 GB available	64-bit Intel or AMD, RAM - 8GB	64-bit Intel or AMD, RAM - 8GB	Intel Core i5 or equivalent, RAM - 8 GB or more, FREE DISK SPACE - 20 GB or more	CPU with SSE2-support 4 GB, RAM - 4 GB, OpenGL 3.2 graphics card (1 GB RAM), min. res. 1920 x 1080 px	CPU - Intel Pentium D or AMD Athlon 64 X2, RAM - 4 GB, FREE DISK SPACE - more than 10 GB	Intel Core i3 or AMD Phenom X2, RAM 2 GB, FREE DISK SPACE - more than 1 GB, OpenGL support for 3D view		Quad core Intel I7 or AMD FX, RAM - 8 GB at least, graphics card - 1 GB DirectX 11		Intel Core i5 or i7, RAM - 8 GB, FREE DISK SPACE - 80 GB	CPU - Intel i7, RAM - 8/16 GB		X[43]		Intel or AMD, RAM - 8 GB, FREE DISK SPACE - 10 GB at least, graphics card needs to support OpenGL		RAM - 8 GB, graphics card must support OpenGL 4.1	2.4 GHz CPU with at least 4 cores per CPU. 4GB of memory per core. 9GB of free disk space. Minimum screen resolution 1024x768 pixels			At least 512 MB of RAM, at least 64 MB VRAM and high resolution in 16M colors	64-bit operative system	RAM: 16gb recommended, Processor: mini 2GHz, Multiprocessor: 64-bit recommended
Distribution modalities																									
Public domain																									
Permissivie Free and open-source softwares (FOSS)									X				X					X			X				
Copyleft FOSS																									
Freeware/Shareware/Freemium						X		X						X		X[47]								X	
Proprietary license	X[2]	Annual license	X[8]	X	X[14]		X[19]	X	X	X[27]	X[33]	X[38]			X[44]		X[50]		X	X[58]			X[66]		X[71]
Subscription				X[11]		X[17]																X[63]			
Trade secret																									
Installation type																									
Trial version	X	X	X	X											X					X[59]		X	X[67]		X[72]
Demo version					X	X	X[7]										X[51]		X						
Custom version(s)							X	X[23]																	
Full version	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Price	X[3]	X[6]	X[9]	X[12]	X[15]	29.99 € / month	X[20]	X[24]	Free	X[28]	X[34]	X[39]	Free	Free	X[45]	Free	X[52]	Free	X[56]	X[60]	Free	X[64]	X[68]	Free	3,800 €

Web site: https://cerc.co.uk/environmental-software/ADMS-Urban-model.html
Two types of licenses are available: the annual license is valid for one year, and the permanent license is valid indefinitely. In addition, the single-user license allows the use of the software by one user at a time. The research license allows the use of the software for non-commercial purposes at research and academic organizations. Finally, the teaching license allows using software for teaching purposes at academic institutions.
Prices vary according to the different types of licenses. More information on prices can be found at http://www.cerc.co.uk/environmental-software/prices.php.
Web site: https://www.akl.co.jp/en/
All types of documentation, support, and training are provided only in Japanese.
A 5% commission is added to overseas sales. For price information, please contact the Company.
Web site: https://www.ansys.com/products/fluids/ansys-fluent
An annual subscription is provided and also gives access to Fusion 360.
For price information, please contact the Company. Financing options available.
Web site: https://www.autodesk.com/products/cfd/overview
An annual subscription is provided and also gives access to Fusion 360.
For price information, please contact the Company. Financing options available.
Web site: https://www.datakustik.com/products/cadnaa/cadnaa
CadnaA licenses are divided into Cloud Licensing (CL) and On-Premise Licensing (PL). In addition, the licensing can be Light or Professional, depending on the different features available.
Regarding the license cost, it is necessary to contact the company.
Web site: https://www.dialux.com/en-GB/dialux
The paid version of DIALux, DIALux Pro, adds some features to those already available in the free version. Nevertheless, the freeware version allows users to run all the tasks entirely. The cost of the Pro version is 29.99 € per month.
Web site: https://www.envi-met.com/
Different license types are provided according to the user's needs. Each of them has limitations.
The Demo version has a limited domain size, provides reduced outputs and analysis options, does not allow running parallel simulations, and is not intended for commercial use.
Price varies according to the license chosen.
Web site: https://dgmrsoftware.com/products/inoise/
The premium support service for iNoise is optional, and it costs 435€ in the case of the iNoise Free license; otherwise, it costs 235€ for an iNoise Pro license. The service provides 3 hours of support: answering questions via email, 2 model reviews, and one online Q/A session.
A custom version is provided to customers who use the free version. Some methods are provided in demo mode, and other limitations are included.
The cost of the pro version changes according to whether or not the CNOSSOS analysis method is included. If not included, it costs 545€; otherwise, it costs 1.320€ per year.
Web site: https://www.ladybug.tools/honeybee.html
Web site: https://geomod.fr/en/expertise/wave-propagation/mithrasig
There is only one type of license, but the cost of it changes according to the number of objects allowed in the model: 100 / 1000 / 10 000 / 100 000 / unlimited.

The cost of the license is not indicated on the website. Please contact the Company.
The basic version of MUKLIMO_3 is used to calculate stationary wind and concentration fields for neutral atmospheric layers. On the other hand, the thermodynamic version can be used to study the climatic impacts of changes in land use patterns and to analyze the climate of entire cities.
Web site: https://www.dwd.de/EN/ourservices/muklimo_thermodynamic/muklimo_thermodynamic.html
User guides and technical references are provided only in German.
The basic version is available for Windows operating systems up to Windows 7. The thermodynamic version is available only for UNIX/Linux operative systems, and no graphical interface is provided.
The basic version can be used free of charge if it is used exclusively for non-commercial purposes. Otherwise, a commercial license is provided. On the other hand, licenses for the thermodynamic version - for non-commercial tasks in research and teaching only - are available on request.
The price for the commercial license for the basic version is €2700
Web site: https://www.noisemap.ltd.uk/wpress/products/noisemap-five/
Some user manuals and guides are free of charge, but it is necessary to be registered to get access to them.
Customer support and other services are only provided after the purchase of the maintenance.
There are different ways of using the tool. It is possible to purchase a 50-year license or an annual one. For all the other possibilities, please refer to the website.
With regards to the cost of the license, please contact the Company
Web site: https://www.openfoam.com/
Web site: https://palm.muk.uni-hannover.de/trac/wiki/palm4u
Web site: https://www.cham.co.uk/phoenics.php
Minimum 4GB RAM. The program is compiled for both 32-bit and 64-bit operative systems. The minimum screen resolution recommended is 1024*768 pixels.
Many licenses are provided: academic, non-profit, and commercial. They can be monthly, annual, or perpetual. There is also the possibility of adopting pay-as-you-go usage via the Microsoft Azure Cloud. In addition, academic users can benefit from a discount.
The annual academic license costs €1,885, and the unlimited version costs €2,600. In contrast to the academic license, the personal license costs €750 and lasts three years, but it is unsupported by software updates.
Web site: https://www.urbanclimate.net/rayman/
RayMan comes in two versions: basic and pro. The basic version is used for education and teaching, academic research, and governmental use; the pro version is accessible only for academic and scientific purposes.
Web site: https://www.cradle-cfd.com/product/scstream.html
The user must register on the company page to access customer support, training materials, and the software itself.
To use the software the purchase of a license is required. But a lite version is available for free
The company offers the possibility of getting a student license, which allows working with a light version of the model.
The prices for the full version are not stated. Please contact the company.
Web site: https://www.gu.se/en/earth-sciences/software-download#SOLWEIG
Web site: https://www.soundplan.eu/en/software/soundplannoise/current-version/
To get customer support, it is necessary to purchase a maintenance contract.
To get an offer for the license, please contact the Company.
Web site: https://www.femto.eu/star-ccm/#contact
Different licenses are provided based on how many sessions are run per time and how many cores are used. Academic license is provided for selected academic institutions only.
The trial version, without limitation, lasts 30 days.
For price information, please contact the Company.
Web site: https://suews-docs.readthedocs.io/en/latest/
Web site: https://www.edsl.net/tas-engineering/
Software is provided with two types of licenses: standalone monthly or annual and network annual. With the standalone, the software can be used only with one machine. On the other hand, the network license allows software sharing between machines.
Standalone monthly costs €300+VAT, standalone annual costs €240+VAT, network annual costs €360+VAT.
Web site: http://www.umr-cnrm.fr/surfex/spip.php?rubrique142
Licenses are provided for academic and non-academic users. Both types of licenses are divided into single-user and multi-user
A trial version of the software is provided but has some limitations.
Academic single-user license costs €450, multi-user license costs €950. Non-academic single-user license costs €700, multi-user license costs €1200. All the prices are considered without VATs.
Web site: https://web.mit.edu/sustainabledesignlab/projects/umi/index.html
Web site: https://meteodyn.com/business-sectors/microclimate-and-urban-planning/13-urba-wind.html
One-year license provided.
It is possible to arrange a trial evaluation.

Table 4
Interoperability and User Interface

	ADMS Temperature and Humidity Model	AKL FlowDesigner	ANSYS FLUENT	Autodesk CFD	CadnaA	DIALux evo	ENVI-met	iNoise	LadyBug + HoneyBee	MITHRA-SIG	MUKLIMO-3 Basic/Thermodynamic Version	NOISEMAP Five	OpenFOAM	PALM-4U	PHOENICS	RayMan	scSTREAM	SOLWEIG	SoundPLAN	STAR-CCM+	SUEWS	TAS	TownScope	UMI	UrbaWind (Meteodyn)
Software interoperability and Data formats									X[78]		X[81]														
Import map from GIS programs	X[73]				X			X	X	X		X	X[85]		X[88]	X		X	X	X[95]			X[97]	X	X[98]
Import/Export to other simulation programs		X		X	X	X		X	X[79]	X		X					X		X			X	X		
Import format data	X[74]							X[77]						X[87]	X[89]	X[90]		X[92]			X[96]				
Design																									
Area Input File (.INX)							X																		
3DS		X				X			X						X		X						X	X	
CAD			X	X	X			X	X			X			X		X					X		X	
DXF					X	X		X	X	X		X			X		X		X				X	X	
Mesh													X[85]												
CFX			X										X												
CGNS			X																						
HYPERMESH ASCII			X																X						
I-deas				X									X												
STL		X							X				X		X		X			X				X	X
Topography											X[82]														
Shapefile					X		X	X		X		X				X[91]	X		X						
Building Information																									
IFC		X		X		X											X								
gbXML		X																				X			
XML																	X		X						
CityGML							X												X						
Export data type	X[75]							X[77]		X[80]		X[84]		X[87]					X[94]						
OBJ		X							X								X							X	
ASCII			X				X					X	X												
gbXML																									
Comma separated value (CSV)				X		X[76]	X		X											X				X	
IDF																						X			
NetCDF							X																		
XLS						X[76]																			X
Text File					X		X		X						X	X		X[93]			X			X	X
Data Explorer																									
User Interface											X[83]														
Graphical User Interface	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
Textual User Interface			X										X	X											

The software is supplied with a Mapper that can be used to visualize, add, and edit sources, buildings, and output points and view the model output. It also links to other software packages, such as ArcGIS and MapInfo GIS, for displaying results and easy data entry.
The software has its input file (.uai). There are five sections in this file:
a. Temperature and Humidity options, which include Anthropogenic heat, Short-term output, Spatial variation, Suppress warning messages, and Terrain height effects;
b. Terrain, which contains defined terrain margins and Limits inner layer depth;
c. Output options;
d. Road source options;
e. Time-varying options.
As with the input formats, the software has its specific file for output. The file refers to Long-term outputs or Short-term outputs.
Only the Pro version allows users to export to Microsoft Word, Excel, and PowerPoint. In addition, it is possible to import/export the IFC format with the Pro version.
Multiple import and export formats are provided with the Pro version of the model.
These tools are plugins for the Rhino 3D modeling software. For this reason, all the features highlighted in this table will refer to Rhino's capabilities.
These tools allow sharing of the model created with Rhino 3D with other simulation tools such as EnergyPlus, Radiance, or OpenFOAM.

The export formats depend on the type of map created. For instance, with sections in the horizontal plane, some formats available are DXF, DWG, BMP, TIFF, GeoTIFF, and PDF.
The project data is entered via the Input file prepared by the user at the beginning of the simulation. The input file has the structure of a FORTRAN namelist divided into several variable blocks.
The topography of the study area can be modeled using a RASTER file (height values are arranged in rows and columns), and it has to be specified in the input file.
The basic version supports a Graphical User Interface, while the Thermodynamic version has only a textual interface.
The tool allows the exporting of many other formats besides ASCII, such as DWG, DXF, and GIS.
It is possible to import topography into OpenFOAM provided that terrain data, orography, and terrain characteristics are provided in digitized format from the GIS system and then converted into the format needed by the CFD program.
OpenFOAM allows the import of many formats of mesh files, but they have to be converted from the starting format to the FOAM suitable.
The model provides a standardized way to input information via the netCDF format. The output, too, is provided with the netCDF format.
PHOENICS does not provide the possibility to import GIS information directly through GIS tools, but topography data can be imported, creating an STL file that will be read as an object (.obj).
PHOENICS can handle different files, provided they are imported through PHOENICS-VR and SimLab Composer.
RayMan allows using a text file (.txt) in which input data are included and separated by tabs or spaces.
The obstacle files added in RayMan can be calculated from Shapefiles using the "Shp to Obs" plugin for Quantum GIS.
SOLWEIG is a model that can estimate spatial variations of 3D radiation fluxes. It has two categories of input data: Spatial Information and Meteorological data. The Spatial information included all the digital surface models necessary to run simulations.
These models refer to Ground and Building DSM, Vegetation DSMs, Digital Elevation Model, and Ground cover grid.
Many export formats are available based on the modules and interfaces.
STAR-CCM+ allows importing terrain data provided that it is in STL format.
SUEWS allows the input of many parameters to describe the site's characteristics. All this information is provided through text files.
TownScope does not allow the import of topography from GIS tools, but it can allow the creation of terrain from 3D points.
The software allows the importation of CAD, topography, and porosity files, provided they are in STL format.

Table 5
Modeling Capacities

	ADMS Temperature and Humidity Model	AKL FlowDesigner	ANSYS FLUENT	Autodesk CFD	CadnaA	DIALux evo	ENVI-met	iNoise	LadyBug + HoneyBee	MITHRA-SIG	MUKLIMO-3 Basic/Thermodynamic Version	NOISEMAP Five	OpenFOAM	PALM-4U	PHOENICS	RayMan	scSTREAM	SOLWEIG	SoundPLAN	STAR-CCM+	SUEWS	TAS	TownScope	UMI	UrbaWind (Meteodyn)
Type																									
Simple calculation tool																		X			X				
Simulation software	X	X	X	X	X	X	X	X	X	X	X	X	X	X[115]	X	X	X		X	X		X	X	X	X
Web-based platform																									
Modelling approach	X[99]										X[112]					X[118]		X[120]			X[124]			X[127]	
Parametric									X																
Mesh-based		X	X	X		X[108]							X		X		X			X					X
3D graphics-based geometry					X	X[108]	X	X		X		X							X			X	X	X	
Structured grids														X											
Geometric description									X[109]		X[112]										X[125]				
Outdoor Environment						X[108]											X[119]								
Topography	X		X[101]		X		X	X	X	X	X[112]	X	X[113]	X	X[116]				X	X[123]			X[126]		X
Site landform	X		X[101]		X		X	X	X	X		X	X	X	X				X	X			X		X
Plants			X[102]	X[105]			X				X[112]		X[114]	X	X[117]								X		X[128]
Waterbodies							X							X											X[128]
Urban Environment						X[108]					X[112]						X[119]								
Canyon geometry			X	X	X		X	X	X	X		X	X	X	X			X[121]	X	X	X[125]	X	X	X	X
Orientation	X	X	X	X			X	X	X	X	X	X	X	X	X	X			X	X		X	X	X	X
Location	X						X	X	X	X	X	X		X		X		X[121]	X		X	X	X	X	X
Adaptation strategies																									
Cool roofs			X	X			X							X											
Cool materials			X	X			X							X											
Green roofs			X	X			X							X											
Green walls			X	X			X																		
Natural ventilation			X	X			X						X							X		X	X		X
Albedo			X	X			X		X[110]					X	X							X	X	X	
Absorption			X	X			X							X	X							X	X	X	
Reflectance			X	X			X							X	X							X	X	X	
External shadings			X	X			X		X				X		X							X	X	X	X
Evaporative cooling			X				X		X[111]					X											
Material properties			X[103]	X[105]		X[108]			X								X[119]								X[129]
Transmission			X	X			X							X	X							X	X	X	
Emissivity			X	X			X							X	X							X	X	X	
Specific heat capacity			X	X			X							X	X							X	X	X	
Thermal conductivity			X	X			X							X	X							X	X	X	
Density			X	X			X							X	X							X	X	X	
Building envelope	X[100]		X[104]	X[106]		X[108]											X[119]	X[122]			X[125]				
Shape			X	X	X		X	X	X	X		X	X		X				X	X		X	X	X	X
Height			X	X	X		X	X	X	X		X	X		X				X	X		X	X	X	X
Walls			X	X	X		X	X	X	X		X			X				X	X		X	X	X	X
Floors			X	X	X		X		X										X			X		X	X
Roofs			X	X	X		X	X	X	X		X			X				X	X		X	X	X	X
Tilted roofs			X	X	X		X		X	X		X	X		X					X		X	X	X	X
Building adjacency			X	X	X		X	X	X	X			X		X				X	X		X	X	X	X
Windows			X	X	X		X		X	X		X	X									X	X	X	X
Thermal zoning				X[107]																					
Definition of a single zone corresponding to the whole building				X																					
Discretization of the building into zones, often rooms							X		X													X			X
Discretization of the zones into control air volumes																									
Manual definition horizontally and vertically of zones within the building																									

The software does not explicitly model the area under study. For every single aspect of the modeling, it is required to upload a specific file to run simulations.
Buildings can be modeled in two different packages: ADMS-Roads package B and C.
Ansys does not allow modeling topography or site landform directly, but importing an STL file of the terrain data is possible.
Fluent uses the Ideal canopy model, which describes a tree only by its crown height, trunk height, and basic plant canopy geometry, such as spherical, oval, and conical.
Material properties can be edited inside the software. In addition, new materials can be created from scratch.
All the characteristics of the building can be modeled inside DesignModeler.

It is possible to model trees inside Autodesk CFD, and all the features are possible through the Materials box.
Material properties can be edited inside the software. In addition, new materials can be created from scratch.
Thanks to the interoperability between Autodesk Revit and Autodesk CFD, it is possible to model the building in all its features, including thermal zones.
In the Pro version, thanks to the possibility of importing the IFC file from any BIM tool, it is possible to include any feature both from the outdoor and built environments.
These tools are plugins of Rhino 3D. For this reason, all the features highlighted in this table refer to the software.
Ladybug does not allow the modification of materials satisfactorily, unlike Honeybee.
Ladybug tools can evaluate evaporative cooling but only for indoor spaces.
In the input file, there is the possibility to insert specific values for many variables like vegetation, buildings, and topography.
OpenFOAM can open .obj files. With this file format, generating the terrain file that can be subsequently imported into the tool and where the mesh will be created is possible.
OpenFOAM to model and describe plants uses the Statistical method, which associates LAI with the plant morphology.
PALM-4U is a numerical model for simulating the urban atmospheric boundary layers. It includes different parameterizations and equations that allow research on urban microclimate and climate change. For this reason, none of these sections are considered in the model.
PHOENICS considers topography only if it is imported as an STL or OBJ file. In this way, the tool does not model the terrain but can create a mesh of the surface and consider it during simulations.
PHOENICS uses the Ideal canopy model, which describes a tree only by its crown height, trunk height, and basic plant canopy geometry, such as spherical, oval, and conical.
RayMan models buildings and plants in a two-dimensional way.
The CAD add-in tool allows scSTREAM to ingest models from BricsCAD, Autodesk Revit, and ARCHICAD. This way, the software can consider all the aspects of the outdoor and the built environment.
SOLWEIG does not allow modeling buildings or trees. It requires spatial information related to ground buildings and vegetation. This information is provided through digital surface models (DSM).
The canyon geometry is provided through the Building and Ground DSM. This file consists of ground and building heights.
The Building and Ground DSM file also provides the area's latitude and longitude for Sun position calculation.
To consider terrain features inside STAR-CCM+, creating an STL file of the topography is necessary.
SUEWS does not take into account the modeling of the environment.
Characteristics of the site and model parameters are provided through text files. Each file's specific parameters can be defined according to the user's needs.
The terrain is generated from 3D points.
The modeling approach is 3D graphics-based geometry since UMI is a tool based on Rhino 3D.
Trees and waterbodies can be considered inside UrbaWind, provided they are included as STL files and uploaded inside the widow POROSITY.
Only the porosity of the material is taken into account.

identifying computational units (i.e., cells, nodes, zones), and assigning parameters to the selected numerical schemes (if the user can).

In the following subsections, we discuss their main modeling capabilities, the implemented computational models, the simulation settings, the data they handle, and the result reporting.

3.4.1. Modeling and simulation capabilities

First, microclimatic tools are categorized according to their general modeling capacities into *simple calculation tools*, which are typically mono-disciplinary, solution-oriented, steady-state models that implement analytical methods; *simulation software*, which is commonly multidisciplinary, problem-oriented, dynamic models that rely on numerical solvers; finally, *web-based platforms*, which are applications that can run on the web and typically work on any web-enabled device. Next, they are clustered according to the way they use to generate the simulation scenario, that is, (i) if they use analytical tools for generating building elements (parametric), (ii) if they require a mesh-based model generation, (iii) a tridimensional geometry or structured grids. Then, their capabilities to generate the geometries of different elements composing a simulation scene like the outdoor environment (topology, site landform, plants, waterbodies), the urban environment (canyon geometry), climate-adaptation strategies (e.g., cool surfaces, nature-based solutions, solar shading, evaporative cooling, natural ventilation) or material properties (e.g., albedo, emissivity, absorbance). Next, focusing on the building items, there is an overview of the modeling approach, whether it is the shape of the entire building or individual building components, and how thermal zones are defined either automatically based on a predefined geometrical resolution or manually defined by the user.

In this context, Table 5 shows the wide variety of modeling approaches and functionalities that emerged from comparing the tools. Besides classifying the tools, indicating whether they are simple calculation tools, simulation software, or web-based platforms, the table considers the geometric description the models adopt for the outdoor and urban environment. Moreover, the table has considered the possibility of modeling adaptation strategies, material properties, and the building envelope with thermal zoning.

Most tools can consider the topography and site landform thanks to the possibility of importing GIS information as previously described. The canyon geometry, the orientation, and the location of the study area are aspects covered by all the tools, with some exceptions among general-purpose CFD programs. ENVI-met is the tool that covers almost every aspect of the table.

3.4.2. Data handling

The microclimate simulation tools are characterized by different complexity in the physical and mathematical model implemented. This also reflects in the input variable required to set the scene and run a simulation and the output variables that can be extracted after the simulation terminates.

For simplicity, the input variables are grouped into three sections: (i) meteorological variables, (ii) built environment variables, and (iii) natural environment variables.

Regarding the first group, we reported whether the tools inherently provide weather data and whether weather data can be downloaded. This group then revised the typical weather formats accepted by each tool.

The *built environment variables* section considers all the variables related to urban systems, such as location, material properties, and height.

Similarly, the *Natural environment variables* refer to all the information required to model and consider elements from the outdoor environment, such as soil properties, type of surface, and vegetation.

The *output variables* are the outcome of the simulation calculated by a tool. They have been gathered into three groups: (i) the *physical variables*, (ii) *outdoor thermal comfort*, and (iii) the *environmental emissions*.

Table 6
Data Handling

	ADMS Temperature and Humidity Model	AKL FlowDesigner	ANSYS FLUENT	Autodesk CFD	CadnaA	DIALux evo	ENVI-met	iNoise	LadyBug + HoneyBee	MITHRA-SIG	MUKLIMO-3 Basic/Thermodynamic Version	NOISEMAP Five	OpenFOAM	PALM-4U	PHOENICS	RayMan	seSTREAM	SOLWEIG	SoundPLAN	STAR-CCM+	SUEWS	TAS	TownScope	UMI	UrbaWind (Meteodyn)
Input variables																									
Meteorological variables	X[130]	X[133]	X[134]	X[136]	X[138]		X[139]	X[140]	X[141]		X[143]	X[146]	X[147]	X[148]	X[149]	X[151]	X[156]	X[157]	X[160]	X[161]	X[162]	X164	X[165]	X[167]	X[168]
Weather data																									
Provided with the program										X[142]															X[169]
Separately downloadable	X	X					X		X						X			X[157]			X	X	X	X	
Accepted weather data formats																									
Any user-specified format (CSV)	X						X											X							
Climate file .cli																									
Horizon file .hor																									
European Test Reference Year		X					X		X						X										
Typical Meteorological Year (TMYx)		X					X		X						X			X				X		X	
Solar and Wind Energy Resource Assessment																									
Weather Year for Energy Calculations 2																									
Solar and Meteorological Surface Observation Network																									
International Weather for Energy Calculations																									
Japan AMeDAS weather data																									
DOE-2 text format																									
BLAST text format																									
ESP-r text format																									
ECOTECT WEA format																									
Text file (txt)	X																	X			X		X[166]		X[169]
EPW		X					X		X						X			X				X		X	
Built Environment variables	X[131]										X[144]				X[150]	X[152]		X[158]			X[163]				X[170]
Location	X						X		X	X		X		X		X[153]						X	X	X	
Surface cover: impervious (buildings, paved, rocks)	X		X	X	X	X	X	X	X	X		X	X	X			X		X	X					X
Roof material	X		X	X			X		X				X	X			X			X		X	X		
Height			X	X	X	X	X	X	X	X		X	X	X			X		X	X		X	X	X	
Material properties			X	X		X	X		X	X			X	X			X			X		X	X	X	
Natural Environment variables											X[144]				X[150]			X[159]			X[163]				X[170]
Non-built surfaces																									
Location	X				X		X		X	X				X		X							X	X	
Surface cover: pervious (vegetation, water, soil)	X				X	X	X	X				X		X		X[154]		X	X				X		X
Soil properties	X		X				X						X	X			X			X					
Vegetation	X[132]										X[144]					X[155]		X[159]			X[163]				X[170]
Location			X				X						X			X	X			X			X	X	
Type (deciduous, coniferous, grass)							X							X		X									
Height							X																X		
Leaf area density (LAI)							X																		
Photosynthetic and evapotranspiration properties			X[135]				X							X											
Output variables																									
Physical variables				X[137]																					
Surface temperature	X						X		X					X	X			X			X				
Air temperature	X		X				X		X		X			X	X		X	X			X				
Relative humidity	X		X				X		X		X			X	X		X	X			X				
Wind speed	X		X				X		X		X			X	X		X	X			X				X
Wind direction	X		X				X		X		X			X	X		X	X			X				X
Long and short-wave radiation	X						X		X		X			X	X	X		X			X		X	X	
Mean radiant temperature							X		X					X		X		X							
Outdoor Thermal Comfort																									
Perceived Temperature (PT)														X		X									
Predicted Mean Vote (PMV)		X		X			X						X		X	X				X		X			
Predicted Percentage of Dissatisfied (PPD)				X			X						X		X					X		X			
Physiological Equivalent Temperature (PET)							X							X		X		X							
Modified Physiological Equivalent Temperature (mPET)																X									
Universal Thermal Climate Index (UTCI)							X		X					X	X	X				X					
Standard Effective Temperature (SET)		X					X		X							X									
Major greenhouse gases											X[145]			X											
Carbon dioxide (CO_2)	X	X					X															X			
Carbon monoxide (CO)	X																					X			
Methane (CH_4)	X																					X			
Nitrogen oxides (NO_x)	X		X																			X			
Criteria pollutants														X											
Carbon monoxide (CO)	X																					X			
Nitrogen oxides (NO_x)	X		X				X															X			
Sulfur dioxide (SO_2)			X																						
Particulate Matter ($PM_{2.5}$, PM_{10})	X						X																		
Ozone (O_3)	X		X				X																		
Lead (Pb)																									
Ozone precursors																									
Methane (CH_4)	X																					X			
Non-methane volatile organic compounds (NMVOC)	X													X											
Ammonia (NH_3)			X											X											

Meteorological variables are provided with a weather data file.
ADMS Urban provides a "Normalised Building Volume" concept that defines the building density on average over a grid cell.
The tool requires only the surface roughness of the green area.
Meteorological variables are provided with a weather data file.
Fluent and all the general-purpose CFD simulation programs cannot import weather files. However, since it is a general-purpose CFD simulation program, it is possible to define, among others, temperature and radiation as boundary conditions.
Fluent requires additional equations or sub-models describing vegetation's physical processes to calculate vegetation properties.
Autodesk CFD and all the general-purpose CFD simulation programs cannot import weather files. However, since it is a general-purpose CFD simulation program, it is possible to define, among others, temperature and radiation as boundary conditions.
Autodesk CFD provides Temperature and Air velocity as outputs.
The model does not provide the possibility to import weather data files, but in the calculations, it allows us to consider the uncertainty caused by many elements like meteorology.
Meteorological variables are provided with a weather data file.
The model does not provide the possibility to import weather data files, but in the calculations, it allows us to consider the uncertainty caused by many elements like meteorology.
Meteorological variables are provided with a weather data file.
The model provides Meteo data for cities already loaded into the program. In the Meteo section, the user can define variables like the simulation's period of occurrence, temperature, and humidity.
MUKLIMO_3 does not allow the use of weather files. In contrast, the tool requires the definition of initial profiles for the wind, the air temperature, and the specific humidity at the start time of the simulation.
In the input file, there is the possibility to insert specific values for many variables like vegetation, buildings, and topography.
MUKLIMO analyzes the pollutants in general without defining those being analyzed.
The calculation method in the tool considers the Atmospheric absorption which depends on relative humidity and temperature. These variables can be set in the Calculation Parameters section.
OpenFOAM and all the general-purpose CFD simulation programs cannot import weather files. However, since it is a general-purpose CFD simulation program, it is possible to define, among others, temperature and radiation as boundary conditions.
PALM-4U is made of different components belonging to PALM, which is a numerical model. The weather data is directly obtained from PALM.
Meteorological variables are provided with a weather data file.
Geometries of the built and outdoor environment are not modeled inside the tool but are imported as STL files.
RayMan considers only the date as a meteorological variable. Therefore, date and elevation are important input data for radiation calculations.
RayMan can consider three obstacles: buildings, deciduous trees, and coniferous trees. For buildings, it is possible to model tilted roofs and walls, which can be disattached from the ground.
RayMan specifies the geographic location studied through a "location.lst" file inside the RayMan program folder. It is possible to add other and new locations to existing ones.
For trees, there are two different shapes. Deciduous trees have a cylindric trunk and ellipsoid crown, while coniferous trees have cone-shaped crowns.
Topography can be created inside the tool. In addition, topography data can be loaded in RayMan as a text file in a specific format.
scSTREAM and all the general-purpose CFD simulation programs cannot import weather files. However, since it is a general-purpose CFD simulation program, it is possible to define, among others, temperature and radiation as boundary conditions.
For the Built Environment, SOLWEIG allows uploading a Digital Surface Model of Ground and Building containing buildings' heights. In addition to the DSM file, a digital elevation model is also required.
Meteorological variables are provided with a weather data file.
Also, for the Outdoor Environment, a specific Ground cover grid file is required.
The tool has a module called Nord2000 Weather Input that allows the user to calculate the noise propagation under a more detailed meteorology. This model considers wind speed, wind direction, and lapse rate. Regarding the environment variables, the tool allows the input of air temperature, humidity, and pressure.
As input variables, SUEWS needs files that include all the most relevant information about the built environment, outdoor environment, and vegetation.
Meteorological parameters should be provided as monthly data.
The tool provides a meteorological database from meteorological stations. It is available only for French territory at the moment.
It is possible to provide a custom weather file provided that it is a text file written in the Windows Format, adopting the "space" character instead of "Tab."
UrbaWind allows importing terrain data, soil properties, and vegetation as STL. Once imported, the only thing that can be modified is the porosity of the layer imported according to the defined values provided by the tool.

The formers refer to the physical quantities characterizing the environmental conditions at a given computational unit (e.g., surface temperature, air temperature, wind speed, mean radiant temperature). The second group gathers different indices used for thermal comfort assessment, mainly in outdoor spaces (e.g., PET, UTCI) and enclosed spaces like PMV and PPD, which must be used with care and only if the subtended assumptions are not violated [56,57].

Next, the *environmental emissions,* beneficial for mitigation estimates to support climate resilience projects, are clustered into three groups: (i) *Major greenhouse gases*, which are the principal responsible for global warming, (ii) *Criteria pollutants*, which are common air pollutants with known health impacts according to the 1970 Clean Air Act[58], and (iii) Ozone precursors, which, in the presence of solar radiation, react with other chemical elements and form ozone, mainly in the troposphere.

The analysis of input variables is presented in Table 9. The table shows the intricate relationship between the tools and the meteorological variables. Most tools rely on weather data files to feed the simulations with accurate meteorological parameters. However, there are two ways of including weather data in the simulation: tools have it already loaded in a database, or data can be downloaded separately.

Most of the tools allow weather data to be imported, and the most frequent weather data format is the EnergyPlus Weather (EPW) format.

Nonetheless, within the group of general-purpose CFD simulation models, some tools do not directly import weather files. Instead, these models allow users to define specific parameters, such as air temperature as boundary conditions.

Moving from the meteorological variables to those belonging to the built and natural environment, one can observe that almost all the tools require defining the surface cover to distinguish the built environment from the natural. Material properties are widely considered essential for defining the case study features in the tools. Information about the vegetation is not very well handled: only a few tools can consider the vegetation, model it, and include it in the simulations.

From the point of view of the output variables, the most simulated are air temperature, relative humidity, and wind speed and direction. The mean radiant temperature is another relevant variable when outdoor thermal comfort needs to be assessed. Regarding outdoor thermal comfort, many indices can be computed. The Universal Thermal Climate Index (UTCI) and Physiological Equivalent Temperature (PET) are the most used. Finally, to not exclude air quality from the comparison, different pollutants have been considered and divided into three categories: major greenhouse gases, criteria pollutants, and ozone precursors. These pollutants are fully considered in the ADMS Temperature and Humidity model since it is an air quality model, while among the other tools, only Fluent, ENVO-met, PALM-4U, and TAS can consider some of them in their calculations.

3.4.3. Computational models

Microclimate simulation tools solve the governing equations of energy and mass balances by implementing different physical models and numerical schemes, which offer different modeling opportunities. The mass and energy balances, represented in Figure 1, are built upon atmospheric, soil and waterbody, vegetation, air quality, and noise models. The physical and mathematical models adopted by the different tools have been reported (Evaluation Framework Table 6 and Evaluation Framework Table 7).

Regarding the atmospheric models, different strategies are used to solve the governing equations of air convection (Direct Numerical Simulations (DNS), Large Eddy Simulation (LES), Detached Eddy Simulation (DES), Unsteady Reynolds-averaged Navier-Stokes (URANS), Reynolds-averaged Navier-Stokes (RANS), and Reynolds-averaged Simulation (RAS)) and the turbulence models, when needed (e.g., 2-equations turbulence kinetic energy (k-ε), Re-Normalization Group (RNG) k-ε, 2-equations k-ω turbulence), the net radiation exchange between the model surfaces (such as Averaged View Factor (AVF) model, Indexed View Factor (IVF) model, Indexed View Sphere (IVS) model, Sky View Factor (SVF) model), and the heat exchange with the sky via different sky models (Isotropic, Anisotropic, CIE Clear Sky, Uniform Cloud Sky). The soil model considers the equations and the features that characterize the behavior of terrains and their sensible and latent heat exchanges with the atmosphere (Energy balance at the ground level, Finite Difference Method (FDM), Discrete Element Method (DEM), Thermal RC-Network). Furthermore, waterbody models have also been scrutinized (Clapp-Hornberger soil hydraulic model, Buoyant Boussinesq Simple Foam, and Volume of Fluid (VOF) model). The Air quality model section is organized based on three different groups: dispersion models, photochemical models, and receptor models.

A few software tools offer the possibility to estimate a few performance aspects of buildings by solving the energy and mass balance at nodes characterizing thermal zones within buildings or implementing daylighting models or light transport algorithms.

The following tables (Table 6 and Table 7) describe the comparison of the tools regarding the numerical models implemented by each of them at the Urban scale (Table 6) and Building scale (Table 7). Once again, the tools show a great variety in their modeling approaches across the different physical processes investigated. At the Urban scale, general-purpose CFD programs showcase advanced algorithms and more flexibility regarding schemes implemented (e.g., wind flow, turbulence, and radiation) than other, more specific, tools. Provided that the urban scale can include different types of land surfaces, we also looked, among the tools collected, for those that can model the soil, water bodies, and vegetation.

To conclude with the urban scale, we included the possibility of modeling air pollution and noise. For air pollution, we considered dispersion, photochemical, and receptor schemes. The noise modeling schemes refer to the principal traffic/road, train, and industrial noise regulations.

It is important to note that noise propagation and lighting calculation tools are strictly topic-oriented, not including other schemes except those specific to noise propagation assessment or lighting studies.

Transitioning to the building scale, we considered different processes typical of the processes happening in the buildings. In this case, the number of tools that own such schemes (e.g., the surface temperature of walls and roofs, indoor air temperature, and daylighting) drops drastically.

The reason for this lies in the computational requirements that microclimate tools require to run and solve processes at the urban and building scales. Moreover, in some cases, the level of detail the tools offer is coarser than the one required to simulate the building scale.

3.4.4. Simulation settings

Given the inherent complexity of microclimate simulation and the high computationally expensive costs, microclimate simulation tools offer different customization options to end-users for choosing the most appropriate simulation setting. They refer to (i) *spatial resolution*, the minimum spatial unit used for solving governing equations; (ii) *spatial domain*, which deals with the dimension of the simulation scene; (iii) *typical period*, which refers to the usual simulated time for a run; (iv) *temporal resolution or timestep*, which is the fixed time interval by which a simulation advances.

Table 8 shows the table responsible for comparing the simulation settings of the tools, particularly on the temporal and spatial aspects.

Although it was impossible to identify the information in the table for some tools, it is still possible to observe some general trends. For instance, most tools allow choosing the model's proper horizontal resolution. This way, the model is more adaptable to different types of problems to be solved. Some tools use the same approach for the temporal resolution, particularly CDF: the number of iterations or time steps required to achieve the convergence level may vary according to the problem setup and the variables considered. ENVI-met stands out from this group, providing the possibility to increase the horizontal resolution up to 0.5 meters and change the time step, allowing the users to set it

Table 7
Computational Models at Urban Scale

	ADMS Temperature and Humidity Model	AKL FlowDesigner	ANSYS FLUENT	Autodesk CFD	CadnaA	DIALux evo	ENVI-met	iNoise	LadyBug + HoneyBee	MITHRA-SIG	MUKLIMO-3 Basic/Thermodynamic Version	NOISEMAP Five	OpenFOAM	PALM-4U	PHOENICS	RayMan	scSTREAM	SOLWEIG	SoundPLAN	STAR-CCM+	SUEWS	TAS	TownScope	UMI	UrbaWind (Meteodyn)
Urban Surface Energy Balance									X[182]												X[197]				
Atmospheric Model																									
Equations for solving Wind Flow	X[166]			X[175]																					
Direct Numerical Simulation (DNS)	X		X																						
Large Eddy Simulation (LES)		X	X	X									X	X			X			X					
Detached Eddy Simulation (DES)			X										X							X					
Unsteady Reynold-averaged Navier-Stokes (URANS)																									
Reynolds-averaged Navier-Stokes (RANS)			X	X			X				X			X						X					X
Reynolds-averaged simulation model (RAS)													X												
Equations for solving Turbulence	X[167]																								
Spalart-Allmaras model			X										X												
Eddy viscosity model			X								X		X												X
2-equations Turbulence kinetic energy model (k-ε)		X	X	X			X						X		X		X								X
Dinamic SGS-TKE														X											
Re-Normalisation Group (RNG) k-ε model			X	X											X		X								
2-equations k-ω Turbulence model			X	X																					
Shear-Stress Transport (SST) k-ω model			X	X									X		X										
Reynolds Stress Model (RSM)			X										X		X					X					
Reynolds-averaged simulation (RAS) model																									
Radiation Model			X[170]	X[176]									X[185]										X[199]		
Wall area approach											X														
Accurate In-Canopy Radiation Transfer scheme							X																		
Surface-to-Surface Radiation Model (S2S)				X										X	X										
Averaged View Factor (AVF) model							X[179]										X								
Indexed View Sphere (IVS) algorithm							X																		
Rapid Radiative Transfer Model (RRTM)														X[189]											
Simple Radiative Transfer Model																									
Rosseland diffusion model															X										
Solar ray tracing			X																						
P1 model			X										X		X[190]										
Sky View Factor (SVF)							X						X		X	X[193]	X	X				X			
Discrete Ordinates (DO) model			X																						
Finite Volume Discrete Ordinates (fvDOM) Method													X												
Clear-sky radiation model														X											
Sky model			X[171]								X[183]														
Isotropic																							X		
Anisotropic																						X			
Clearness Index																		X							
CIE Overcast Sky						X																			
CIE Clear Sky						X																			
Clear Sky without sun																									
Uniform cloudy sky																									
Climate sky (Perez)																									
Soil Model	X[168]		X[172]				X[180]						X[186]				X[194]								X[200]
Energy balance at ground level	X										X														
Finite Difference Method																									
Thermal RC-Network																									
SIMPLEST algorithm for solving Finite-Domain equations																									
Discrete element method (DEM)																									
Waterbody Model			X[172]	X[177]			X[180]				X		X[186]								X[198]				X[200]
Clapp–Hornberger soil hydraulic model							X																		
Buoyant Boussinesq Simple Foam															X										
Volume of fluid model (VOF)																	X								
Vegetation Model	X[169]		X[172]								X[184]		X[187]		X[191]		X[195]								X[200]
One dimensional (Only height)							X																		
Three dimensional (RAD - LAD)							X																		
Lindenmayer-System (L-System)							X																		
Air Quality Model																	X[196]								
Dispersion Modeling			X[173]				X[181]				X														
Steady-state plume model (AERMOD)																									
Refined point source Gaussian air quality model																									
Straight line Gaussian model																									
Modified box model																									
Gaussian plume model	X																								
Gaussian puff model																									
Short-range dispersion model																									
Steady-state Gaussian dispersion model																									
Non-steady-state Gaussian puff model																									
Sequential Gaussian plume model																									
Single source Gaussian plume model																									
Photochemical Modeling																									
Lagrangian trajectory model				X			X[181]						X	X	X[192]		X								
Eulerian grid model													X												
Receptor Modeling																									
Chemical Mass Balance (CMB)																									
Unmix																									
Positive Matrix Factorization (PMF)																									
Noise Modeling			X[174]		X[178]								X[188]												
NMPB2008 (octave and 1/3 of octave)										X									X						
Nord2000					X			X											X						
ISO 9613					X			X		X		X							X						
CNOSSOS-EU					X			X		X		X							X						
NMPB96 (XP S 31133)					X					X															
Harmonoise (1/3 of octave)					X					X															
BS5228					X							X							X						

ADMS adopts algorithms that account for friction velocity u*, roughness length z0, the distance z above the surface, and von Karman's constant k.
For turbulence, the formulae adopted are based on three different conditions of the ratio h/LMO. h represents the reference length scale, and LMO represents the Monin-Obukhov length.
The conditions considered refer to unstable (convective) conditions, near neutral flow, and stable conditions when the ratio is smaller than -0.3, between -0.3 and 1, and greater than 1, respectively.
ADMS 5, particularly ADMS-Urban, can consider the effects of buildings, complex terrains, and variable surface roughness. In addition, the tools allow using advanced street canyon and urban canopy flow modules.
Fluent has many radiation models, such as the P-1 Radiation Model, Rosseland Radiation Model, Discrete Transfer Radiation Model (DTRM), Discrete Ordinate (DO) Radiation Model, Surface-to-Surface Radiation Model (S2S), and Radiation in combusting flows.
In addition, the tools also provide a Solar load model that can be used to calculate radiation effects from the sun's rays that enter a computational domain. For this model, two options are available: Solar ray tracing and the DO model.

Fluent does not use a sky model to assess the clearness of the sky. Instead, it consdiers either a constant value, a value computed through the solar calculator within the tool, or a value obtained from a user-specified function called define_solar_intensity.
Since Fluent is a general-purpose CFD program, it allows rough modeling of soil, waterbodies, and vegetation. However, it is possible to couple Fluent's model with additional sub-models describing different physical processes.
Fluent can predict particle dispersion using the stochastic tracking and Particle cloud models.
Fluent provides different Broadband Noise source models: Proudman's Formula, The Jet Noise Source mode, The Boundary Layer Noise Source, Source Terms in the Linearized Euler Equations, and Source Terms in Lilley's Equation.
Autodesk CFD can solve both steady-state and transient modes.
Autodesk CFD has two approaches to calculate view factors: a hybrid ray-tracing/DO model and the second, which implies that an image of the surrounding element faces onto a sphere surrounding the element face being considered.
In addition, this method allows the inclusion of solar radiant heat flux in calculations.
Autodesk CFD has the Free Surface modeling option that is useful to simulate the interface between liquids and gases, an important aspect to be considered when studying phenomena like waves and spills.
CadnaA has been implemented with many calculation methods according to countries' regulations and directives. The main ones are presented in the table; the others can be found in the tool's user guide.
ENVI-met's Average View Factor (AVF) method for solving radiation is a three-dimensional ray tracing analysis performed for every cell.
ENVI-met's soil model is organized in 14 layers between the surface and its lower boundary at a depth of 2m. The exchange processes are simulated regarding heat and water transfer between layers.
The uppermost soil layer is considered 3-dimensional, while all the other layers are calculated only along a single vertical dimension. Therefore, the equation adopted for heat distribution and soil volumetric moisture content is a one-dimensional prognostic equation.
For natural soils, the hydraulic parameters considered in the equations volumetric water content η, its saturation value ηs, the hydraulic conductivity Kη, and the hydraulic diffusivity Dη. All the coefficients are calculated using the equations by Clapp-Hornberger.
ENVI-met adopts the standard advection-diffusion equation to solve gas/particle dispersion and deposition. In addition, a Lagrangian Stochastic Particle Model (LaStTraM), a post-processing tool, uses Envi-MET output to simulate concentration and flux footprints.
Since Ladybug is a collection of tools and Butterfly is the one that runs CFD simulations exploiting OpenFOAM capabilities, the features selected refer to those of OpenFOAM.
The sky model represents a sky cover value between 0 and 1. Cloudless sky has a 0 value, and full cloud cover equals 1.
The vegetation in the canopy model has three vertical layers: tree crown, tree trunk, and low vegetation. Grid cells with buildings include only low vegetation.
OpenFOAM has many radiation models, including the solar load model that can be coupled with fvDOM and viewFactor.
Refer to the ADMS annotation about turbulence for OpenFOAM soil and waterbodies models.
Inside the OpenFOAM's "Sources" library, three codes related to the Plant Canopy are stored: atmPlantCanopyTSource, atmPlantCanopyTurbSource, and atmPlantCanopyUSource.
These codes apply sources on temperature, turbulence, and velocity to incorporate the effects of plant canopy for atmospheric boundary layer modeling. They can be applied to any RAS turbulence model.
OpenFOAM provides a library called libAcoustics, developed to simulate far-field acoustics using Curle and FWH analogies with an integral approach.
The radiation model adopted is the RRTM for Global models, RRTMG.
PHOENICS adopts the P-1 T3 radiation model derived from IMMERSOL to produce a composite-radiosity model with radiant temperature as a dependent variable. This model is similar to the P1.
PHOENICS has a system called FOLIAGE, which helps analyze cooling and humidity effects from vegetation. It has many features, such as the possibility of specifying the mass transfer rate of moisture from the air.
GENTRA Particle Tracker is an add-on for PHOENICS that tracks particles moving through a field, solving the dispersed phase equations using Lagrangian methods.
RayMan also allows the use of the fish-eye image approach to approximate SVFs.
scSTREAM does not provide a specific soil model but allows the modeling of a porous media.
scSTREAM provides a Plant Canopy Model that accounts for the coefficient of friction and leaf area density (LAD).
In addition, the model simulates the cooling effect by the latent heat of vaporization on a leaf surface by using the fixed temperature and setting the amount of absorbed heat.
scSTREAM can simulate the behavior of particles depending on their characteristics (diameter, density, and sedimentation speed) and the action/reaction between particles and a fluid.
SUEWS adopts the urban energy balance equation proposed by *Oke, 1987*: $Q^* + Q_F = Q_H + Q_E + \Delta Q_S$
Q^* is the net all-wave radiation, Q_F the anthropogenic heat flux, Q_H the turbulent sensible heat flux, Q_E the latent heat flux, and ΔQ_S the net storage heat flux.
SUEWS adopts the urban water balance equation proposed by Grimmond et al., 1986: $P + I_e = E + R + \Delta S$
P is precipitation, I_e the water supplied by irrigation or street cleaning, E the evaporation, R the runoff (both above-ground and deep soil), ΔS the net change in water storage (including water in the soil and water held on the surface).
TownScope adopts spherical projections for calculating solar radiation.
Urbawind, like other CFD simulation tools, accounts for soil, waterbodies, and vegetation as porous media.

according to their needs. Finally, the typical period, i.e., the duration of the simulation, has been considered. While some tools indicate an hourly typical period, others allow the user to choose the simulation duration. In this case, ENVI-met suggests setting a minimum time of six hours so that the spin-up period does not affect the results.

Finally, the modalities of output reporting and the output representation have been conveyed to inform about the type of report each tool produced (e.g., comma-separated value reports, textual reports, plots) and how the output is primarily presented.

Table 10 shows that plots are the most common means of reporting simulation results. In addition, some tools can report results in Word, Excel, and PowerPoint files. Others can adopt web-based reports or table formats for more precise and immediate visualization of numerical results.

4. Conclusions and future perspectives

Cities and urban areas play a critical role in climate change. They host more than half of the world's population and the majority of societies' assets and economic activities. Therefore, cities are the major contributor to climate change, but at the same time, they are very vulnerable to its impacts. Given the increasingly fast escalation in frequency, magnitude, and duration of threatening climate change phenomena affecting severely human health, it is essential to understand better the complex interactions between different urban and environmental elements and find solutions to adapt and mitigate climate change. In particular, seeing the enormous burden on people's lives and the need to act urgently, a change in the paradigm is required, shifting from the global to the local scale and from individual actions to

Table 8
Computational Models at Building Level

	ADMS Temperature and Humidity Model	AKL FlowDesigner	ANSYS FLUENT	Autodesk CFD	CadnaA	DIALux evo	ENVI-met	iNoise	LadyBug + HoneyBee	MITHRA-SIG	MUKLIMO-3 Basic/Thermodynamic Version	NOISEMAP Five	OpenFOAM	PALM-4U	PHOENICS	RayMan	scSTREAM	SOLWEIG	SoundPLAN	STAR-CCM+	SUEWS	TAS	TownScope	UMI	UrbaWind (Meteodyn)
Building Surface Energy Balance									X[206]															X[206]	
Surface temperature of walls and roofs			X[201]										X[207]												
Steady-state energy balance		X		X							X				X		X								
Multiple-node transient model							X[203]							X			X								
Finite difference / volume method																	X								
Frequency domain																									
Time response factor		X		X																		X			
Indoor Air Temperature							X[204]								X[208]										
Dependent on airflow		X	X	X													X					X			
Dependent on surface heat coefficient													X	X			X								
Daylighting Model							X[205]																		
Daylight Factor (DF)						X																X			
Daylight Coefficient (DC) method																									
3-Phase method																									
4-Phase method																									
5-Phase method																									
Light Transport Algorithm (LTA)							X[205]																		
Radiosity						X[202]									X[209]							X[210]			
Forward Raytracing																									
Backwards Raytracing																									
Monte-Carlo-based raytracing			X																			X			
Path Tracing																									
Photon Mapping																									

Fluent allows for calculating the temperature of walls and defining heat transfer calculations at wall boundaries.
The software adopts a modified version of the Radiosity scheme.
Envi-MET provides a dynamic multiple-mode model made of seven nodes that allow the construction of up to three layers per wall or roof.
The facade's energy budget calculates the outside surface temperature and is iteratively adjusted until the balance of the energy budget equals zero.
The inside volumes of the buildings are treated as empty volumes filled with air to simplify the model. So, according to this simplification, indoor air temperature is estimated as a prognostic variable.
According to the multiple-node model adopted in Envi-MET, inside the building, the reflection of shortwave radiation and radiative transfers between inner walls are not accounted for when calculating the indoor surface temperature.
In addition, the net absorbed shortwave radiation at the inside node can be ignored, and the longwave radiation budget can be assumed tp be equal to zero. For this reason, neither the daylighting model nor the light transport algorithm is considered.
The Ladybug tools collection and UMI create, run, and visualize daylight simulations using Radiance. At the same time, other energy simulations are run with EnergyPlus. Specific features for the EnergyPlus model are presented in the work of Crawley et al.
As for Ansys Fluent, OpenFOAM also allows the calculation of the temperature of walls, defining heat transfer calculations at wall boundaries. In addition, OpenFOAM has many solvers for heat transfer analysis.
PHOENICS estimates the surface temperature to calculate the convective and conductive heat fluxes at the radiative zones.
In PHOENICS, Radiosity is called Composite Radiosity.
TAS has a link with Lumen Designer that allows calculating radiosity.

Table 9
Simulation Settings

	ADMS Temperature and Humidity Model	AKL FlowDesigner	ANSYS FLUENT	Autodesk CFD	CadnaA	DIALux evo	ENVI-met	iNoise	LadyBug + HoneyBee	MITHRA-SIG	MUKLIMO-3 Basic/Thermodynamic Version	NOISEMAP Five	OpenFOAM	PALM-4U	PHOENICS	RayMan	scSTREAM	SOLWEIG	SoundPLAN	STAR-CCM+	SUEWS	TAS	TownScope	UMI	UrbaWind (Meteodyn)
Simulation settings									X[218]																
Spatial resolution	X[211]											X[219]													
Minimum resolution							X[215]																		
User-selected resolution					X					X	X			X					X						X
Typical period	X[212]						X[216]																		
Sub-hourly																									
Hourly					X													X			X		X		
Daily										X						X[220]									
Monthly																									
User defined			X[214]	X[214]							X		X[214]	X	X[214]		X[214]			X[214]					X
Temporal resolution	X[213]																								
Variable time intervals											X														X
User-selected			X[214]	X[214]	X		X[217]			X	X		X[214]	X	X[214]		X[214]			X[214]					
Dynamically varying based on solution transients											X														

There are no limits to both vertical and horizontal spatial resolution.
The calculation refers to average times ranging from second to years.
The model is time-independent, so there are no time steps.
The number of iterations or time steps required to achieve the convergence level depends on the problem set-up and all the variables considered.
In ENVI-met, the user can change the spatial resolution of the project down to 0.5 m.
The simulation period can change based on the problem studied. It should be at least 6 hours so as not to be affected by the initialization.
ENVI-met provides a dynamical adaptation of the primary time step. This function is activated by default, but the user can set his time step according to the needs.
Each tool from the suite uses different simulation programs, such as EnergyPlus, OpenFOAM, OpenStudio, and Radiance. For this reason, please refer to OpenFOAM simulation settings, as EnergyPlus, OpenStudio, and Radiance are not included in the tables because they are outside this comparison's scope. For further details about these tools, please refer to the work of Crawley et al.
The horizontal resolution of the tool depends on the file imported from other design tools.
RayMan provides two types of periods for results: a Data table that provides only values selected in the input file window and a Daily data table that provides the same values for the data table but for every day of the year.

Table 10
Results Reporting

	ADMS Temperature and Humidity Model	AKL FlowDesigner	ANSYS FLUENT	Autodesk CFD	CadnaA	DIALux evo	ENVI-met	iNoise	LadyBug + HoneyBee	MITHRA-SIG	MUKLIMO-3 Basic/Thermodynamic Version	NOISEMAP Five	OpenFOAM	PALM-4U	PHOENICS	RayMan	scSTREAM	SOLWEIG	SoundPLAN	STAR-CCM+	SUEWS	TAS	TownScope	UMI	UrbaWind (Meteodyn)
Results reporting									X[221]				X[222]	X[223]											
Standard reports																			X			X			
Word files				X	X																	X			
Comma-separated or tab-separated value reports					X		X			X										X					
Text reports					X		X			X		X			X	X		X	X		X	X			X
HTML reports					X																				
Plots	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X		X	X			X	X	
Output representation									X[221]					X[223]											
Graphical	X		X	X	X	X	X	X	X	X	X	X	X		X[224]	X	X		X	X		X	X	X	X
Tabular			X	X	X		X		X	X	X	X			X[224]	X	X	X	X	X	X				X

All the tools from the collection produce a graphical output representation of the simulation run.
OpenFOAM has a native postprocessor tool named ParaView, but it is also possible to post-process results using Fluent and EnSight.
The model provides netCDF files as output. These file can be processed to obtain graphical outputs.
Graphical results are provided through a native package PHOTON.
Tabular results are provided in the RESULT file.

interdisciplinary and holistic ones which consider the human not as part of the process but as the main character for inverting the trend. Based on this holistic approach, research-based tools, particularly microclimate software tools, can help identify, link, and deal with different aspects of climate change. Hence, the main goal of this study was to collect, compare and contrast the modeling and simulation capabilities of microclimate software tools specifically to address the impacts of climate change on public health in the built environment. This article aims to provide a thorough, coherent, transparent, and unbiased overview of the capabilities of microclimate simulation tools developed and used so far for helping end-users to identify the most suitable tools for their specific analysis.

Leveraging the capabilities of the CIMO logic and the PRISMA methodology, a systematic literature review was conducted to identify which tools have been used to analyze and simulate the mass and energy flows of urban systems and support the performance assessment of adaptation strategies against climate change. Based on this, an evaluation framework has been established to compare the tools and highlight their features and capabilities concerning different evaluation aspects.

Therefore, this work suggests that through these tools is possible to investigate many aspects related to urban health, the built environment, climate change, and human comfort by testing different adaptation strategies. Furthermore, practitioners, researchers, and users of various fields can use these tools to implement and support their activities. By sharing ideas and findings, we can obtain a cross-cutting vision of the issue of climate change in the built environment which will enrich and increase our knowledge to gain a holistic understanding of city behavior. Nonetheless, it's worth noting that in most cases, to understand better the impacts of microclimate on buildings or on street comfort, a modeling chain combining two or more tools is used. That happens because most programs focus on modeling specific phenomena happening in the built environment.

On the other hand, those tools that compute the different mass and heat flows and characterize the built environment as an all-in-one computational platform carry a trade-off of physical representation, accuracy, and computational cost. It is encouraging to see that many tools leverage interoperability to facilitate data sharing and model enrichment for practical decision-making support. Nevertheless, despite these tools' enormous capabilities, users must carefully assess their implementation. Some present substantial limitations and approximations in the numerical solvers, while others do not consider fundamental variables like anthropogenic heat loads, making the results unreliable.

Finally, looking at the future development in the field, two main goals seem to be pivotal. First, much more effort should be put into trying to simplify the interoperability of the tools to make it easier to gain a holistic understanding of city behavior. Secondly, it would be desirable to exploit more thoroughly urban digital twins to enable advanced data processing from different strata combining simulated data with actual observations. The extraordinary richness of output values provided by the microclimate simulation tools and the increasing wealth of data from sensors installed in the built environment would offer several opportunities to detect environmental anomalies and develop operational procedures to enhance the climate resilience of urban areas.

Limitations of this work are the possible and unintentional omission of articles containing other relevant tools, in addition to those presented, not spotted by the literature search and not known to the authors. However, the PRISMA methodology is designed to minimize this kind of error.

CRediT authorship contribution statement

Giandomenico Vurro: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Salvatore Carlucci:** Writing – review & editing, Supervision, Resources, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix 1. Description of Tools

ADMS temperature and humidity model version 5.0.1 [59–62]

ADMS Temperature and Humidity Model (hereafter ADMS-TH) (https://cerc.co.uk/environmental-software/ADMS-Urban-model.html) supplements the ADMS Urban software. It predicts spatial changes in temperature and humidity resulting from spatial variations in land use and anthropogenic heat emissions. The variations in temperature and humidity are described as turbulences of the input wind values. The tool takes input data from four sources: Detailed land-use dataset, building data, traffic data, and meteorological measurements or mesoscale model output. Detailed land-use datasets and building data provide ADMS-TH with two parameters: (i) those that modify humidity and temperature due to land use and (ii) parameters that increment temperature and humidity due to anthropogenic heat sources. Traffic data provide the software with only inputs linked to anthropogenic heat emissions.

The model calculates the spatial heat flux variation due to spatial variations of the input land-use parameters. From these variations, ADMS-TH determines a temperature and humidity field. To do this, the model solves linearized forms of the heat transfer equations with appropriate boundary conditions.

The model, however, provides the possibility to input directly the spatially varying heat flux perturbations. Moreover, the dispersion of anthropogenic heat emissions is included in the output temperature perturbations. After that, it is modeled and converted into temperature increments.

The model calculates the output temperature and humidity for specific receptor locations on a grid of values covering the entire domain, considering a range of vertical heights above the ground. These outputs are available for both hour-by-hour calculations and long-term averages.

AKL FlowDesigner version 2021 [63]

AKL FlowDesigner (https://www.akl.co.jp/en/) is a CFD computational tool that evaluates wind flows. The 3D model can be easily added as a plugin from many modeling tools such as Autodesk® Revit, Graphisoft Archicad®, Rhinoceros®, and Google SketchUp. The software can provide cross-ventilation and wind simulations for exterior urban environments and internal building spaces. In addition, it allows modifying materials according to their physical and thermal properties. The tool provides various optional tools, such as the Solar analysis module, which can evaluate thermal comfort for indoor and outdoor environments. Furthermore, the tool can import weather data (e.g., EPW files).

ANSYS Fluent version 2023 R2 [64–67]

ANSYS Fluent (https://www.ansys.com/products/fluids/ansys-fluent) can model fluid flow, heat transfer, and chemical reactions. Moreover, it can be used for complex geometries. The tool allows total mesh management. This way, leveraging the model's capacity to generate easily unstructured mesh from complex geometries, flow problems are solved. Different meshes are supported (i.e., 2D, 3D, and mixed (hybrid)). In addition, ANSYS Fluent also allows sharpening or coarsening mesh based on the flow solution. The program has two modes: meshing mode and solution mode. In the meshing mode, it can read meshes or, for 3D geometries, create them. In the solution mode, it is possible to set boundary conditions, define fluid properties, execute the simulation, refine the mesh, post-process, and view results. ANSYS Fluent serial solver handles file input and output, data storage, and flow field calculations, relying on a single solver process on a computer. In contrast, Fluent's parallel solver allows computing a simulation using multiple processes running on a single computer or different computers in a network. This computer program is designed for incompressible fluid-flow simulations in complex geometries. Fluent can simulate, among others, heat transfer. This includes forced, natural, and mixed convection. The model can also be used for conjugate (solid/fluid) heat transfer and radiation. In addition, Fluent adopts a lagrangian trajectory calculation to analyze dispersed phases (particles/droplets/bubbles), including coupling with continuous phase and spray modeling. Finally, the tool provides acoustic models for predicting flow-induced noise and simulations using a material property database.

Autodesk CFD version2023 [68–70]

Autodesk CFD (https://www.autodesk.com/products/cfd/overview) Autodesk is software that provides computational fluid dynamics features and thermal simulation tools. The tool can be opened both from Autodesk Inventor or launched independently. The possibility of being opened from a CAD package provides consistency between simulations, reducing setup time for design iterations. On the other hand, when the CAD is imported directly into Autodesk CFD, a model assessment toolkit can be activated to assist during import. The software can model multi-component fluids or gases and steady or unsteady flows. In addition, it has a built-in material database a many pre-and-post processing tools. Autodesk CFD is a finite element tool; for this reason, meshes are triangular, and volume elements are set tetrahedral by default. However, it is possible to generate meshes whose density can be correctly set through a set of tools in the software. The tool simulates different fluid-flow conditions: (i) steady-state (time-independent) and (ii) transient (time-varying). In addition, Lagrangian particle tracking, and compressible and incompressible flows, are considered in the software.

Heat transfer is also considered; the tool evaluates conduction and conjugate heat transfer, radiation heat transfer, solar loading, forced, natural, mixed convection, and thermal comfort calculation.

CadnaA version 2023 MR2 [71–73]

CadnaA is an advanced software tool designed for the assessment and prediction of environmental noise. It can analyze noise pollution in urban areas, industrial zones, and transportation infrastructure. Some key features are noise mapping, enabling the users to predict noise distribution in detail, and source modeling, allowing the simulation of various noise sources with specific parameters. The tool supports regulatory compliance by assessing noise levels against standards. Moreover, it facilitates scenario analysis for effective noise impact reduction strategies. CadnaA is used for multiple applications such as urban planning, infrastructure development, and environmental impact assessment.

CityFFD [74–76]

CityFFD (City Fast Fluid Dynamics) [74]is an urban microclimate model. This tool is based on the fractional step method and semi-Lagrangian algorithm. In addition, it adopts the LES turbulence model, particularly the Smargorinsky LES method (SGS). The pre-processing process is divided into the 3D urban geometry generation and meshing and boundary conditions. The former is obtained from OpenStreetMap (OSM) and Google Earth API. OSM provides 3D separate building geometry, while Google Earth includes vegetation, terrain, and body sources. These data are then converted into an STL file. The meshing is defined through a CFDOEditor, a grid generator, and the boundary conditions are set with CityBEM and EnergyPlus. In addition, CityFFD can also interact with Global Environmental Multiscale Model (GEM) and WRF. Once the input files are set, the simulation can be run, and the output obtained can be used with Paraview, Tecplot, and OpenGL. This tool has not been included in the evaluation framework because the executable file was unavailable at the time of the review.

DIALux evo version12 [77–79]

DIALux evo is a lighting design software widely used in architectural and urban planning contexts. It is characterized by advanced lighting design capabilities that allow users to create complex lighting plans for both indoor and outdoor spaces. In particular, thanks to the 3D visualization tool and the daylight simulation feature, it is possible to obtain a realistic preview of the lighting effects and assess the interplay between natural and artificial lighting, promoting optimal illumination and energy efficiency. In addition, the software provides insights into the energy consumption associated with proposed lighting schemes. Finally, DIALux streamlines the documentation process by generating comprehensive reports that cover different aspects like lighting calculations, technical specifications and visualization details.

ENVI-met version 5.5 [80–84]

ENVI-met (https://www.envi-met.com) is a three-dimensional, non-hydrostatic model for simulating a micro-climate, mainly in the urban canyon, considering physical interactions between solid surfaces (e.g., ground and building surfaces), vegetation, and air. ENVI-met is a CFD software that implements the finite difference method (FDM) discretization scheme, employing advanced numerical algorithms to solve airflow governing equations (i.e., conservation of mass, momentum, thermal energy). Furthermore, the tool also considers the concentration of chemical species, turbulence parameters, and particle dispersion. The software provides many parameters as input. For instance, relative humidity and wind properties like speed, direction, and temperature are considered. Furthermore, the description of the built environment is simplified, considering only structured grids and cartesian geometries. Still, the thermophysical properties of soil, as well as building materials and vegetation, are also adopted in the simulations. Finally, ENVI-met is equipped with personal parameters related to pedestrians (i.e., metabolic rates and clothing insulation) taken into account when BIO-met is employed. The tool runs an iterative solution that produces many outputs. They are helpful for studying differences in temperature, relative humidity, pollutant concentration, turbulence parameters, wind speed, and outdoor thermal comfort indicators. Among those are the Universal Thermal Climate Index (UTCI), Predicted Mean Vote (PMV), and mean radiant temperature. ENVI-met's background system consists of submodels specifically adopted for solving unique physical mechanisms:

1. Long and short-wave radiation fluxes, accounting for shading,
2. Radiation reflection from building facades, ground materials, and vegetation,
3. Evapotranspiration and sensible heat fluxes from vegetation,
4. Evaporation from water surfaces,
5. Chemical species' propagation,
6. Particles' dispersion,
7. Heat and water transfer within the soil mass,
8. Body/skin airflow interactions for thermal comfort calculations.

This tool is handy for predicting and evaluating UHI effects within the urban canopy with reasonable accuracy, provided that the model settings are correctly defined.

iNoise version 2024 [85,86]

iNoise is a software tool designed for environmental noise assessment. It can model various noise sources in realistic scenarios and provide detailed insights into potential impacts. Leveraging advanced algorithms, it simulates noise propagation, considering factors like topography and structures (e.g., roads and buildings) for precise predictions at different locations. Furthermore, the model creates a noise map providing a visual representation of the noise level distributions in specific areas to improve the understanding of the results. The tool features different visualization tools, such as maps, graphs, and charts, aiming at improving the interpretation and readability of the noise assessment results. Finally, the model can produce scenario analysis to evaluate scenarios and mitigation strategies and define optimal strategies for noise impact reduction

Ladybug Tools version 1.7 [87–90]

Ladybug Tools (https://www.ladybug.tools) is a suite of four tools specialized in different aspects useful for environmental building design. The tools are Ladybug, Honeybee, Butterfly, and Dragonfly. Ladybug imports standard EnergyPlus weather data files (.EPW) into Grasshopper and Dynamo. It performs analysis of climate data providing many different 2D and 3D results such as climate data plots, sun path graphics, shadow studies, radiation studies, adaptive comfort charts, and outdoor thermal comfort evaluations. Honeybee relies on Radiance and energy models such as EnergyPlus/OpenStudio to create, run and visualize the result of radiation and daylight simulations. Honeybee links the Grasshopper/Rhino CAD environment to these engines to make this possible. Butterfly is the CFD tool of the suite. It is a Grasshopper/Dynamo plugin and object-oriented python library that creates and runs CFD simulations through OpenFOAM. The strength of Butterfly is its ability to export the geometry to OpenFOAM quickly and then run several types of airflow simulations that can be useful to building design. Finally, the last member of the suite is Dragonfly, which allows the creation of district-scale energy models for energy simulation, electrical stimulation, renewables optimization, and urban heat island modeling. Again, as previously stated, these tools leverage OpenStudio and EnergyPlus to run energy simulations. In addition, Dragonfly relies on the Urban Weather Generator (UWG) to morph rural EPW files to evaluate and analyze the effects of UHI.

MITHRA-SIG version 5.6 [91–93]

MITHRA-SIG is a software module of the MITHRA-Suite. It is designed to simulate noise propagation from stationary and mobile sources. For this reason, it can be used for assessing noise propagation from roads, rail (e.g., train and tramway), and industry. The calculations leverage the next-generation engines, such as the ray tracing and physics engines dedicated to acoustics. In addition, the model features a dynamic visualization of the results, allowing create sophisticated maps in PDF format, export data for web display, and visualization in Google Earth thanks to the KML format. Another important characteristic of the software is the full integration between GIS and the calculation engine. Moreover, the model can import/export data in many different formats, like GIS, CAD, database, and graphic formats.

MUKLIMO_3 Basic Version/Thermodynamic Version [94–97]

MUKLIMO_3 (https://www.dwd.de/EN/ourservices/muklimo_thermodynamic/muklimo_thermodynamic.html) is the abbreviation of the Microscale Urban Climate Model, a 3-dimensional model. This model primarily aims to evaluate and calculate stationary wind and pollutant fields in small-scale model areas with block-shaped obstacles. These obstacles represent buildings but can also be edited and shaped to represent orographic structures. In addition, the modeling of trees is considered. The basic version of MUKLIMO_3 does not solve thermodynamic processes, which are solved by the Thermodynamic version. The software has a graphic user interface that enriches the calculation model written in Fortran. In addition, the graphical user interface has some visual elements that allow animation of the simulations. MUKLIMO_3 basic version has been improved with a Eulerian dispersion model that allows simulating the propagation of chemical inert air admixtures. The tool adopts the stream function vorticity to solve prognostic equations for the velocity components, also known as the stream function method. Compared to the basic version, the thermodynamic version of the tool takes into account budget equations for heat and moisture within the atmosphere. A one-dimensional soil model with prognostic equations for heat and volumetric water content is coupled to the atmosphere using an interface model representing the low vegetation. As in the basic version of the model, the flow function's vorticity method is adopted to integrate the atmospheric flow equation. On the other hand, unresolved built-up areas and forests are treated numerically and coupled with atmospheric heat and moisture balance equations for surfaces' heat, radiation, and water vapor.

NOISEMAP Five version 5.2.10 [98,99]

NOISEMAP Five is a software designed for environmental noise mapping. It can analyze different types of open-air noise, including road traffic noise, railway noise, and construction noise. The model, for its calculations, strictly complies with many different regulations, including ISO 9613. The model can simulate vast areas that can be directly converted from a GIS shapefile or DXF format. Otherwise, the tool provides the option of drawing the area of study. NOISEMAP Five generates a solid view of the noise model with all the noise levels at the topographical location and specific receivers. There's also the possibility of comparing different scenarios by editing the baseline to create new ones.

OpenFOAM version 2312 [100–102]

OpenFOAM (https://www.openfoam.com) is a C++ library used to create executables. These executables can be divided into two categories: solvers and utilities. The former solves specific problems in continuum mechanics, and the latter is designed to perform tasks that require data manipulation. The user itself can create solvers and utilities. The software is equipped with pre-and post-processing environments. OpenFOAM is a numerical simulation software with extensive CFD and multi-physics capabilities. The model uses a Polyhedral Finite Volume Method for discretization. In addition, the Finite Element Method ensures the automatic mesh motion, and the Lagrangian particle tracking is pursued by adopting the Finite Area Method (2-D FVM on curved surfaces). Finally, the physics model can be implemented through equation mimicking. The tool can study incompressible and compressible flow through segregated pressure-based algorithms. Furthermore, heat transfer is analyzed according to buoyancy-driven flows, and conjugate heat transfer is also considered. RANS are considered using the 2-equations Reynolds turbulence stress model (RSTM) for turbulent flows. Moreover, OpenFOAM has full LES capability. In conclusion, by default, the tool defines a mesh of arbitrary polyhedral cells in 3-D, bounded by random polygonal faces. This way, the cells can have an unlimited number of faces for whose there is no limitation on the number of edges nor any restriction on its alignment. This kind of mesh offers a great range of freedom in mesh generation and manipulation, in particular when the geometry of the model is complex or changes over time. On the other hand, the downside of this freedom comes out when converting meshes generated with conventional tools.

PALM-4U version 6.0 [103–105]

PALM-4U (Parallelized Large-Eddy Simulation Model for Urban Applications) is a component of the PALM model designed for simulating urban atmospheric boundary layers. It is mostly used for academic research and for practical city planning related to urban microclimate and climate change. The model, besides the turbulence-resolving LES mode, features a Reynolds-averaged Navier Stokes (RANS) type turbulence parameterization. To run the simulations, PALM-4U requires some boundary conditions that can be provided by larger-scale models' output. The model has the capacity to solve the energy balance equation for all the different types of surfaces present in the area of the study. In addition, a multi-layer soil model has been implemented to account for the vertical diffusion of heat and water transport in the soil. For the representation of the urban surface elements, the model includes an adapted version of the land surface scheme, which consists of an energy balance solver for the surface temperature and a multi-layer wall material model. PALM-4U can also calculate indoor climate and building energy demand, consider the radiative transfer in the urban canopy layer, and run chemistry simulations by considering chemical species as Eulerian concentration fields that may react with each other. Finally, the model can evaluate the human thermal and wind comfort/stress producing some standard biometeorological thermal indices like PET, PT, and UTCI.

PHOENICS version 1.0 2023 [106–108]

PHOENICS (https://www.cham.co.uk/phoenics.php) is a general-purpose software CFD package for studying fluid flows inside and around engines, buildings, and human beings and predicting temperature changes and chemical and physical composition. The model has similar modeling features and capabilities for modeling airflows within the urban canopy to those of Ansys Fluent and CFX. PHOENICS is a CFD program that can solve most conservation equations for mass, momentum, heat, chemical species, and turbulent parameters. Microclimate parameters such as relative humidity, wind speed, turbulence intensity, and temperature can be produced as output. The tool can also incorporate other physical models, such as evapotranspiration from vegetation. A strength of PHOENICS is the opportunity provided to users to access the source Fortran-based code, thus allowing them to incorporate user-defined models. It has various models for simulating turbulence, heat, and radiation transfer. The model is not a microclimate-oriented tool, so a high level of knowledge is required in computing and transport phenomena to use it for microscale simulations. For complex geometries, PHOENICS adopts either a Body-Fitted or a hexahedral-unstructured grid. In addition, the software has implemented a plant canopy module, FOLIAGE, to consider vegetation evaporation phenomena.

RayMan version 1.2 [109–112]

RayMan (https://www.urbanclimate.net/rayman/) RayMan is a micro-scale model that calculates radiation fluxes in simple and complex environments. The tool allows for estimating the Mean Radiant Temperature, an important parameter related to calculating biometeorological indices like PT, UTCI, and PET. It is a variant of energy balance models and mainly calculates the conservation of radiant heat between the human skin and its environment. In RayMan, all the calculations are performed for one point because of its one-dimensional nature. Moreover, the tool follows the time-independent diagnostic approach. Thanks to the graphical user interface, the user can control all the functions and settings. In addition, the tool can run calculations for long datasets covering several years in high temporal resolution. Finally, RayMan requires only a few standard meteorological inputs to run simulations. RayMan can determine the Solar View Factors (SVF) using Fish-eye images, free drawing of the horizon limitation, a topographic raster, or an obstacle dataset. The obstacle dataset is made of particular vector files based on semicolon-delimited text files that can be created manually using the obstacle editor inside the tool or automatically based on shapefiles using the Quantum GIS plugin "Shp to Obs."

Another essential input parameter is global radiation, specified as a fixed input parameter, part of a meteorological data file, or calculated according to time, date, geographic location, and a cloud cover observation. Once the initial global radiation is determined from these parameters, it is corrected by SVF and shading. It should be emphasized that RayMan does not consider the evapotranspiration effects of vegetation but considers trees as mere obstacles. In addition, wind-induced effects and turbulence flow are also ignored.

scSTREAM version 2022.1 [113–115]

scSTREAM is a computational fluid dynamics software. It is designed to simulate fluid flow and heat transfer in complex geometries. The model leverages the structured Cartesian mesh to streamline grid generation and enhance the efficiency of the simulations. The thermal analysis capabilities of the model allow the users to model and simulate heat transfer processes as well as temperature distributions in many different fields of application. The software interface supports BIM 2.0. Autodesk Revit and GRAPHISOFT ARCHICAD have a direct interface through which specific parts can be imported directly into scSTREAM. The software can also calculate the illuminance of various types of lights, such as daylight through a building's window. The solar radiation is controlled by climate data provided by ASHRAE and NEDO. By setting values for longitude, latitude, date, and time, the solar altitude and the azimuth are calculated automatically.

SOLWEIG version 2022a [116,117]

SOLWEIG (Solar and Longwave Environmental Irradiance Geometry-model) (https://www.gu.se/en/earth-sciences/software-download#SOLWEIG) is a radiation model that can simulate three-dimensional daytime radiation fluxes and mean radiant temperature in complex urban settings. This model can be a module of the Urban Multi-scale Environmental Predictor (UMEP) or a stand-alone processing tool. SOLWEIG simulates 3D radiation fluxes and the mean radiant temperature. The simulated MRT is generated by modeling short- and long-wave radiation fluxes in six directions: upwards, downwards, and from the four cardinal points, including the angular factors. The model does not consider the velocity pattern in the domain of interest nor its fluctuations (turbulence). In addition, SOLWEIG does not calculate evapotranspiration from vegetation.

SoundPLAN version 9.0 [71,118]

SoundPLAN is a noise propagation modeling software which employs advanced algorithms to simulate how noise propagates in the environment. The model considers many factors like topography, building structures, and ground features allowing accurate predictions of noise levels at different locations. SoundPLAN features an array of visualization tools, including maps, graphs, and charts improving users' ability to interpret the result. The tool supports data integration, permitting the incorporation of various data sources such GIS and measurement data. Finally, SoundPLAN can also produce scenario analysis providing different noise reduction strategies and mitigation measures.

STAR-CCM+ version 2302 [119–122]

STAR-CCM+ (https://www.femto.eu/star-ccm/#contact) is a Computational Aided Engineering (CAE) tool to solve multidisciplinary fluid and solid continuum mechanics problems. Users can import CAD drawings, create new projects using the built-in CAD modeling tools, or import mesh from third-party tools. The tool provides a wide range of physics models and methods for solving many phenomena, such as turbulence, heat transfer, and multi-phase fluid flow. The software's solver capability allows for managing laminar or turbulent flows, incompressible and compressible flows, porous interfaces or volumes, conduction, convection, radiation, and reacting flows and motion. Like many other tools, STAR-CCM+ has a material database divided into many categories (e.g., solid, liquid, gas, and electrochemical species) and various turbulence modeling options, including RANS, DES, and LES models. The mesh-based software can handle tetrahedral, polyhedral, and hexahedral (trimmed) meshes.

SUEWS version 2020a [123–126]

Surface Urban Energy and Water Balance Scheme (SUEWS) (https://suews-docs.readthedocs.io/en/latest/) is a neighborhood-scale or local-scale model that simulates urban radiation and water balances using measurements of meteorological variables, like precipitation and temperature, plus information about the surface cover, such as vegetation and impervious surfaces. The model also simulates evaporation from urban surfaces adopting an evaporation-interception approach. The model requires the classification of the land cover for each grid cell. The classification considers non-vegetated areas, vegetation, water, and snow. For each category, it is possible to identify surface types, including paved surfaces, buildings, grass, water, and snow. In every time step, the state of the surface is calculated by running the water balance equation of the canopy, in which the evaporation is considered using the Penman-Monteith equation. Also, the soil moisture below each surface type is taken into account. The user can define the model time step, but a five-minute time step is recommended. The model provides the components of radiation and energy balance for each surface, in addition to surface and soil wetness, runoff, and drainage.

TAS version 9.5.6 [127]

Tas (https://www.edsl.net/tas-engineering/) is a building modeling and simulation tool capable of performing the thermal performance of buildings and their systems. The tool consists of several modules:

- TAS 3D Modeller deals with the geometry creation of the model and evaluation of daylighting using radiosity and ray tracing,
- TAS Building Simulator manages the building information modeling and the simulation program; TAS Results Viewer provides tabular, graphical, and 3D results of building loads,
- TAS Systems is designed for HVAC design and simulation; TAS Ambiens is a 2D CFD module that models buildings' airflow.

The tool has a 3D graphics-based geometry input that allows a linkage to CAD drawings. In addition, it can easily communicate with EnergyPlus and EnergyPlus-based tools through IDF files. In addition, gbXML files are also supported, allowing import from third-party programs. The Ambiens module, the 2D CFD package, produces space microclimate at the cross-section level evaluating radiant temperature from surfaces, local speed, and local airflow temperature, humidity, and metabolic rate.

TownScope version 3.4.1 [128]

TownScope (http://www.umr-cnrm.fr/surfex/spip.php?rubrique142) is a CAD-based tool that can simulate spatial variations of solar access and mean radiant temperature in complex urban environments. Users can evaluate direct, diffuse, and reflected solar radiation, assess human thermal comfort in urban open spaces, and obtain a perceptive quality of urban areas through sky opening, view lengths, and visibility analysis. Thermal comfort parameters can only be calculated daily, monthly, or annually.

UMI version 3.0 [129]

The Urban Modeling Interface (UMI) (https://web.mit.edu/sustainabledesignlab/projects/umi/index.html) is a platform to evaluate the environmental performance of neighborhoods and cities. The tool considers operational and embodied energy use, neighborhood walkability, and access to daylight. The platform is a design environment for Rhinoceros 3D but also includes an application programming interface (API) that allows adding additional performance modules and metrics.

UrbaWind (Meteodyn) version 3.3 [130–132]

UrbaWind (https://meteodyn.com/business-sectors/microclimate-and-urban-planning/13-urba-wind.html) is a tool developed by Meteodyn to evaluate the effects of wind within the city and its microclimate. The CFD-based tool allows for computing local wind and modeling airflows in 3D. In addition, it considers pedestrian wind comfort by assessing different standards of comfort depending on the country of reference. It analyzes natural ventilation, optimizing the positioning and the nature of openings; it estimates potential energy production from wind, allowing the positioning of small wind turbines. The software solves RANS equations using the turbulent viscosity model, automatically generating boundary conditions. A "Blasius-type" ground law has been implemented to describe the frictions at surfaces (ground and buildings). First, a mesh is created by following the direction of the wind. The domain size is automatically generated to keep the minimum distance between buildings and boundaries at six times the height of the tallest building in the simulation. The mesh that has been created is Cartesian and with automatic refinement near the ground, obstacles, and at result point locations.

References

[1] A.D. von Moos, World Meteorological Organization., Climate and urban development, World Meteorological Organization, 1996.
[2] P.D. United Nations, Department of Economic and Social Affairs, World Population Prospects 2019: Data Booklet, 2019.
[3] Ionesco, Dina, Mokhnacheva, Daria, Gemenne, François, The Atlas of Environmental Migration, 2016.
[4] U. (United N.D. Programme), Human Development Report 2009, UNDP (United Nations Development Programme) (2009).
[5] W.N. Adger, A.S. Crépin, C. Folke, D. Ospina, F.S. Chapin, K. Segerson, K.C. Seto, J.M. Anderies, S. Barrett, E.M. Bennett, G. Daily, T. Elmqvist, J. Fischer, N. Kautsky, S.A. Levin, J.F. Shogren, J. van den Bergh, B. Walker, J. Wilen, Urbanization, Migration, and Adaptation to Climate Change, One Earth 3 (2020) 396–399, https://doi.org/10.1016/j.oneear.2020.09.016.
[6] A. Baklanov, L.T. Molina, M. Gauss, Megacities, air quality and climate, Atmos Environ 126 (2016) 235–249, https://doi.org/10.1016/j.atmosenv.2015.11.059.
[7] C. Giannaros, A. Nenes, T.M. Giannaros, K. Kourtidis, D. Melas, A comprehensive approach for the simulation of the Urban Heat Island effect with the WRF/SLUCM modeling system: the case of Athens (Greece), Atmos Res 201 (2018) 86–101, https://doi.org/10.1016/j.atmosres.2017.10.015.
[8] UN HABITAT, Urban Energy, (2020). https://unhabitat.org/topic/energy (accessed July 2, 2022).
[9] I. Ribeiro, A. Martilli, M. Falls, A. Zonato, G. Villalba, Highly resolved WRF-BEP/BEM simulations over Barcelona urban area with LCZ, Atmos Res 248 (2021), https://doi.org/10.1016/j.atmosres.2020.105220.
[10] K.H. Schluenzen, S. Grimmond, A. Baklanov, Guidance to Measuring, Modelling and Monitoring the Canopy Layer Urban Heat Island, in: EMS Annual Meeting 2021, 2021.
[11] H. Hans-O. Pörtner , Debra C. Roberts, Climate Change 2022 - Impacts, Adaptation and Vulnerability - Summary for Policymakers, 2022.
[12] G. Ulpiani, M. Zinzi, Introducing the Built Environment in a Changing Climate: Interactions, Challenges, and Perspectives, (2021). 10.3390/cli9070104.
[13] G. Ulpiani, On the linkage between urban heat island and urban pollution island: Three-decade literature review towards a conceptual framework, Sci. Total Environ. 751 (2021), https://doi.org/10.1016/j.scitotenv.2020.141727.
[14] I. Kousis, A.L. Pisello, For the mitigation of urban heat island and urban noise island: two simultaneous sides of urban discomfort, Environ. Res. Lett. 15 (2020) 103004, https://doi.org/10.1088/1748-9326/abaa0d.
[15] D. Bristow, C. Kennedy, Why Do Cities Grow? Insights from Nonequilibrium Thermodynamics at the Urban and Global Scales, J Ind Ecol 19 (2015) 211–221, https://doi.org/10.1111/jiec.12239.
[16] M. Palme, A. Salvati, Urban Microclimate Modelling for Comfort and Energy Studies, Springer International Publishing, Cham, 2021. 10.1007/978-3-030-65421-4.
[17] N. Filchakova, D. Robinson, J.L. Scartezzini, Quo vadis thermodynamics and the city: A critical review of applications of thermodynamic methods to urban systems, Int. J. Ecodyn. 2 (2007) 222–230, https://doi.org/10.2495/ECO-V2-N4-222-230.
[18] N. Marchettini, F.M. Pulselli, E. Tiezzi, Entropy and the city, WIT Trans. Ecol. Environ. 93 (2006) 263–272, https://doi.org/10.2495/SC060251.
[19] R. Pelorosso, F. Gobattoni, A. Leone, The low-entropy city: A thermodynamic approach to reconnect urban systems with nature, Landsc Urban Plan 168 (2017) 22–30, https://doi.org/10.1016/j.landurbplan.2017.10.002.
[20] T.R. Oke, G. Mills, A. Christen, J.A. Voogt, Urban climates, Cambridge University Press (2017), https://doi.org/10.1017/9781139016476.
[21] I. Prigogine, I. Stegers, Order Out of Chaos, Bantam, 1984.
[22] B. Purvis, Y. Mao, D. Robinson, Entropy and its application to urban systems, Entropy 21 (2019), https://doi.org/10.3390/e21010056.
[23] A. Wolman, The metabolism of cities, Sci Am 213 (1965) 178–193.
[24] S. Derrible, L. Cheah, M. Arora, L.W. Yeow, Springer Singapore (2021) 85–114, https://doi.org/10.1007/978-981-15-8983-6_7.
[25] I. Douglas, The urban environment (1983).
[26] Germany's National Meteorological Service (DWD), Urban climate - urban heat islands, 2018. https://www.Dwd.de/EN/Climate_environment/Climateresearch/Climate_impact/Urbanism/Urban_heat_island/Urbanheatisland.Html.
[27] T. Raap, R. Pinxten, M. Eens, Light pollution disrupts sleep in free-living animals, Sci Rep 5 (2015) 13557, https://doi.org/10.1038/srep13557.
[28] N. Frantzeskaki, T. McPhearson, M.J. Collier, D. Kendal, H. Bulkeley, A. Dumitru, C. Walsh, K. Noble, E. van Wyk, C. Ordóñez, C. Oke, L. Pintér, Nature-based solutions for urban climate change adaptation: linking science, policy, and practice communities for evidence-based decision-making, Bioscience 69 (2019) 455–466, https://doi.org/10.1093/biosci/biz042.
[29] M. Batty, Inventing future cities, MIT press, 2018.
[30] A. Battisti, An Approach for Climate Change Mitigation, 2020. 10.14459/1543270md2020.
[31] SDGs, The sustainable development goals report 2019, United Nations Publication Issued by the Department of Economic and Social Affairs (2019) 64.
[32] U.N.G. Assembly, Transforming our World: The 2030 Agenda for Sustainable Development A/RES/70/1, Eur J Health Law 22 (2015) 508–516, https://doi.org/10.1163/15718093-12341375.
[33] B.L. Keeler, P. Hamel, T. McPhearson, M.H. Hamann, M.L. Donahue, K.A. Meza Prado, K.K. Arkema, G.N. Bratman, K.A. Brauman, J.C. Finlay, A.D. Guerry, S.E. Hobbie, J.A. Johnson, G.K. MacDonald, R.I. McDonald, N. Neverisky, S.A. Wood, Social-ecological and technological factors moderate the value of urban nature, Nat Sustain 2 (2019) 29–38. 10.1038/s41893-018-0202-1.
[34] L. Klotz, E. Weber, E. Johnson, T. Shealy, M. Hernandez, B. Gordon, Beyond rationality in engineering design for sustainability, Nat Sustain 1 (2018) 225–233, https://doi.org/10.1038/s41893-018-0054-8.
[35] M.J. Page, J.E. Mckenzie, P.M. Bossuyt, I. Boutron, T.C. Hoffmann, C.D. Mulrow, L. Shamseer, J.M. Tetzlaff, E.A. Akl, S.E. Brennan, R. Chou, J. Glanville, J.M. Grimshaw, A. Hróbjartsson, M.M. Lalu, T. Li, E.W. Loder, E. Mayo-Wilson, S. Mcdonald, L.A. Mcguinness, L.A. Stewart, J. Thomas, A.C. Tricco, V.A. Welch, P. Whiting, D. Moher, The PRISMA 2020 statement: an updated guideline for reporting systematic reviews, (n.d.). 10.1136/bmj.n71.
[36] D. Denyer, D. Tranfield, Producing a Systematic Review, The SAGE Handbook of, Organ. Res. Methods (2009) 671–689.
[37] C. Wohlin, Guidelines for snowballing in systematic literature studies and a replication in software engineering, ACM International Conference Proceeding Series (2014), https://doi.org/10.1145/2601248.2601268.
[38] M. Aria, C. Cuccurullo, bibliometrix: An R-tool for comprehensive science mapping analysis, J Informetr 11 (2017) 959–975, https://doi.org/10.1016/j.joi.2017.08.007.
[39] M.J. Cobo, A.G. López-Herrera, E. Herrera-Viedma, F. Herrera, An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field, J Informetr 5 (2011) 146–166, https://doi.org/10.1016/j.joi.2010.10.002.
[40] M. Schaefer, H. Ebrahimi Salari, H. Köckler, N.X. Thinh, Assessing local heat stress and air quality with the use of remote sensing and pedestrian perception in urban microclimate simulations, Science of the Total Environment 794 (2021). 10.1016/j.scitotenv.2021.148709.
[41] S. Yilmaz, M.A. Irmak, A. Qaid, Assessing the effects of different urban landscapes and built environment patterns on thermal comfort and air pollution in Erzurum city, Turkey, Build Environ 219 (2022) 109210, https://doi.org/10.1016/J.BUILDENV.2022.109210.
[42] H. Li, S. Sodoudi, J. Liu, W. Tao, Temporal variation of urban aerosol pollution island and its relationship with urban heat island, Atmos Res 241 (2020) 104957, https://doi.org/10.1016/J.ATMOSRES.2020.104957.
[43] S. Zhang, B. Wang, S. Wang, W. Hu, X. Wen, P. Shao, J. Fan, Influence of air pollution on human comfort in five typical Chinese cities, Environ Res 195 (2021) 110318, https://doi.org/10.1016/J.ENVRES.2020.110318.
[44] E. Kalisa, S. Fadlallah, M. Amani, L. Nahayo, G. Habiyaremye, Temperature and air pollution relationship during heatwaves in Birmingham, UK, Sustain Cities Soc 43 (2018) 111–120, https://doi.org/10.1016/J.SCS.2018.08.033.
[45] H. Li, F. Meier, X. Lee, T. Chakraborty, J. Liu, M. Schaap, S. Sodoudi, Interaction between urban heat island and urban pollution island during summer in Berlin, Sci. Total Environ. 636 (2018) 818–828, https://doi.org/10.1016/J.SCITOTENV.2018.04.254.
[46] Z. Qian, Q. He, H.-M. Lin, L. Kong, C.M. Bentley, W. Liu, D. Zhou, High Temperatures enhanced acute mortality effects of ambient particle pollution in

the “oven” city of Wuhan, China, Environ Health Perspect 116 (2008) 1172–1178, https://doi.org/10.1289/ehp.10847.
[47] C. Miao, X. He, Z. Gao, W. Chen, B.J. He, Assessing the vertical synergies between outdoor thermal comfort and air quality in an urban street canyon based on field measurements, Build Environ 227 (2023) 109810, https://doi.org/10.1016/J.BUILDENV.2022.109810.
[48] Y. Hu, Y. Wu, Q. Wang, J. Hang, Q. Li, J. Liang, H. Ling, X. Zhang, Impact of indoor-outdoor temperature difference on building ventilation and pollutant dispersion within urban communities, Atmosphere (Basel) 13 (2021) 28, https://doi.org/10.3390/atmos13010028.
[49] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renew. Sustain. Energy Rev. 13 (2009) 1819–1835, https://doi.org/10.1016/j.rser.2008.09.033.
[50] S. Jebaraj, S. Iniyan, A review of energy models, Renew. Sustain. Energy Rev. 10 (2006) 281–311, https://doi.org/10.1016/j.rser.2004.09.004.
[51] M. Kavgic, A. Mavrogianni, D. Mumovic, A. Summerfield, Z. Stevanovic, M. Djurovic-Petrovic, A review of bottom-up building stock models for energy consumption in the residential sector, Build Environ 45 (2010) 1683–1697, https://doi.org/10.1016/j.buildenv.2010.01.021.
[52] J. Keirstead, M. Jennings, A. Sivakumar, A review of urban energy system models: Approaches, challenges and opportunities, Renew. Sustain. Energy Rev. 16 (2012) 3847–3866, https://doi.org/10.1016/j.rser.2012.02.047.
[53] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, Build Environ 43 (2008) 661–673, https://doi.org/10.1016/j.buildenv.2006.10.027.
[54] S. Saneinejad, P. Moonen, T. Defraeye, D. Derome, J. Carmeliet, Coupled CFD, radiation and porous media transport model for evaluating evaporative cooling in an urban environment, J. Wind Eng. Ind. Aerodyn. 104–106 (2012) 455–463, https://doi.org/10.1016/j.jweia.2012.02.006.
[55] F. Sonnenwald, I. Guymer, V. Stovin, A CFD-Based Mixing Model for Vegetated Flows, Water Resour Res 55 (2019) 2322–2347, https://doi.org/10.1029/2018WR023628.
[56] P.O. Fanger, Thermal comfort: analysis and applications in environmental engineering, McGraw-Hill, New York, 1972.
[57] ISO_7730_2005_11_15_Ergonomics_of_the_Th, (n.d.).
[58] J.E. McCarthy, C. Copeland, L. Parker, L.J. Schierow, Clean Air Act: A summary of the act and its major requirements, New Trends in Environmental Science (2014) 147–168.
[59] ADMS Temperature and Humidity, Http://Www.Cerc.Co.Uk/Environmentalresearch/Boundary-Layer.Html (n.d.).
[60] S. Righi, P. Lucialli, E. Pollini, Statistical and diagnostic evaluation of the ADMS-Urban model compared with an urban air quality monitoring network, Atmos Environ 43 (2009) 3850–3857, https://doi.org/10.1016/J.ATMOSENV.2009.05.016.
[61] S. Di Sabatino, R. Buccolieri, B. Pulvirenti, R.E. Britter, Flow and Pollutant Dispersion in Street Canyons using FLUENT and ADMS-Urban, Environ. Model. Assess. 13 (2008) 369–381, https://doi.org/10.1007/s10666-007-9106-6.
[62] A. Tiwari, P. Kumar, G. Kalaiarasan, T.B. Ottosen, The impacts of existing and hypothetical green infrastructure scenarios on urban heat island formation, Environ. Pollut. 274 (2021) 115898, https://doi.org/10.1016/J.ENVPOL.2020.115898.
[63] J. Huang, T. Hao, S.S. Hou, P. Jones, Simulation-Informed Urban Design: Improving Urban Microclimate in Real-World Practice in a High Density City, in: IOP Conf Ser Earth Environ Sci, 2019.
[64] F.R. Menter, Best practice: scale-resolving simulations in ANSYS CFD, (2012). https://cfd.grs.de/sites/default/files/downloads/ansys/ANSYS_BPG-SRS-2.01.pdf (accessed January 28, 2024).
[65] F.R. Menter, R. Lechner, A. Matyushenko, Best practice: generalized k-ω two-equation turbulence model in ANSYS CFD (GEKO), (2019). https://fluidcodes.com/wp-content/uploads/2020/06/geko-tp-1.pdf (accessed January 28, 2024).
[66] M. Szudarek, A. Piechna, P. Prusiński, L. Rudniak, CFD Study of High-Speed Train in Crosswinds for Large Yaw Angles with RANS-Based Turbulence Models including GEKO Tuning Approach, Energies (Basel) 15 (2022) 6549, https://doi.org/10.3390/en15186549.
[67] M. Zhou, T. Hu, G. Jiang, W. Zhang, D. Wang, P. Rao, Numerical simulations of air flow and traffic-related air pollution distribution in a real urban area, Energies (Basel) 15 (2022) 840, https://doi.org/10.3390/en15030840.
[68] R.J. Schnipke, A STREAMLINE UPWIND FINITE-ELEMENT METHOD FOR LAMINAR AND TURBULENT FLOW, 1986. https://www.researchgate.net/profile/Rita-Schnipke/publication/35099771_A_streamline_upwind_finite_element_method_for_laminar_and_turbulent_flow/links/58077b2908ae5ed04bfe5c99/A-streamline-upwind-finite-element-method-for-laminar-and-turbulent-flow.pdf (accessed January 28, 2024).
[69] A. Albatayneh, D. Alterman, A. Page, Adaptation the Use of CFD Modelling for Building Thermal Simulation, in: Proceedings of the 2018 International Conference on Software Engineering and Information Management, ACM, New York, NY, USA, 2018: pp. 68–72. 10.1145/3178461.3178466.
[70] F. Bakir, R. Rey, A.G. Gerber, T. Belamri, B. Hutchinson, Numerical and Experimental Investigations of the Cavitating Behavior of an Inducer, Int. J. Rotating Mach. 10 (2004) 15–25, https://doi.org/10.1155/S1023621X04000028.
[71] P. Karantonis, T. Gowen, M. Simon, Further Comparison of Traffic Noise Predictions Using the CadnaA and SoundPLAN Noise Prediction Models, in: Proceedings of 20th International Congress on Acoustics, 2010. https://www.acoustics.asn.au/conference_proceedings/ICA2010/cdrom-ICA2010/papers/p730.pdf (accessed January 28, 2024).
[72] M. Kiani Sadr, Prediction of Airport Noise Using CadnaA Model and GIS: Case Study of IKIA Airport, ECOPERSIA 5 (2017) 1933–1940. https://ecopersia.modares.ac.ir/article-24-11536-en.html (accessed January 28, 2024).
[73] I. CadnaA, State of the art noise prediction software, n.d. https://www.datakustik.com/fileadmin/user_upload/CadnaA/Technical_Brochures/CadnaA_2023_Brochure_EN.pdf (accessed January 28, 2024).
[74] M. Mortezazadeh, L.L. Wang, M. Albettar, S. Yang, CityFFD – City fast fluid dynamics for urban microclimate simulations on graphics processing units, Urban Clim 41 (2022), https://doi.org/10.1016/j.uclim.2021.101063.
[75] M. Mortezazadeh, Z. Jandaghian, L.L. Wang, Integrating CityFFD and WRF for modeling urban microclimate under heatwaves, Sustain Cities Soc 66 (2021) 102670, https://doi.org/10.1016/J.SCS.2020.102670.
[76] A. Katal, M. Mortezazadeh, L. (Leon) Wang, Modeling building resilience against extreme weather by integrated CityFFD and CityBEM simulations, Appl Energy 250 (2019) 1402–1417, https://doi.org/10.1016/J.APENERGY.2019.04.192.
[77] D. Witzel, DIALux evo–New calculation method, 2022. https://www.dialux.com/fileadmin/documents/DIALux_evo-_New_calculation_method.pdf (accessed January 28, 2024).
[78] M. Hemmerling, M. Seegers, D. Witzel, Calculation of energy saving potential for lighting with DIALux evo, Energy Build 278 (2023) 112475, https://doi.org/10.1016/J.ENBUILD.2022.112475.
[79] A. Hangga, A.M. Nisa, M. Apriliyanto, M. Afandi, D. Pratama, M.A. Aziz, A. Wijanarko, S. Witrianto, Modelling of lighting system utilizing natural and artificial lighting using DIALux, IOP Conf Ser Earth Environ Sci 969 (2022) 012024, https://doi.org/10.1088/1755-1315/969/1/012024.
[80] H. Simon, Modeling urban microclimate: development, implementation and evaluation of new and improved calculation methods for the urban microclimate model ENVI-met, 2016. https://openscience.ub.uni-mainz.de/rest/bitstreams/c2dc5eaf-e785-4418-8eea-d2dd7d3eb8e2/retrieve (accessed January 28, 2024).
[81] T. Sinsel, Advancements and applications of the microclimate model ENVI-met, 2022. https://openscience.ub.uni-mainz.de/handle/20.500.12030/6726 (accessed January 28, 2024).
[82] M. Bruse, H. Simon, T. Kropp, F. Sohni, Development and implementation of a high-resolution dynamical wall and roof model for ENVI-met., (2019). https://www.researchgate.net/profile/Michael-Bruse/publication/374372595_Development_and_implementation_of_a_high-resolution_dynamical_wall_and_roof_model_for_ENVI-met_Part_2_Vegetated_walls_and_roofs/links/651a8903321ec5513c2b2676/Development-and-implementation-of-a-high-resolution-dynamical-wall-and-roof-model-for-ENVI-met-Part-2-Vegetated-walls-and-roofs.pdf (accessed January 28, 2024).
[83] M. Bruse, H. Simon, T. Sinsel, Development and implementation of a high-resolution dynamical wall and roof model for ENVI-met Part 2: Vegetated Walls and Roofs, (2023). https://www.researchgate.net/profile/Tim-Sinsel/publication/371761708_Development_and_implementation_of_a_high-resolution_dynamical_wall_and_roof_model_for_ENVI-met_Part_2_Vegetated_Walls_and_Roofs/links/6494129c8de7ed28ba4bd740/Development-and-implementation-of-a-high-resolution-dynamical-wall-and-roof-model-for-ENVI-met-Part-2-Vegetated-Walls-and-Roofs.pdf (accessed January 28, 2024).
[84] H. Simon, T. Sinsel, M. Bruse, Advances in Simulating Radiative Transfer in Complex Environments, Appl. Sci. 11 (2021) 5449, https://doi.org/10.3390/app11125449.
[85] H. de Haan, V. Senden, True North: A Comparison of Measured vs Modelled Noise Levels with iNoise, Canadian Acoustics (2018). https://jcaa.caa-aca.ca/index.php/jcaa/article/view/3164 (accessed January 28, 2024).
[86] Y. Wan, Y. Zhou, M. Yu, G. Yi, Research on the application of acoustic simulation based on iNoise in the evaluation of factory boundary noise, J Phys Conf Ser 2253 (2022) 012037, https://doi.org/10.1088/1742-6596/2253/1/012037.
[87] M.S. Rousdari, M. Pal, Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design., in: 13th Conference of International Building Performance Simulation Association, 2013. https://www.aivc.org/sites/default/files/p_2499.pdf (accessed January 28, 2024).
[88] M.S. Rousdari, Seeing the Process: Ladybug + Honeybee, Dynamic Building Simulation Solutions for Integrated Iterative Design, in: Energy Accounts: Architectural Representations of Energy, Climate and the Future, 2016. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315690995-15/seeing-process-ladybug-honeybee-dynamic-building-simulation-solutions-integrated-iterative-design-mostapha-sadeghipour-roudsari (accessed January 28, 2024).
[89] G. Evola, V. Costanzo, C. Magrì, G. Margani, L. Marletta, E. Naboni, A novel comprehensive workflow for modelling outdoor thermal comfort and energy demand in urban canyons: Results and critical issues, Energy Build 216 (2020) 109946, https://doi.org/10.1016/J.ENBUILD.2020.109946.
[90] E. Badino, M. Ferrara, L. Shtrepi, E. Fabrizio, A. Astolfi, V. Serra, Modelling mean radiant temperature in outdoor environments: contrasting the approaches of different simulation tools, J Phys Conf Ser 2069 (2021) 012186, https://doi.org/10.1088/1742-6596/2069/1/012186.
[91] Q.M. Tenailleau, N. Bernard, S. Pujol, A.L. Parmentier, M. Boilleaut, H. Houot, D. Joly, F. Mauny, Do outdoor environmental noise and atmospheric NO2 levels spatially overlap in urban areas? Environ. Pollut. 214 (2016) 767–775, https://doi.org/10.1016/J.ENVPOL.2016.04.082.
[92] P. Alina, T. Claudia, F. Ricardo, N. Gey, I. Florin, Oana, Noise prediction, calculation and mapping using specialized software, Journal of Engineering Studies and Research 21 (2016), https://doi.org/10.29081/jesr.v21i3.19.
[93] Acoustic Simulation Software For Outdoor Applications, n.d.
[94] B. Hollósi, M. Žuvela-Aloise, S. Oswald, A. Kainz, W. Schöner, Applying urban climate model in prediction mode—evaluation of MUKLIMO_3 model

performance for Austrian cities based on the summer period of 2019, Theor Appl Climatol 144 (2021) 1181–1204, https://doi.org/10.1007/s00704-021-03580-6.
[95] U. Sievers, Das kleinskalige Strömungsmodell MUKLIMO_3 Teil 1: Theoretische Grundlagen, PC-Basisversion und Validierung, (2012).
[96] U. Sievers, Das kleinskalige Strömungsmodell MUKLIMO_3. Teil 2: Thermodynamische Erweiterungen., (2016). https://refubium.fu-berlin.de/bitstream/handle/fub188/18630/248_pdf.pdf?sequence=1 (accessed January 28, 2024).
[97] M. Žuvela-Aloise, Enhancement of urban heat load through social inequalities on an example of a fictional city King's Landing, Int J Biometeorol 61 (2017) 527–539, https://doi.org/10.1007/s00484-016-1230-z.
[98] NoiseMap fi√e Guide to Digital Mapping NoiseMap fi√e GUIDE TO DIGITAL MAPPING 1. CONTENTS, 2018.
[99] NoiseMap five, n.d. http://www.noisemap.ltd.uk/wpress/wp-content/uploads/2015/11/NoiseMapFiveBrochure2.pdf (accessed January 28, 2024).
[100] X. Jurado, N. Reiminger, J. Vazquez, C. Wemmert, On the minimal wind directions required to assess mean annual air pollution concentration based on CFD results, Sustain Cities Soc 71 (2021) 102920, https://doi.org/10.1016/J.SCS.2021.102920.
[101] G. Lobaccaro, S. Croce, D. Vettorato, S. Carlucci, A holistic approach to assess the exploitation of renewable energy sources for design interventions in the early design phases, Energy Build 175 (2018) 235–256, https://doi.org/10.1016/J.ENBUILD.2018.06.066.
[102] R. Mohan, S. Sundararaj, K.B. Thiagarajan, Numerical simulation of flow over buildings using OpenFOAM®, in (2019:) 020149 https://doi.org/10.1063/1.5112334.
[103] B. Steuri, S. Bender, J. Cortekar, Successful user-science interaction to co-develop the new urban climate model PALM-4U, Urban Clim 32 (2020) 100630, https://doi.org/10.1016/J.UCLIM.2020.100630.
[104] J. Geletič, M. Lehnert, P. Krč, J. Resler, E.S. Krayenhoff, High-Resolution Modelling of Thermal Exposure during a Hot Spell: A Case Study Using PALM-4U in Prague, Czech Republic, Atmosphere (Basel) 12 (2021) 175, https://doi.org/10.3390/atmos12020175.
[105] G. Halbig, B. Steuri, B. Büter, I. Heese, J. Schultze, M. Stecking, S. Stratbücker, L. Willen, M. Winkler, User requirements and case studies to evaluate the practicability and usability of the urban climate model PALM–4U, Meteorol. Z. 28 (2019) 139–146, https://doi.org/10.1127/metz/2019/0914.
[106] D.B. Spalding, Simultaneous fluid-flow, heat-transfer and solid-stress computation in a single computer code, in: 1999. https://www.osti.gov/etdeweb/biblio/357211 (accessed January 28, 2024).
[107] V. Goncalves, Y. Ogunjimi, Y. Heo, Scrutinizing modeling and analysis methods for evaluating overheating risks in passive houses, Energy Build 234 (2021) 110701, https://doi.org/10.1016/J.ENBUILD.2020.110701.
[108] X. Liu, L. Yang, S. Niu, Research on the effect of different position on classroom ventilation in a "L" type teaching building, Journal of Building Engineering 33 (2021) 101852, https://doi.org/10.1016/J.JOBE.2020.101852.
[109] A. Matzarakis, F. Rutz, H. Mayer, Modelling the thermal bioclimate in urban areas with the RayMan Model, in: International Conference on Passive and Low Energy Architecture, 2006. Modelling the thermal bioclimate in urban areas with the RayMan Model. (accessed January 28, 2024).
[110] A. Matzarakis, F. Rutz, H. Mayer, Modelling radiation fluxes in simple and complex environments: basics of the RayMan model, Int J Biometeorol 54 (2010) 131–139, https://doi.org/10.1007/s00484-009-0261-0.
[111] A. Matzarakis, Estimation of Thermal Indices in Urban Structures-Simulations by micro scale models, in: Third International Conference on Countermeasures to Urban Heat Island, 2014. https://www.researchgate.net/profile/Andreas-Matzarakis/publication/267867792_Estimation_of_Thermal_Indices_in_Urban_Structures_-_Simulations_by_micro_scale_models/links/545be4050cf249070a7a82a3/Estimation-of-Thermal-Indices-in-Urban-Structures-Simulations-by-micro-scale-models.pdf (accessed January 28, 2024).
[112] P.J. Crank, A. Middel, M. Wagner, D. Hoots, M. Smith, A. Brazel, Validation of seasonal mean radiant temperature simulations in hot arid urban climates, Sci. Total Environ. 749 (2020) 141392, https://doi.org/10.1016/J.SCITOTENV.2020.141392.
[113] C. Ding, K.P. Lam, N.H. Wong, Coupled natural ventilation modeling for contextual parametric design decision support, Procedia Eng 169 (2016) 264–271, https://doi.org/10.1016/J.PROENG.2016.10.032.
[114] M. Dash, M. Chakraborthy, Influence of climate on building codes: Comparative analysis of indian cities, Environ Prog Sustain Energy 37 (2018) 2109–2115, https://doi.org/10.1002/ep.12875.
[115] N. Yoon, O. Nobuyuki, Y. Ando, AUTOMATED CFD SIMULATION SYSTEM WITH BIM FOR BCA GREEN MARK CERTIFICATION , in: ASHRAE/IBPSA-USA Building Simulation Conference, 2014. https://publications.ibpsa.org/proceedings/simbuild/2014/papers/simbuild2014_16.pdf (accessed January 28, 2024).
[116] D. Jeswani Dewan, SOLWEIG: a climate design tool , 2009.
[117] F. Lindberg, B. Holmer, S. Thorsson, Solweig,, 1.0 – Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings, Int J Biometeorol 52 (2008) 697–713, https://doi.org/10.1007/s00484-008-0162-7.
[118] S. Sheying, S.B. Lacrampe, Evaluation on overlapping Barriers Design using SoundPLAN, Canadian Acoustics (2017). https://jcaa.caa-aca.ca/index.php/jcaa/article/view/3160 (accessed January 28, 2024).
[119] H. Zhang, S. Gong, L. Zhang, J. Ni, J. He, Y. Wang, X. Wang, L. Shi, J. Mo, H. Ke, S. Lu, Development and application of a street-level meteorology and pollutant tracking system (S-TRACK), Atmos Chem Phys 22 (2022) 2221–2236, https://doi.org/10.5194/acp-22-2221-2022.
[120] H. Huo, F. Chen, X. Geng, J. Tao, Z. Liu, W. Zhang, P. Leng, Simulation of the urban space thermal environment based on computational fluid dynamics: a comprehensive review, Sensors 21 (2021) 6898, https://doi.org/10.3390/s21206898.
[121] I. Abohela, E. Aristodemou, A. Hadawey, R. Sundararajan, Assessing the Horizontal Homogeneity of the Atmospheric Boundary Layer (HHABL) Profile Using Different CFD Software, Atmosphere (Basel) 11 (2020) 1138, https://doi.org/10.3390/atmos11101138.
[122] S. Liu, W. Pan, H. Zhang, X. Cheng, Z. Long, Q. Chen, CFD simulations of wind distribution in an urban community with a full-scale geometrical model, Build Environ 117 (2017) 11–23, https://doi.org/10.1016/J.BUILDENV.2017.02.021.
[123] Y. Zheng, M. Havu, H. Liu, X. Cheng, Y. Wen, H.S. Lee, J. Ahongshangbam, L. Järvi, Simulating heat and CO 2 fluxes in Beijing using SUEWS V2020b: sensitivity to vegetation phenology and maximum conductance, Geosci Model Dev 16 (2023) 4551–4579, https://doi.org/10.5194/gmd-16-4551-2023.
[124] L. Järvi, C.S.B. Grimmond, A. Christen, The Surface Urban Energy and Water Balance Scheme (SUEWS): Evaluation in Los Angeles and Vancouver, J Hydrol (Amst) 411 (2011) 219–237, https://doi.org/10.1016/J.JHYDROL.2011.10.001.
[125] T.V. Kokkonen, C.S.B. Grimmond, O. Räty, H.C. Ward, A. Christen, T.R. Oke, S. Kotthaus, L. Järvi, Sensitivity of Surface Urban Energy and Water Balance Scheme (SUEWS) to downscaling of reanalysis forcing data, Urban Clim 23 (2018) 36–52, https://doi.org/10.1016/J.UCLIM.2017.05.001.
[126] H.C. Ward, S. Kotthaus, L. Järvi, C.S.B. Grimmond, Surface Urban Energy and Water Balance Scheme (SUEWS): Development and evaluation at two UK sites, Urban Clim 18 (2016) 1–32, https://doi.org/10.1016/J.UCLIM.2016.05.001.
[127] N.H. Wong, S. Kardinal Jusuf, A. Aung La Win, H. Kyaw Thu, T. Syatia Negara, W. Xuchao, Environmental study of the impact of greenery in an institutional campus in the tropics, Build Environ 42 (2007) 2949–2970, https://doi.org/10.1016/J.BUILDENV.2006.06.004.
[128] J. Teller, S. Azar, Townscope II—A computer system to support solar access decision-making, Sol. Energy 70 (2001) 187–200, https://doi.org/10.1016/S0038-092X(00)00097-9.
[129] C.F. Reinhart, T. Dogan, J.A. Jakubiec, T. Rakha, A. Sang, Umi-an urban simulation environment for building energy use, daylighting and walkability., in: 13th Conference of International Building Performance Simulation Association, 2013. https://www.aivc.org/sites/default/files/p_1404.pdf (accessed January 28, 2024).
[130] K. Fahssis, G. Dupont, P. Leyronnas, UrbaWind, a Computational Fluid Dynamics tool to predict wind resource in urban area, in: Nternational Conference of Applied Energy, 2010.
[131] G. Caniot, W. Li, G. Dupont, Validations and applications of a CFD tool dedicated to wind assessment in urban areas, in: 13th International Conference on Wind Engineering, 2011. https://meteodyn.fr/media/g_caniot_validations_and_applications_of_a_cfd_tool_dedicated_to_wind_assessment_in_urban_areas.pdf (accessed January 28, 2024).
[132] G. Caniot, S. Sanquer, G. Huang, Optimization of numerical parameters in CFD tools to improve natural ventilation assessment in complex urban area, in: 15th International Conference on Wind Engineering, 2019. https://meteodyn.com/media/optimization_of_numerical_parameters_in_cfd_tools_to_improve_natural_ventilation_assessment_in_complex_urban_area.pdf (accessed January 28, 2024).