energies

Review

Basic Principles, Most Common Computational Tools, and Capabilities for Building Energy and Urban Microclimate Simulations

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Abstract: This paper presents basic principles of built-environment physics' modelling, and it reviews common computational tools and capabilities in a scope of practical design approaches for retrofitting purposes. Well-established simulation models and methods, with applications found mainly in the international scientific literature, are described by means of strengths and weaknesses as regards related tools' availability, easiness to use, and reliability towards the determination of the optimal blends of retrofit measures for building energy upgrading and Urban Heat Island (UHI) mitigation. The various characteristics of computational approaches are listed and collated by means of comparison among the principal modelling methods as well as among the respective computational tools that may be used for simulation and decision-making purposes. Insights of coupling between building energy and urban microclimate models are also presented. The main goal was to provide a comprehensive overview of available simulation methods that can be used at the early design stages for planning retrofitting strategies and guiding engineers and technical professionals through the simulation tools' options oriented to the considered case study.

Keywords: building energy performance; urban heat island; building physics; simulation tools

Citation: Stavrakakis, G.M.; Katsaprakakis, D.A.; Damasiotis, M. Basic Principles, Most Common Computational Tools, and Capabilities for Building Energy and Urban Microclimate Simulations. *Energies* **2021**, *14*, 6707. https://doi.org/10.3390/en14206707

Academic Editor: Marcin Kamiński

Received: 29 August 2021
Accepted: 12 October 2021
Published: 15 October 2021

1. Introduction

The building sector in Europe is considered as the largest consumer of energy, using up to 40% of the final energy consumption [1,2]. As reported in the EU directive 2018/844/EU, almost 50% of the Union's final energy consumption is used for heating and cooling, 80% of which is allocated to buildings. This indicates that the achievement of the Union's targets regarding energy efficiency and resilience to climate change depends on the increase of renovation rates of its building stock, in fact, by giving priority to energy efficiency as well as by considering deployment of renewables [3]. According to its (EU) 2019/786 recommendation on building renovation [4], the Commission invites Member States to establish long-term renovation strategies focused on the national building stock, including both public and private buildings, towards highly energy efficient and decarbonized building stock by 2050, also prescribing measures for the cost-effective transformation of existing buildings into nearly zero-energy buildings (the so-called NZEBs). In this framework, it is acknowledged that the design approaches followed in order to achieve the highest possible energy-saving potential require advanced calculation techniques at the design stage, with the highest possible accuracy of predictions. In the context of evaluating building energy performance, many parameters are required, such as the thermo-physical properties of the envelope, indoor–outdoor physical interactions, energy end uses, building systems' operating schedules, etc. Considering all these influencing factors, building energy upgrading is indeed not an easy task. Especially now with more strict regulations and policies, building energy renovation plans require precise estimations of energy indicators, as specific thresholds of these indicators should be satisfied, and at the same time least-cost renovation measures should be identified.

On the other hand, a crucial factor that affects the energy performance of building complexes is the external microclimate, i.e., the microclimatic conditions in the vicinity of buildings determines cooling and heating loads, thus the energy demand and the decision of most appropriate energy-efficiency measures. Especially in densely built environments, the external microclimatic conditions should not be disregarded in the design stage as, indeed, the Urban Heat Island (UHI) effect is ever more intense and impacts many aspects of quality of life in cities, e.g., building energy efficiency, thermal comfort, and indoor and outdoor air quality. Over the last 30 years, heat waves in Europe in combination with the Urban Heat Island (UHI) phenomenon have dramatically deteriorated quality of life in densely built-up Cities, by means of mortality rates due to heat strokes, and of hygiene conditions as well as of the energy demand for cooling purposes. UHI is well documented in terms of its intensity. Indicatively, in Europe, the mean value of recorded maximum UHI intensities ranged between 0.3 °C and 6.8 °C (yielding an average of 2.6 °C), with absolute peaks close to 12 °C [5,6]. Such conditions of unusually high temperatures for long periods favor high energy consumption in buildings. For example, it has been documented that the increase in urban temperature may lead to an average increase of cooling loads from 20% to 45% in the Mediterranean climate [7]. This means that a holistic confrontation over the improvement of building energy performance should not disregard the impact of UHI on energy consumption. Apart from benefiting building energy performance, UHI mitigation projects ensure more comfortable and healthy open spaces for pedestrians.

To deal with the requirements of the latest EU directives as well as of the design challenges, EU Member States have developed their own national methodologies and computational tools (e.g., based on the CEN Standards), aiming to assess building energy performance in the pre-renovation (or pre-construction) and the post-renovation (or post-construction) situations in order to determine renovation measures. However, the available national tools are much more biased to single-building energy simulation, while, concerning the effect of local microclimate, it is often omitted from the numerical-simulation toolboxes used for purposes of compliance with building energy regulations. In current policies and regulatory frameworks, only the general bioclimatic-design principles are adopted regarding urban planning, without addressing the quantification of microclimatic indicators; hence, still no computational tools and/or concrete calculation methodologies are recommended to estimate microclimate and environmental indicators in the study phase specifically for design-for-compliance purposes.

On the other hand, considering the issues raised above, it becomes obvious that in order to comply with the latest energy efficiency policies and much stricter regulations, as well as to obtain sustainably built and urban environments, accurate methods and computational tools to estimate the impact of retrofit options based on the aspects of building and urban physics are required. The use of such methods is considered crucial even in the early study phase, especially for major renovation projects, for the following reasons:

- They assess the pre-renovation situation revealing the energy consumption level of buildings and microclimate conditions of open spaces. This capability contributes to the recognition of vulnerable areas, energy savings potential and, generally, actual needs of the renovation cases under consideration. The provision of such estimations contributes to determining and prioritizing the interventions.
- They can be used to assess the impact of various interventions in a desk-study (fast and with least cost) manner, i.e., computational tools may be executed for various design configurations and calculate the corresponding values of performance indicators (energy indicators for buildings and microclimate indicators for open spaces).
- In a more advanced level aiming at improving estimations' accuracy, many computational tools allow the possibility to conduct coupled simulations in order to account

for the impact of the UHI effect, i.e., of the local microclimate rather than relying on the wider climate zone, on building energy consumption.
- Hourly based calculations prescribed in dynamic simulation tools, provided that occupancy and systems' operation schedules are accessible, allow for energy-behaviour assessments.
- In combination with optimization schemes and algorithms, they support decision making towards the determination of cost-effective renovation measures that ensure minimum requirements of performance indicators, either energy or microclimate ones.

The present paper provides an overview of commercial or freely available computational tools that can be used to assess building energy performance and UHI effect in open spaces. The major categories of physical models are presented, i.e., multi-zonal (also known as nodal models) for building energy performance assessments and field models for UHI assessments. The capabilities of the most popular computational tools of each category are presented together with case studies found in the scientific literature. Furthermore, nodal/field models coupling possibilities to assess UHI effect on building energy consumption are discussed.

2. Physical Models

2.1. Building Thermal-Performance Modelling

Physical models are used to simulate the thermal performance of various buildings with their own special demands and uses, e.g., dwellings, offices, schools, etc. These models involve interpreting of space heating [8], natural ventilation [9], air conditioning systems [10], solar-thermal systems [11], Photovoltaic panels [12], occupants' behaviour [13,14], etc. The physical modelling techniques are based mainly on the solving of heat transfer equations.

To solve such physical problems, numerous simulation software packages are available, many of them also associated by benchmarking activities performed by many authors and researchers. Theoretically, each building software is able to include thermal physical phenomena encountered in buildings. Most computational tools provide the choice to users to select the physical mechanisms and the associated equations required. There are two major building thermal models' categories most commonly used [15] (mainly in the framework of research activities and projects):

- Field models, such as Computational Fluid Dynamics (CFD) models, and
- Multi-zonal or nodal models.

The present paper focuses on the application of the multi-zonal method in case of building energy simulation and provides an extensive presentation of the principles of this method and available computational tools to assess building energy performance. As far as field models are concerned, this paper focuses on their uses for simulating the urban microclimate. Therefore, the overview of field modelling principles and computational tools is restricted herein mainly to open spaces (Section 2.2), while only a short presentation of their uses for indoor airflows and building thermal simulation is provided.

2.1.1. Field Models for Indoor Airflow Assessments

The most complete field modelling approach in building thermal simulation is (so far) the CFD method. This is a "microscopic" approach of heat transfer modelling providing a detailed resolution of the airflow pattern. It is based on the discretization of a building zone into control volumes in the form of structured or unstructured mesh [16]. The CFD approach is essentially based on the solution of the so-called Navier–Stokes equations. A large number of CFD software exists such as Ansys Fluent, Ansys CFX, COMSOL Multi-physics, MIT-CFD, Phoenics, etc., most of them possessing additional capabilities to simulating indoor airflows and building thermal behaviour. They are general-purpose CFD platforms and can be applied to every system involving fluid flow phenomena. The CFD method is mainly employed for its ability to solve for mass, momentum, heat, chemical species, and turbulence parameters' conservation equations. While available software present similar characteristics in terms of the conservation equations solved or on the mathematical formulation of boundary conditions (for example, Dirichlet or Neuman formulations), some of them differ on the equations' discretization method or on the solver used for processing the algebraic system of discretized differential conservation equations. There are three fundamental methods for discretization purposes: The Finite Difference (FDM), the Finite Volume (FVM), and the Finite Element Method (FEM). These methods present different precision and numerical efforts, but they are all based on the discretization of Navier–Stokes equations. On the other hand, the treatment of boundary conditions in these methods is still a key issue in fluid flow numerical simulations depending on the engineering application studied. Indeed, in non-isothermal fluid flows, where design parameters or physical properties have fluctuations, boundary conditions require special treatment. This has led to enhancements of numerical methods, for example, on the basis of fluctuation-based equations, the so-called Stochastic Finite Element Method (SFEM), which was introduced and exercised in benchmark fluid-flow case studies by Kamiński and Carey [17].

The CFD analysis produces a detailed description of the airflow field within indoor environments including velocity vector distribution (magnitude and direction), temperature distribution, chemical species dispersion, etc. The prediction of the aforementioned properties of the flow field is very useful even in the early design stages as it reveals areas with unpleasant droughts and thermal discomfort (refer, for example, to ref. [18]) and areas of pollutants' confinement, for different design alternatives. Hence, it helps the building design practitioner to review and decide the best among the design alternatives. The main disadvantage of the CFD method, however, still is the high computational time required to solve accurately for the conservation equations in full 3D geometries adopting fine meshes respecting the grid-independent solution principle [19] as far as possible. However, given that the airflow in at least 75% of the building volume is almost stagnant (velocity magnitude below 0.5 m/s) [15], it is not always necessary to apply the CFD approach for the entire building but only to certain parts, e.g., within spaces affected by installed Heating Ventilating and Air-Conditioning (HVAC) systems or within naturally ventilated spaces. This allows reducing computational time significantly. For this reason, the CFD is frequently coupled with less time-consuming multi-zonal techniques or other statistical ones. Tan and Glicksman [20] compared the full CFD simulation results with those obtained by the coupling between CFD and a multi-zonal tool for captivating natural ventilation through large openings or an atrium. It was demonstrated that the latter required 10 times less duration of computations until full convergence in relation to the full CFD method, exhibiting similar accuracy. Kato [21] provided an extended review of coupled CFD and zonal or network techniques and applications in building heat-transfer simulations and reported the required theoretical conditions for reliable coupled simulations, balancing fidelity in predictions and reasonable computational times and resources.

2.1.2. The Multi-Zonal (Nodal) Approach

The multi-zonal approach assumes that each building zone is a homogeneous volume with uniform state variables. Thus, each zone is approximated as a node with a unique flow property, e.g., temperature, pressure, pollutant concentration, etc. Generally, a computational node stands for a room, a wall, or the exterior of the building, to which specific loads, such as internal occupancy, equipment gains, heat sources, etc., are allocated. The heat transfer equations are solved for each node and it can be considered as a one-dimensional approach. In international literature, one can find two main methods used for the multi-zonal approach [15]:

- Solution of the state variables transfer equations, and
- Finite difference method.

Most available software is designed based on the former technique. The latter method is applied for nodal approaches through the representation of heat transfer from electrical analogy, which was introduced by Rumaniovski et al. [22]. The usefulness of this method lies in the fact that it drastically simplifies the mathematical representation of the physical problem through the linearization of conservation equations, leading to reduced computational time.

The major advantage of this method is that it describes the behaviour of a building with many zones on a large time scale within modest computational resources. It is a particularly well-adopted technique for energy-consumption estimations and of the dynamic changes of space-averaged temperature into a room. In addition, it is useful to estimate air-change rates and the distribution of airflow properties among different rooms. Ventilation efficiency or pollutant transport in buildings can also be studied by this method [23].

Due to the zero-spatial-gradient assumption regarding the airflow state variables within a node, the multi-zonal method presents the following limitations:

- The study of thermal comfort and air quality in thermal zones is difficult, as the spatial heterogeneity of physical parameters (air velocity, turbulence intensity, relative humidity, temperature, etc.) involved in the conservation equations (heat transfer, mass, momentum, chemical species) is roughly approximated.
- The impact of heating and cooling loads on their close environment is not adequately addressed (for example, a radiator causing buoyant plumes or an air blower causing air drafts).
- It presents significant deviations in airflow predictions, especially in large spaces (e.g., atriums, athletic halls, auditoriums, etc.) where significant non-uniformities of indoor airflow are expected.
- Although it remains a good option to depict the distribution of pollutant concentration between building zones, it prevents the assessment of local effects by a heat or pollutant source within each building zone separately.

According to Kato (2018) [21], one effective way to "heal" the aforementioned limitations is through CFD nodal-coupled simulations. CFD and network-model coupled simulation is particularly useful when ventilation effectiveness of a large indoor space is required to be included in the energy simulation for long-term use. In this case, the nodal model serves as the boundary conditions' generator for the CFD model, which then undertakes the solution of the airflow field within the building zone at each user-defined time step.

One additional limitation acknowledged in the common multi-zonal approach is that the effects of air infiltration through openings, cracks, etc. are not adequately addressed. Indeed, most computational tools for building energy simulation incorporate mainly empirical correlations and default infiltration rates depending on different leakage properties of the building envelope. On the other hand, it is true that air infiltration is a case-sensitive issue, which requires appropriate modelling treatment to account for wind- and/or buoyancy-driven air movement through openings and cracks. It is also true that intervention measures referring to air tightness and consequent infiltration may lead to high amounts of energy savings related to heating/cooling. For instance, simulations of a large number of building types document that reducing air leakage can save 5–40% of heating and cooling energy [24]. An extensive investigation involving real-scale measurements of air leakage in 129 single and multi-family houses in Spain revealed mean air-change rates of 6.1 h^{-1} for single-family dwellings and 7.1 h^{-1} for multi-family housing, which advocate relatively high contributions to the energy consumption of the tested buildings [25]. Considering the fact that air infiltration greatly affects buildings' energy consumption as well as the accuracy of simulation predictions in terms of heating and cooling loads, thus the predicted energy consumption, it deserves a great deal of attention in simulation environments. Han et al. [26] explored different modelling strategies of infiltration rates for an office building and compared their performance in terms of predictions' accuracy. They proposed a coupled approach associated with time-dependent infiltration rates by integrating multi-zone airflow modeling and CFD results into energy simulations. It was demonstrated that the suggested simulation method provides improvement of the accuracy of energy simulations with up to 11% reduction of the root mean square error and of the normalized mean bias error. Prescribing air-tightness interventions, among other envelope interventions, in higher education buildings in Egypt, total energy savings of up to 33% were documented using the multi-zonal simulation approach [27].

2.1.3. Collation of Simulation Methods

The previous paragraphs described the two major methods to deal with building physics' modelling. The CFD method provides a detailed view of the physical mechanisms occurring in building systems. It is particularly adopted to solve for the convective phenomenon that takes place in large building spaces. In such spaces, the convective phenomenon, which causes airflow parameters' non-uniformity, is well analyzed, providing an accurate prediction of the Convective Heat Transfer Coefficient (CHTC) and, thus, of heat transfer. On the contrary, the multi-zonal approach underestimates CHTC and other variables' heterogeneity in these specific cases. However, it should be pointed out that it is difficult to conduct entire building simulations using CFD due to the associated high computational time and resources. Alternatively, coupled CFD with a multi-zonal model can be used.

On the other hand, the multi-zonal method is really well adopted to treat global building physics' resolution, assuming a uniform airflow field in each thermal zone. The main objective of this method is to simplify the algebraic system by linearizing a large part of the governing conservation equations (when it is physically accepted). As a result, the technical complexity is substantially reduced and so is the required time of computations. The multi-zonal method is more appropriate when more "macroscopic" effects are of interest, such as building energy consumption, rather than when the airflow pattern is the main goal. It should be mentioned, however, that the airflow properties' variations significantly affect indoor–outdoor interactions and, in this way, the envelope thermal behaviour as well as air infiltration rates. This causes variations in systems' operation schedules, which, in turn, influence building energy consumption. In this sense, the computational tool or method used to conduct a building energy study requires experience to understand which tool is more appropriate or to know when coupled multizonal/field modelling approaches are required for more accurate and reliable studies. A summary of the capabilities of the methods discussed above is reported in Table 1.

Table 1. Collation of major building physics' simulation methods.

Method	Technical Approach	Application Field	Advantages	Drawbacks
Multi-zonal	A building is discretized into thermal zones, often being rooms. The state variables are considered uniform in each zone.	Estimation of building energy consumption; indoor air temperature; thermal loads; Dynamic change of energy consumption.	Whole building energy simulation over user-defined time periods; reasonable computational time within modest computational resources.	Difficulty to study large volume systems; Unable to study local effects caused by heat or pollutant sources; Rough approximation of air infiltration rates.
CFD	A building zone is further discretized into control volumes.	Contaminant dispersion; Indoor air quality; local thermal comfort; HVAC systems.	Detailed description of the airflow field within large spaces in buildings.	High computational time and resources; modelling complexity; requires advanced knowledge of building physics.

It should be clarified that the techniques described above need input parameters, such as the meteorological data, thermo-physical properties of the building envelope, occupancy parameters, systems' operating schedules, etc. Obviously, all these parameters are interpreted with a degree of uncertainty. In addition to these uncertainties, there are certain assumptions adopted in order to reduce the complexity of building physical mechanisms. The combination of uncertainties in interpreting collected data (physical properties, materials, and occupancy-related) with the adoption of assumptions often leads to discrepancies between the simulated results and reality. The major challenge scientists and engineers currently face is to reduce uncertainties without compromising simulations' time, practicability, and accuracy. One major source of uncertainty in building energy analysis is the end users' behaviour, considering the fact that, ultimately, the building consumes energy in accordance with the habits of occupants over building systems. Hence, it is important to realize that, in view of realistic building energy simulation, the setup of systems' operation schedules should reflect occupants' behaviour as accurately as possible. Motivated by the discrepancy between the measured and the calculated heat consumption of residential buildings, Hansen et al. [28] investigated heat-related habits of occupants, utilizing extensive questionnaire surveys, and correlated practices of adjusting thermostats, clothing conditions, perceived thermal comfort, building envelope, and systems' installations. Their study demonstrated that material arrangements substantially affect occupant expectations and practices, associated with increased indoor temperatures and energy demand. The behavioral effect is evident even in more stable buildings, such as office buildings, as presented by Liu et al. [29]. They conducted a field study in office buildings in the UK and concluded that the adaptive behaviors of occupants showed substantial seasonal and daily variations. It was shown that non-physical parameters such as habit affect the adaptive responses of occupants, sometimes yielding to absurd behavior, which could lead to increased use of energy. The key delivery of the study was the illustration of how occupants would adapt and interact with their built environment, which can be adopted in building retrofitting strategies or in energy management systems for comfortable built environments. The aforementioned studies, but also many others (for example those reported in ref. [30]), suggest that any simulation method, either multi-zonal, CFD, or other, should account for building systems' operation schedules reflecting realistic end users' behaviors. This means that accessibility to building systems' operation schedules is a prerequisite of the computational tool used for energy simulations.

As far as computational time is concerned, several solutions consisting of reducing system size exist in the scientific literature (refer, for example, to refs. [31,32]. Another idea is to reduce the detail of building geometry by merging rooms or merging walls. Such simplifications should speed up significantly the solution process. Generally, an important limitation of the physical formulation is the need for a detailed description of the physical behaviour. Therefore, it implies detailed knowledge of the physical processes, especially of the ones occurring in the interior and the exterior of the building geometry. Within the scope of this paper is to help designers in understanding better the available methods to assess building energy performance and in identifying the most appropriate computational tools in order to balance accuracy and practicability in terms of easiness to use and of calculation time. In the next subsection the most popular and widely used building energy (mainly multi-zonal) simulation tools are described, highlighting their strengths and weaknesses.

2.1.4. Building Energy Simulation Tools

There is indeed a vast amount of available computational tools for building energy simulation purposes. IBPSA-USA has developed and manages the so-called Building Energy Software Tools (BEST) directory [33], which enlists more than 200 building software tools for evaluating building energy performance. The energy tools listed in the directory range from simple databases and spreadsheets to whole building energy simulation programs. In agreement with other review studies [15,34], the current paper focuses on the most popular tools used mainly for whole building energy performance assessments regarding at least commercial and residential buildings. In the following subsections, a short overview of each tool's capabilities is reported, supported by a summary of their characteristics presented in Table 2.

Table 2. Strengths, weaknesses, and special features of computational building energy simulation tools.

Tool	Strengths	Weaknesses	Special Features			Most Common Applications	Availability
			Handling of Climate Conditions	Handling of Building Systems' Operating Schedules and Occupancy	Building Systems		
Autodesk Green Building Studio (GBS)	>Provision of hourly whole building energy, emissions, and water analysis >Reduces setup and processing time, providing possibilities for extensive tests of design alternatives >Facilitates analysis for LEED compliance	>The level of detail of the resulting DOE-2 and EnergyPlus models implies quite advanced knowledge to understand the outcomes	>Input available data of specific climate zones >User-defined climate data time series	>User-defined schedules	>Common building systems for heating, cooling, Domestic Hot Water (DHW), etc. are easily compiled >Provision of renewable energy potential (solar and wind)	>Whole building thermal performance >Building Information Modelling (BIM) > BIM-LCA coupled simulations >LEED compliance assessments	Subscription web-based service
BEAVER	>Hourly-based whole building energy performance >Calculation of building construction and systems' types to retain desired environmental conditions >Modelling of a wide range of building end uses >ASHRAE-based building load calculation and on-site generation >Numerous options of air handling systems including provisions for modifications >Fast set-up compared to most other similar programs	>Some system types are not included, e.g., chillers and condensers > limited range of window types available for selection >Does not provide environment to analyze building impact on grid >Poor approximation of natural ventilation and daylighting >Limited database of climatic conditions	>Input available data of specific climate zones >User-defined climate data time series (measured or simulated) can be fed	>User-defined schedules may be prepared and fed to the simulation engine	>Detailed representation of heating and cooling systems >Various extra components or operating strategies can be added including Heat Recovery, Preheating Coils, Exhaust Fan, Temperature reset on heating and cooling coils, etc.	>Whole building energy performance >Used mainly for residential buildings energy assessments	Commercial
Bsim	>High flexibility in the assessment of indoor environment and energy performance and in designing HVAC systems >Simultaneous simulation of heat and moisture transfer through building walls >Multi-zone air flow simulations >Graphical user interface >Reliable representation of building systems >User-friendly optimization platform >hybrid system simulation >Flexible compatibility of results' files with other Windows programs	>Cannot simulate all renewable-energy sources >Limited ready-to-use climate data (only for certain regions and Countries)	>It integrates a built-in function for converting text-based time series to the binary format >User-defined climate data time series may be prepared and inserted	>Default library of systems' schedules >User-defined schedules may be prepared and inserted	>Automatic control strategies for each ventilation plant >heating, cooling, and ventilation systems	>Phase Change Materials >Building energy performance >Building hygrothermal performance	Commercial

Table 2. *Cont.*

Tool	Strengths	Weaknesses	Special Features			Most Common Applications	Availability
			Handling of Climate Conditions	**Handling of Building Systems' Operating Schedules and Occupancy**	**Building Systems**		
ENER-WIN	>Hourly whole building energy analysis >HVAC loads' calculations >Energy consumption and demand > Life cycle cost analysis >Graphic sketch interface > Libraries for windows, wall materials, profiles, costs, lights, world-wide weather data >Thermal comfort, greenhouse gas emission, and life-cycle cost calculations	>It uses simplified algorithms >Only nine HVAC systems available >Not recommended for HVAC design analysis >Cannot simulate RES technologies	>Hourly weather data generator based on data for 1500 cities worldwide	>Limited interpretation of building systems' schedules' impact on electrical energy use	>Equipment mainly handled as thermal loads	>Large commercial buildings >Economic analysis of building energy systems and emission calculation	Commercial
EnergyPlus	>It includes innovative simulation capabilities including time steps of less than an hour >Simulation modules are integrated with a heat balance-based zone simulation >It facilitates third party interface development for co-simulation purposes >Inclusion of multizone airflow, electricity simulation including fuel cells and other distributed energy systems > Designbuilder: User-friendly graphics interface, CFD module, Optimization module	>Relatively high level of complexity >No grid-integration analysis >Energy simulation and computer skills are required >Building physics' knowledge is a prerequisite >DesignBuilder: Offers a user-friendly interface and well-structured input wizards, which simplify simulation setup	>Extensive library of weather of specific locations >User-defined climate data time series >DesignBuilder: the CFD suite allows for estimating local microclimate effects	>User-defined systems' schedules >DesignBuilder: Vast menu of default occupancy schedules are available according to the building use	>The majority of systems (HVAC, Air handling units and control, DHW, etc.) of various building types can be employed >DesignBuilder: Provides vast lists of building systems, construction materials, and properties	>Whole building energy analysis for various building types >DesignBuilder: Widely used for extensive parametric analysis and optimization of alternative energy-upgrading measures >Proof-of-concept purposes for new technologies	>EnergyPlus: Free >DesignBuilder: Commercial
eQUEST	>User friendly building energy analysis tool >It provides interactive graphics, parametric analysis, and rapid execution >Flexible application to the entire design process, from the conceptual design stage to the final design >It offers detailed analysis throughout the construction documents, commissioning, and post-occupancy phases	>Supports only IP units (no SI units) >Ground-coupling and infiltration/natural ventilation models are simplified and limited >Does not include RES technologies >Does not calculate thermal comfort indices > Weather files	>Library of pre-defined weather data limited for US regions >User-defined climate data time series may be prepared and inserted	>User-defined systems' schedules	>It contains a relatively large database of HVAC systems	>Whole building energy analysis for various building types >It is particularly useful to assess occupants' behaviour in tertiary buildings >Suitable for EPC projects (when calibrated in comparison with actual energy consumption data)	Free

Table 2. *Cont.*

Tool	Strengths	Weaknesses	Special Features			Most Common Applications	Availability
			Handling of Climate Conditions	Handling of Building Systems' Operating Schedules and Occupancy	Building Systems		
ESP-r	>Provision of in-depth appraisal of the factors that influence the energy and environmental performance of buildings >Flexible and powerful enough to simulate many innovative or cutting-edge technologies including daylight exploitation, natural ventilation, combined heat and electricity generation and photovoltaic facades, CFD, multi-gridding, and control system	>It is a general-purpose tool and requires user efforts to set up modelling for certain cases; thus it implies advanced expertise >It is focused mainly on building thermal performance >No automatic optimization is provided >No economic analysis is provided	>User-defined climate data time series	>Limited interference with thermal-related building systems >User-defined schedules may be imported	>Handled mainly as heat sources >Supports simulations for RES technologies (mainly PVs)	>Whole building energy simulation >Used mainly to estimate energy demand >Often used to study behaviour relevant to daylighting >Study of combined heat and power applications	Free
IDA-ICE	>Annual dynamic multi-zone simulation application for indoor climate assessments and energy performance >Early-Stage Building Optimization >Complete energy and design studies >Accessibility to incorporate user-defined models	>Time-consuming calculations due to the employment of the airflow network modelling method, which often requires a large number of zones	>Library of climate data >User-defined climate data time series	>User-defined systems' schedules >Adjustable windows' modelling is also included	>HVAC systems may be analyzed >DHW >Renewable energy systems	>Whole building energy simulation >It is widely used to assess the efficiency of heating systems >PCM applications	Commercial
IESVE	>Provision of in-depth suite of building performance analysis modules >Useful to identify best passive options and renewable energy measures >HVAC system modelling >Natural ventilation modelling >Daylight and shading analysis >CFD analysis	>Energy and building physics' expertise are required >Linux environment is not supported	>Library of climate data included >User-defined climate data time series may be imported	>Menu of default HVAC schedules >User-defined HVAC schedules	>pre-defined HVAC component libraries and Manufacturer properties	>Whole building energy simulation >Often used for assessing renovation projects >Investigation of future-proof energy-upgrading measures	Commercial
SUNREL	>Appropriate for passive solar buildings >Predicts occupant behavior >Includes algorithms for Trombe walls, glazings, controllable window shading, active-charge/passive-discharge thermal storage, and natural ventilation	>Limited HVAC modelling >Does not calculate thermal comfort indicators >Does not provide RES simulations >Does not model building-to-grid integration	>Available hourly weather data >User-defined hourly weather data may be imported	>User-defined schedules mainly for envelope parameters, such as windows >Occupancy schedules	>In its early versions, HVAC performance was not supported	>Building thermal performance >Shading analysis >Insulation performance analysis >Energy load modelling >Mainly used for single- and multi-family buildings	Free

Table 2. *Cont.*

Tool	Strengths	Weaknesses	Special Features			Most Common Applications	Availability
			Handling of Climate Conditions	Handling of Building Systems' Operating Schedules and Occupancy	Building Systems		
TAS	>Prediction of energy consumption, CO2 emissions, operating costs, and occupant comfort >Building thermal simulation >Plant and systems' operation modelling >Offers comprehensive capabilities for all types of energy modelling >User-defined special building physics' models, such as evaporation and evapotranspiration >Can simulate large and complex buildings	>Energy and building physics' expertise are required >Computer skills are required	>User-specified detailed weather data >Default weather files	>User-defined systems and occupancy schedules>Default schedules based on building type	>HVAC systems with HVAC manufacturers' databases >DHW systems >Daylighting >Renewable energy systems	>Whole building energy analysis >Often used to test planted roofs and walls >Able to test CHP applications in buildings	Commercial
TRNSYS	>Whole building energy analysis >HVAC analysis and customization, multi-zone airflow analyses, electrical power simulation, solar design, building thermal performance, control schemes >It interfaces with various other simulation software such as FLUENT for airflow impact on energy consumption, GenOpt and MATLAB for optimum building control	>Energy and building physics' expertise are required >Fluent computer skills are required in case of co-simulations >Grid interconnection analysis is not included >Direct economic analysis is not included	>User-specified detailed weather data >Extensive Default weather files >Interconnects with CFD tools to account for local microclimate effects	>User-defined systems and occupancy schedules>Default schedules available based on building type	>HVAC systems with manufacturers' databases >DHW systems >Daylighting >Renewable energy systems' databases	>Whole building energy analysis >Often used to test PCM performance >Coupling with CFD tools >Building energy management systems (model-predictive control cases) >HVAC and power systems' analysis >Solar systems design	Commercial

The tools of interest herein are:

- Autodesk Green Building Studio
- BEAVER
- BSim
- ENER-WIN
- Energy plus
- eQUEST
- ESP-r
- IDA Indoor Climate and Energy (IDA-ICE)
- IES Virtual Environment (IESVE)
- SUNREL
- TAS
- TRNSYS

Autodesk Green Building Studio

The Autodesk Green Building Studio is a web-based service that envisages whole building energy, water resources, and CO_2 emission analyses of buildings. The analysis is conducted via the Internet in a personalised web environment. This streamlines the entire setup process and facilitates immediate feedback on design alternatives. Based on the building's basic characteristics, such as size, type, and climate zone, the web-based service defines default values for construction materials and equipment by adopting regional building regulations. Using simple drop-down menus, the user can test different settings of the design, orientation, thermal transmittance, window glazing, or various HVAC systems. The service includes hourly weather data, as well as historical rain data as inputs. It calculates carbon emissions and presents the output in a web browser, for instance, the energy consumption and cost indicators as well as the potential for carbon neutrality. The output also tabulates the consumption of water resources and energy costs, providing an ENERGY-STAR score. Other useful indicators are also calculated such as solar and wind energy potential, LEED daylighting credit, and natural ventilation potential.

Najjar et al. (2017) [35] used the software in the case of a typical multi-storey office building located in Brazil in the framework of Building Information Modelling (BIM)—Life Cycle Analysis (LCA) simulation concept. In their modelling approach they incorporated Green Building Studio (GBS) to assess building energy performance for different construction materials. In a design control volume extending from the extraction of raw materials through construction and operation to disposal and recycling, they demonstrated that most of the negative environmental impacts are occurring during the manufacturing and operation phases. The methodology proposed can successfully determine which building elements have major importance in the LCA at the early design stage, thus providing an adequate decision-making tool for minimizing buildings' environmental impacts throughout the building lifespan. Using Revit, Abanda and Byers [36] developed a house model that was exported into Green Building Studio (GBS) for further calculations. The energy-efficiency potential was explored by means of a parametric analysis for building orientation. GBS is particularly efficient to conduct extensive parametric analyses regarding building energy performance. Indeed, it has been successfully used to study the energy impacts of extensive combinations of envelope and internal configurations, e.g., Window-to-wall ratios, wall and roof construction materials, and HVAC, and of external conditions such as climatic ones, and orientation and building exposure levels (by means of building complexes) [37].

BEAVER

BEAVER [38,39] is a Windows environment for the APEC ESPII Building Energy calculation Program. It provides easy input of data, model set-up, and results' preview. The program computes building energy consumption over a defined period, taking into account climate zone and location, construction materials, and systems' types required to satisfy the desired environmental conditions. It allows parametric analysis regarding building configurations and air conditioning systems. Data input is inserted via windows wizards, which include drop-down menus and entry fields on consecutive screens going through the general Project information to individual space data and building systems, capacities, operating schedules, etc. It includes default air handling systems, primary plant, and control schemes enabling the compilation of a wide range of building services. The Air Handling system type is quite easily prepared through a graphic-based manner of the units' assembly. Various extra components and operation schedules may be imposed referring, for instance, to Heat Recovery, Preheat Coils, Exhaust Fan, Temperature reset on heating and cooling coils, etc.

An extensive application study of BEAVER for assessing building energy performance was presented by ACADS-BSG Pty Ltd. and Elms Consulting Engineers [40]. The software was used to review and provide comments on suitability of the climate zones proposed in terms of the theoretical energy use. It facilitated proposing a representative location within each zone that can be adopted to reflect the thermal resistance of the predefined buildings and define the least number of other locations required to define the thermal-response extremes within each zone. The substrates used for the review of zones were various types of office buildings with and without infiltration conditions. The software was successfully used for the revision of climate zones used as inputs to assess building energy performance.

BSim

BSim [41] envisages user-friendly simulation of energy and hygrothermal simulations of buildings. The software consisted of the following modules: SimView (user interface and graphic model editor), tsbi5 (simultaneous thermal and moisture building simulation tool), XSun (dynamic solar and shadow simulation and visualisation), SimLight (daylight calculation tool), SimDXF (CAD import facility), and SimPV (building-integrated PV system calculation). Furthermore, there are export facilities to external tools: Be06 (Danish compliance checker), Radiance (advanced light simulations), and boundary conditions for CFD simulations and visualisation in tools using DirectX input files. BSim has been used extensively over the past 20 years in Denmark, presenting increased interest abroad, as it provides both energy and moisture analysis [42]. BSim applies the quasi-steady approach in building modelling, and it is often used for phase change materials' modelling using the heat capacity method. The BSim software has been successfully applied for the determination of the effect of the basic heat gains on building energy consumption by Sikula et al. [43] and it was demonstrated that the highest heat gain comes from solar radiation. Model validation procedures showed a deviation of only 8% between the simulated annual energy consumption and the measured one. Applications of the BSim, among other tools, may be also found in a report under the International Energy Agency (IEA) Programme for energy conservation in buildings and Community systems [44]. The software was used mainly to simulate energy performance of typical residences located in different locations (climatic zones) in the pre-renovation situation in order to assess the impact of different climatic conditions on building energy consumption. The high fidelity of BSim simulations is documented by the fact that it has been also used as a generator of reference building energy performance indicators over which other novel energy calculation methods are tested, for example, in the case of a smart glazing facade under different control contexts (night shutter, solar shading, and natural ventilation) [45]. Sorensen et al. [46] used the software to develop an integrated building energy design of a Danish office building, incorporating a Monte Carlo Simulation method, and produced a pool of engineering solutions with enough design freedom for architects. The study explores global design with Monte Carlo Simulations, in order to form feasible solutions for architects and facilitates the collaboration linkages between architects and engineers.

ENER-WIN

The ENER-WIN [47] simulates hourly based energy consumption, including annual and monthly averages, peak demand, peak heating and cooling loads, solar-fraction through glazing, daylighting contribution, and life-cycle cost analysis. Design parameters are separately tabulated for each zone, also providing duct sizes and electrical power requirements. The software comprises several modules, i.e., an interface module, a weather-data retrieval module, and a sketching and an energy simulation module. ENER-WIN requires the following inputs: the building type, location and geometry, external ground parameters, operation patterns and loads (e.g., occupancy, lighting, equipment, and domestic hot water), and heating and cooling inputs (ventilation rate and schedules, thermostat settings and heating/cooling equipment types, systems' efficiency and set points).

Using ENERWIN in order to evaluate the reasons for high electrical use in 30 residences in Kuwait allowed for researchers to conclude that annual energy use in residential buildings was directly related to occupants' behavior and that data relating to the type of occupant should be taken into account as accurately as possible [48]. ENER-WIN was applied by Soebarto and Williamson [49] for the development of a multi-criteria decision-making approach based on the "Reference Building" concept. Using the databases of building materials, climate conditions, and systems incorporated in the ENER-WIN tool, they integrated an approach of creating a reference building that satisfies ASHRAE Standard 90.1 [50] requirements. The energy performance of the actual building was evaluated based on the deviations between the actual and reference building and it was concluded that the approach was useful for testing different design strategies. It should be clarified that the referred ASHRAE Standard has been replaced by the latest version 90.1-2019, i.e., the study cited previously is limited only to the older version of the Standard. As indicated by the software vendor [47], the latest Enerwin 2020 version incorporates ASHRAE Standards 90.1-2019.

EnergyPlus

EnergyPlus [51] is a modular-based code that is built upon the well-known models BLAST and DOE-2 [52]. It is a simulation engine that manipulates input and output in text-command formats. A heat-balance engine undertakes the calculation of loads at a user-specified time step, which is then passed to the building systems' simulation module at each time step. The systems' simulation module computes heating and cooling system and electrical system responses. This integrated solution ensures precise space temperature prediction, which is crucial for system design, occupant comfort, and air quality calculations. Integrated simulation provides possibilities to evaluate plausible system controls, moisture transfer through construction elements, radiant heating and cooling systems, and interzone airflow.

Tsikaloudaki et al. (2012) [53] used EnergyPlus to evaluate the cooling performance of a wide variety of geometrical, thermo-physical, and optical properties of windows. The maximum cooling loads were documented when windows' solar transmittance is high and thermal transmittance is low. It was demonstrated that in Mediterranean climates the combined high efficiency of transparent elements and controlled ventilation in office buildings reduce heat losses and ultimately result in higher cooling energy loads. Goia et al. [54] used EnergyPlus to develop a methodology for determining the optimal glazing percentage in a façade unit for low-energy office buildings. The investigation involved three alternative building design versions with different HVACs' efficiency. It was shown that, regardless of the orientation and building façade area, the optimal configuration corresponds to a transparent-area percentage ranging between 35% and 45% of the total façade area. Due to its fully accessible suites, it has been widely used for coupled Building Energy/Computational Fluid Dynamics (BES-CFD) simulations for the quantitative analysis of building energy performance, taking into account the external microclimate conditions, thus accounting better for local environmental effects in the vicinity of the buildings [55–57]. Due to its modular nature, it requires advanced knowledge of building physics as well as high computer skills, especially in case of complex physical systems such as those focusing particularly on indoor–outdoor interactions.

The DesignBuilder software [58] confronts the aforementioned barrier as it essentially represents a user-friendly version (in fact, with elegant graphical interface), including additional modules such as that of CFD computations for both indoor and outdoor airflow simulations. DesignBuilder software stands for a general purpose simulation engine allowing for energy analysis and automatic optimization for various building systems (HVAC, lighting, DHW), RES technologies, and construction materials, calculating additional key performance indicators such as thermal comfort (PMV, PPD), carbon and GHG emissions, and financial analysis. Thus, it serves for holistic decision-making strategies. In the framework of the IMPULSE project (Interreg MED 2014–2021), it has been used to prioritize retrofitting measures towards the gradual energy-upgrading plan for public buildings (in accordance with the EU directive 2012/27/EU) in the Municipality of Heraklion, Greece [59]. Among many applications for both practical and research purposes, it has been used to demonstrate proof of concept regarding energy-upgrading measures, for example, for reflective (cool) materials' applications [60,61]. Specifically, for PCM applications it has become evident that EnergyPlus contains numerical models much more accurate than those of other popular BES tools, such as TRNSYS [62]. The tool has been also used with success to prescribe retrofitting strategies, focused on the building envelope, for higher education buildings in Egypt [27], concluding with useful suggestions for design codes ensuring balance between thermal comfort and energy efficiency.

eQUEST

eQUEST [63] is a user-friendly building energy simulation tool consisting of a building creation wizard, an energy systems' wizard, and a graphical interface module. It incorporates an enhanced DOE-2 simulation program, which performs an hourly based energy simulation based on properties of opaque and glazing construction elements, occupancy patterns, loads, and ventilation. The simulation module also accounts for the performance of conditioning systems, such as fans and chillers, boilers, and other energy-consuming devices. The eQUEST foresees utilities for parametric analysis of alternative designs and viewing of immediate, collated results. It foresees energy-cost estimating, daylighting, and lighting system control as well as quickly imposing energy-efficiency measures (by selecting preferred measures from a list).

Azar and Menasa [13] used eQUEST to conduct a sensitivity analysis on the occupancy behavioral parameters of typical office buildings of different sizes and in different climate zones. Sensitivity levels varied with building size and weather conditions, and the highest sensitivity was observed when altering the "heating temperature set-point" parameter in small-size buildings located in dry climatic conditions. Recently, the software was used to review the effects of thermal and optical properties of electrochromic windows (ECWs) on the energy performance of a typical office building configuration in Korea [64]. Kim et al. [65] demonstrated the flexibility in incorporating user-defined solar models as input conditions into the software towards the estimation of typical office building energy performance. In view of the important need for the lowest possible deviation between simulated and actual energy consumption when it comes to Energy Performance Contracts (EPC), the eQUEST has been already used to calibrate energy simulation results using actual electricity bills and further applied to investigate EPC reliability for an actual office building in Taiwan [66]. The software allows detailed techno-economic assessment of novel technologies in buildings, as demonstrated by Seyednezhad and Najafi [67]. They investigated various operating conditions for a Thermoelectric-based cooling and heating system on an office-type building in Melbourne, FL, USA, and determined the cost, as well as potential savings, for each tested operating condition. Wang et al. [68] used the software to develop a strategic approach on the energy efficient analysis of the water-heating-system retrofit by applying a heat pump system in a university dormitory located in a central part of Taiwan.

ESP-r

ESP-r [69] is a general purpose, multi-domain-building thermal, interzone airflow, intrazone air movement, HVAC systems, and electrical power flow-simulation environment. It supports CFD models for analyzing air quality and comfort calculations. By addressing all design and systems' aspects simultaneously, ESP-r permits the investigation of complex relationships among building form, envelope, airflow, systems, and control. It employs a finite volume conservation approach in which a problem is transformed into a system of algebraic transfer equations of dependent variables (energy, mass, momentum, etc.), which are then integrated at successive time steps with respect to climate, occupant, and control system conditions. It comprises a central Project Manager providing navigation through support databases, a simulator, performance assessment tools, and a variety of third party applications for CAD, visualization, and report generation.

Hoseggen et al. [70] applied ESP-r to conclude whether a double-skin façade should be applied to the east façade of an office building in Trodheim, Norway, towards the reduction of heating demand. The paper also demonstrates how a double-skin façade with controllable windows and hatches for natural ventilation can be implemented in the simulation program. Bourgeois et al. [71] studied the occupancy behavioral patterns on building energy consumption using ESP-r. They demonstrated the implementation and integration of a sub-hourly occupancy-based control model that enabled advanced behavioral models. It was shown that building occupants seeking daylighting can lower the primary energy consumption by more than 40% compared to occupants relying on constant artificial lighting. The software (among others) has been employed to develop guidelines for seasonal energy consumption for heating and ventilation based on short periods of heat demand measurements and to determine the optimal duration of the measurement period [72]. Bonetti and Kokogiannakis [73] revealed a fine performance of the software in the framework of exploring exergy potential of seven different building wall types for utilizing nocturnal ventilation as a passive cooling strategy. Eller et al. [74] used the software to explore the potential of a bio-based phase change material (PCM) applied to construction components regarding the impacts on thermal performance under several climates, and determined the associated potential of energy savings.

IDA-ICE

IDA Indoor Climate and Energy (IDA-ICE) [75] software is a whole year detailed and dynamic multi-zone simulation application for the study of indoor climate and energy. The IDA-ICE user interface is designed to ease the development and simulation of both simple and advanced cases, in a 3D environment, in combination with comprehensive tables, providing the optimal feedback. A simple procedure for calculating and reporting thermal loads and energy demand, together with a built-in version handling system, facilitates comparisons among different systems and results.

IDA physical systems are described using symbolic equations, in either Neutral Model Format (NMF) or Modelica. IDA-ICE offers separated but integrated user interfaces to different user categories, e.g., wizard interfaces for developing the building model, standard interface serving for model setup by means of concepts and objects (such as zones, radiators, and windows), interfaces for advanced users to import, browse, and edit the mathematical formulations, etc.

Salvalai [76] used IDA-ICE as a building energy simulation platform within which a water-to-water heat pump model was implemented. Results obtained were in good agreement with experimental data. Hesaraki and Holmberg [77] also used IDA ICE to investigate the impact of low-energy heating systems in newly built semi-detached dwellings in Stockholm, in relation to the Swedish building regulations. They demonstrated that the installation of heating systems in combination with under-floor and ventilation radiators not only met energy requirements of regulations but also provided thermal comfort. Numerical results were validated with measured data. Rabani et al. [78] used the software to develop a fully integrated BES optimization CFD daylight simulation applied for a generic office building located in Oslo. The proposed model successfully optimized building envelope properties, fenestration parameters, and HVAC systems' set points towards minimization of building energy consumption and acceptable thermal and visual comfort conditions. As far as its accuracy is concerned, very good agreement with internal air temperature has been documented in comparison with measurements obtained at controlled free-floating conditions regarding PCM performance [62]. Recently, IDA-ICE was used for the energy-renovation study of two Danish heritage/historical buildings [79]. Two renovation cases were studied through the available measurement and calculation results before and after renovations and significant energy-saving amounts were demonstrated without compromising the cultural values of buildings.

IESVE

IES Virtual Environment (IESVE) IESVE [80] is an in-depth suite of building performance analysis tools. It allows the design and operation of energy efficient buildings. Whether working on a new building or existing building renovation project, IESVE offers the ability to test different options, identify the optimal passive solutions, compare low-emission and renewable-energy technologies, and formulate conclusions on building energy indicators. It includes numerous utilities providing sustainable analysis compatible with the needs of different design team members and design stages. The main modules included in this software are the following:

- Model, IT geometry creation and editing

- ApacheCalc, loads' analysis
- ApacheSim, thermal
- MacroFlo, natural ventilation
- Apache HVAC, component-based HVAC
- SunCast, shading visualization and analysis
- MicroFlo, 3D CFD
- FlucsPro/Radiance, Lighting design
- DEFT, model optimization
- LifeCycle, life cycle energy and cost analysis
- Simulex, building evacuation

Murray et al. [81] applied IESVE to plan a retrofitting project of a case study building located at Cork University College, for which both modelling and actual interventions were applied. This approach allowed the comparison between simulated and measured data and a good agreement between them was concluded. Ouedraogo et al. [82] used IESVE to investigate the impact of climate change on future trends of electricity demand for air conditioning in public buildings within the period 2010–2080. Their study highlights the fact that the predicted mean temperature using a specific climate-change data scenario will increase by about 2 °C by 2050, yielding to a significant increase in air-conditioning energy consumption for case-study buildings in the Burkina Faso built environment. For this specific region, they concluded that shading devices could reduce the cooling load by 40%; thus, they could play an important role in climate-change resilience strategies for buildings. Recently, the tool was used to investigate the energy-saving potential obtained by the application of bio-based wall construction in rural residential buildings in Northeast China [83]. Interestingly, it was found that reductions of 45.82–204.07 kWh/m^2/year in heating energy demand and more than 40% in coal consumption are possible through the application of bio-based wall constructions.

SUNREL

SUNREL [84] developed by the National Renewable Energy Laboratory (NREL) is an hourly based building energy simulation software oriented to the design of small, energy-efficient buildings where the loads are governed by the dynamic interactions among the building envelope, environment, and occupants. It has a simplified multi-zonal airflow algorithm that can be used to calculate infiltration and natural ventilation. Users can enter the optical interactions of windows with identical layers of clear or tinted glass and no coatings on the layers. Thermal properties are modelled with a fixed U-value and fixed interface coefficients. SUNREL is particularly appropriate for passive solar buildings and incorporates specialized algorithms that treat the physical effects of Trombe walls, glazing, controllable window shading, active-charge/passive-discharge thermal storage, and natural ventilation. The building is represented by a thermal network model solved with forward finite differencing, among other techniques. Additionally, a simple graphical interface allows users to easily provide input and preview the output. Elzafraney et al. [85] used SUNREL to demonstrate the benefit of enhanced concretes containing coarse aggregates of recycled plastics. The tool was used to simulate the thermal and building energy performance of two building configurations with and without polymer aggregates, and it was found that the former one led to a substantial reduction of heating and cooling loads while ensuring thermal comfort.

TAS

TAS [86] simulates the dynamic thermal performance of buildings and their systems. Its prevailing module is the TAS Building Designer, which undertakes dynamic simulation with integrated convective airflow. It has a 3D graphics-based geometry input that includes a CAD link. TAS incorporates an HVAC systems/controls' simulator, which can be directly interconnected with the building simulator. The TAS Ambiens module incorporates a 2D CFD package, which produces space microclimate at a cross-section level. TAS combines dynamic thermal simulation with natural ventilation calculations, which include advanced control functions on aperture opening as well as the ability to simulate mixed mode systems. The software has heating and cooling plant sizing procedures, which include optimum start.

Wong at al. [87] used TAS to investigate the impact of vertical greenery systems on the temperature and energy consumption of buildings. The results revealed a linear correlation between shading coefficient and leaf area, where a lower shading factor leads to a greater thermal insulation. As far as the use of TAS for understanding the influence of different architectural design strategies in energy demand is concerned, Pino et al. [88] demonstrated its efficient use for such purposes, especially for office buildings. Recently, it was employed to compare traditional and contemporary mosque buildings by means of dry bulb air temperature and various thermal loads in Oman [89]. As shown by Salem et al. [90], the software can adequately predict the impacts of both combined heating power (CHP) and combined cooling–heating power (CCHP) in a real-case scenario of a hotel building in the UK, regarding energy efficiency, energy cost, payback, and carbon emissions. In the same study, additional simulations under climate-change projections revealed that a CCHP system outperforms a CHP system. Amirkhani et al. [91] investigated the impact of a Low-emissivity window film on the overall energy consumption of an existing hotel building in the UK using the software, and estimated that by applying the suggested low-e film, savings in heating, cooling, and total energy consumptions may reach 3%, 20%, and 2.7%, respectively.

TRNSYS

TRNSYS (Transient system simulation program) [92] is a program with a modular structure that implements a component-based approach. Its components extend from simulating a single pump or pipe to a multi-zonal building model. Its components assemble in a fully integrated visual interface called TRNSYS Simulation Studio, while building input data are entered through a dedicated visual interface (TRNBuild). The simulation engine then solves the algebraic system of the discretized differential conservation equations consisting of the energy system. HVAC system components are solved simultaneously with heat conservation through the building envelope and the air network at each time step. In addition, the TRNSYS library includes components for solar thermal and photovoltaic systems, low-energy buildings, HVAC systems, renewable energy systems, cogeneration, fuel cells, etc. The modular nature of TRNSYS facilitates the compilation and integration of new mathematical models to the program regarding, for example, walls' boundary conditions, systems' properties, and operation schedules. It presents high flexibility and compatibility with other software (e.g., Matlab/Simulink, Excel/VBA) for co-simulation, optimization, and optimal control purposes. TRNSYS can generate redistributable applications that allow less-skilled users to run simulations and parametric studies. It has been widely used and tested for whole building energy simulations for more than 20 years. It exhibits perhaps the highest sophistication regarding modelling of solar radiation passing through windows since it considers variable optical properties with incidence angle and in terms of treatment of direct and diffuse solar radiation distribution into a zone [62].

Ibanez et al. [93] used TRNSYS to simulate the impact of Phase Change Materials (PCM) integrated into walls, ceiling, and floor of an experimental room built with concrete panels with PCM, on the whole building energy balance. An acceptable agreement between the simulated and experimental results was obtained. Beausoleil-Morrison et al. [94] developed an ESP-r/TRNSYS co-simulator, which was applied for evaluating the performance of a solar-thermal system in a low-energy building. The suggested co-simulation environment proved to be an effective tool for designing solar buildings, particularly when architectural, energy conversion, and storage systems are all integrated. The software has been also used to present and compare a series of passive and active measures for energy upgrading of various building types (educational, museum, sports facility, Municipal Office building, and a residential, detached building) in a typical Mediterranean climate [95]. In such climatic conditions, Pérez-Andreu et al. [96] applied TRNSYS to study the benefits of passive construction measures in a typical Mediterranean dwelling, in terms of energy consumption and thermal comfort, taking into account site wind and occupants' behavioral conditions. Validation and model-calibration processes revealed excellent agreement between simulated and actual (measured) data referring to indoor monthly averaged air temperature and relative humidity.

2.2. Urban Microclimate Modelling

The global trend towards urbanization in parallel with climate-change implications justifies the growing interest in the study of combating adverse effects of extreme microclimate conditions on urban activities relating to building energy consumption and health. The Urban Heat Island (UHI) effect presented evermore high intensities during the last 10 years, which significantly impacted pedestrians' thermal comfort and perception of air quality as well as energy demand of buildings in dense urban environments. Landsberg [97] states that the UHI phenomenon is the most obvious climatic manifestation of urbanization. Indeed, numerous studies in the scientific literature have highlighted the adverse effects of urban extreme microclimates, especially UHI, on building energy demand and consumption as well as thermal comfort and well-being [98–100]. In accordance with the scientific evidence, the European Commission indicated the requirement to account for local climate, especially in developing strategies to meet the Nearly-Zero Energy Building (NZEB) goal (refer, for example, to its 2012 release "Evaluating and Modelling Near-Zero Energy Buildings: are we ready for 2018?" [101]). Considering the latest research findings as well as trends in energy policies that necessitate building energy design with accurately predicted performance indicators, building simulation techniques, taking into account the external microclimate effects, should no longer be considered as "for research purposes only" and move to the practitioner level at the early design stages. Accepting the suggestion that in modern case studies indoor and outdoor physical effects are inseparable, this paper extends the review to include basic computational methods and tools for quantifying urban microclimate effects. The present section reviews the methods and popular computational tools that can be used to quantify the physical variables comprising urban microclimate (mainly by means of its UHI manifestation) in open spaces, such as wind speed, temperature, and relative humidity, including thermal comfort indicators of pedestrians.

The Urban Heat Island effect is related to higher urban temperatures in city centres compared to the surrounding rural or suburban areas [102]. This situation emanates from anthropogenic heat sources, e.g., vehicles, power plants, air-condition units, etc., as well as by other heat stresses produced by the use of ground or building materials of poor thermal behaviour and the lack of heat sinks (e.g., water surfaces) and of vegetation [103]. Fundamental causes of the UHI were indicated by Oke [104] and their relative importance was further validated in numerous follow-up studies:

- Trapping of short- and long-wave radiation in areas between buildings
- Reduced long-wave radiative heat loss due to low sky-view factors
- Increased sensible-heat storage in the construction materials
- Anthropogenic heat released mainly from fuel combustion (domestic heating, vehicles, etc.)
- Reduced evapotranspiration due to limited plantation, which means that energy is converted into sensible rather than latent heat
- Reduced heat displacement due to reduced wind speed

Studies of the UHI are usually focused on the so-called heat island intensity, which is the maximum temperature difference between the city and the surrounding rural or suburban area. The intensity is mainly determined by the heat conservation of the region and is, therefore, subject to diurnal variations and short-term weather conditions [105,106]. There are two major simulation methods often used to assess UHI [107]:

- Energy balance models
- Computational Fluid Dynamics (CFD) models

In the following subsections, the background of the simulation methods and a comparative analysis between them is discussed, while the most popular computational tools of each method are briefly described in terms of their strengths and weaknesses.

2.2.1. Energy Balance Models

The energy-balance (or urban energy-budget) concept was first suggested by Oke [104]. This method adopts the principle of energy conservation for a given control volume, and manipulates the wind-induced phenomena, i.e., turbulence and velocity fields, as simple heat fluxes. These fluxes are generally defined by analytical or empirical equations. In the last two decades the energy-budget concept has been enhanced to the so-called Urban Canopy Model (UCM), which is derived from the energy balance equation for a control volume containing two adjacent buildings. The model considers the energy exchanges between solid surfaces of the domain and the urban canopy and predicts the ambient temperature and solid-surfaces' temperature of the urban fabric components. However, the airflow is decoupled from the temperature field, being treated as a separate input into the control volume. For this purpose, the logarithmic or the power law [16] is widely used in order to represent airflow in the domain of interest. In the UCM approach, all surfaces and control volumes are interconnected by means of an electrical analogue. The energy conservation equation [107] is then applied to each node, thus being discretized to an algebraic system comprised of matrices of temperature and humidity coefficients. An iterative solution of the system provides the temperature and relative humidity distributions throughout the domain. One-layer [108] and multiple-layer [109] schemes depend on the nodes' number on the building walls, while such models can be also developed into one to three dimensions. This approach is fast, in general, as it treats building canopies with a low number of nodes. It provides acceptable predictions but mainly in large-scale cityscapes.

The omission of an air velocity pattern represents the major drawback of UCM models. Indeed, the resolution of the air velocity field facilitates the study of special airflow effects, e.g., eddy circulation and dissipation, wake regions, and turbulence intensity, and of the atmospheric phenomena (e.g., precipitation and stratification), towards the determination of heat fluxes' components. The consequent approximation of heat fluxes using empirical correlations in UCM models rarely captivate the interaction between velocity and temperature fields. Provided that data for three-dimensional geometries of building canopies and urban structures correspond to high computer loads, the urban complex is often represented by homogeneous columns as building boxes. Cityscape geometry is also approximated with coarse grids on ground, roofs, and walls, hence, weakening the reliability of the energy-conservation solution, especially when the focus is on pedestrians' thermal comfort.

2.2.2. Computational Fluid Dynamics

Unlike the energy-balance models, CFD simultaneously solves all the governing equations of airflow within the urban fabric, i.e., conservation equations of mass, momentum, thermal energy, chemical species, and turbulence parameters for single- and multi-phase flow phenomena. As a result, CFD can produce more accurate information about the UHI effect within and above building canopies compared to the energy budget models. Consideration of complex details in addition to complicated atmospheric interactions of the cityscape is, nonetheless, both a computational and theoretical challenge. The former refers to the high number of the computational nodes to simulate the airflow, while the latter is related to the unmatched temporal and spatial resolution of the physical mechanisms occurring within the cityscape. For example, turbulence length scales within and above the canopy differ significantly; thus, they cannot be modelled in the same scale. This suggests the division of the CFD simulation into different scales for UHI studies [107]: Meso-scale and Micro-scale (within the urban canopy).

Meso-scale models present horizontal resolutions ranging from one to several hundreds of kilometres. Vertically, they vary with the depth of the so-called Planetary Boundary Layer (PBL) (the layer between the earth surface and geostrophic wind), i.e., in between 200 m and 2 km [107]. In such models, large-scale interactions under the PBL are analysed, involving treatment of the atmospheric stratification and surface layer. In this approach, the atmospheric stratification is resolved by adopting either the hydrostatic or the non-hydrostatic assumption in the Navier–Stokes equations. The hydrostatic assumption refers to a simplified motion equation in the vertical axis in terms of a balanced correlation between the buoyancy and the pressure term. On the other hand, the non-hydrostatic assumption refers to the full Navier–Stokes equation in the vertical axis. Meteorological schemes mostly use Monin–Obukhov or other similarity schemes to model the surface sublayer [110], and building canopies are simulated by means of aerodynamic roughness. This means meso-scale models manipulate the complex phenomena within the urban canopy only by a roughness value. Consequently, information about variations of dependent variables within the canopy layer is extremely limited. However, this simplification facilitates the understanding of physical phenomena (for instance, surface drag, shear stress) at least within the urban surface layer but above the canopy layer. The precision of meso-scale modelling is strongly dependent on the available land-use parameters. Detailed information of solid surfaces at micro-scale level (e.g., thermo-physical properties, geometry, optical properties) is rarely available for the entire urban area of interest. Even in the contrary case, applying these details to a meso-scale model increases the required computational resources. Since the spatial resolution is in the order of a few kilometres, it is also necessary to assume a meso-scale zone as a homogeneous area and estimate the surface properties with bulk values, e.g., albedo, emissivity, and roughness.

On the other hand, micro-scale CFD resolves the conservation equation inside the canopy layer. In the meso-scale layer, the horizontal spatial quantities are usually accounted for as homogeneous values, while the quantities within the actual geometry are simulated in detail, taking into account surface physical interactions in the micro-scale layer. These interactions are generally represented by the Monin–Obukhov similarity theory to represent the PBL in meso-scale layers. Obviously, it is not realistic to apply micro-scale modelling for an entire city, with all geometric details, due to the high computational cost. Therefore, the common approach is to limit the simulation into a small domain in the magnitude of some blocks of buildings (few hundreds of meters), as done, for example, by Stavrakakis et al. [103]. On the other hand, the treatment of the PBL in a micro-scale model is not as comprehensive as in the meso-scale model, which means that micro-scale modelling does not account for atmospheric interactions such as vertical mixing or Coriolis effect. Observational schemes [107] can significantly improve the aforementioned limitations. However, providing boundary conditions in the micro-scale model is even more complicated than in the meso-scale model. In micro-scale modelling more measurements are necessary due to high fluctuations of airflow quantities near surfaces. Although the assumptions of a homogeneous boundary layer [111] and corresponding boundary conditions [103] may be adopted, these approaches are physically weak considering the stochastic nature of airflow velocity and the variety of height and geometry of buildings. Similar to the meso-scale modelling, the treatment of turbulent closure and radiation significantly affects the precision of the micro-scale model prediction.

As far as turbulence modelling is concerned, many theories have been proposed, such as the Direct Navier–Stokes (DNS) simulation, Large Eddy Simulation (LES), and Reynolds Averaged Navier–Stokes (RANS) [16]. Although the precision can be improved using LES and DNS, the application of these schemes is very demanding in terms of CPU resources. On the other hand, RANS models (such as the Standard k-ε model or its modifications [112]) are widely used for turbulence modelling in UHI studies as their requirements for computational resources are moderate in comparison to LES and DNS. However, it should be mentioned that RANS modelling provides limited representation of physical phenomena such as the so-called "horse-shoe vortex" around buildings [113].

This implies that accurate modelling of turbulence phenomena is still one of the weakest points of RANS modelling. Additionally, the size scale of the case considered substantially affects RANS modelling as it is related to the turbulence-length scale i.e., the size of the large energy-containing eddies in the turbulent layer.

2.2.3. Collation of Urban Microclimate Modelling Methods

Table 3 contrasts the capabilities of UHI study methods by means of the governing equations, limitations, domain-size restrictions, resolution in time and space, and computational cost. It becomes obvious that the meso-scale method is practical when urban surface details are less important, i.e., heat transfer at the urban scale, pollutant dispersion, and thermal comfort are not adequately assessed by this method. On the contrary, for cases that such information is required, meaning that the physical phenomena within the urban canopy are of interest, micro-scale CFD or UCM methods are more useful. It should be pointed out, however, that when CFD models are applied in near real-time and -size manner, small time steps and detailed geometries may be prohibitive due to extremely high computational costs for simulations of whole cityscapes. This implies that major assumptions should often be adopted in order to produce realistic results, at least for practical engineering purposes. The most common assumptions followed when micro-scale CFD models were applied for UHI assessments are:

- Restricted computational domain near the area of interest, i.e., the rest of the actual city is represented by roughness equations only (without detailing building geometries).
- Geometry simplifications in order to avoid high spatial resolution.
- Assume homogeneous boundary layer, ignoring the interactions with PBL (200 m height and above).
- Application of unstructured grids (tetrahedral or polyhedral) in order to avoid dense grid propagation along the Cartesian axis of the domain.

Table 3. Collation of major UHI simulation methods.

Key Feature	UCM	CFD	
		Meso-Scale	Micro-Scale
Governing equations	-Energy balance equation -Empirical velocity equation within the urban canopy -Heat conduction equation on solid surfaces	-Navier–Stokes equations including the Coriolis term with hydrostatic or non-hydrostatic assumption -Monin–Obukhov for ground surface effects -Heat conduction equation for soil	-Momentum equations (Navier–Stokes) -Wall functions representing laminar-turbulent stratification near solid surfaces. -Heat transfer equation near surfaces -Chemical-species conservation equations -Turbulence model
Major limitations	-Decoupled velocity field from hygrothermal effects -Representation of cityscape using arrays of similar buildings -Low resolution of model geometry -Assumes steady-state conditions mainly -Empirical assumptions for convective latent and sensible heat	-Treatment of the urban canopy layer as roughness -Difficult to provide Land-use database (user-defined functions are required) -Turbulent effects not captured	-PBL effects are ignored -Difficult to create database for canopy details (user-defined functions are commonly required) -Precise boundary conditions are required, often produced from external, sophisticated physical models -Homogeneous inflow boundary layer, especially when RANS modelling for turbulence is applied
Maximum size of cityscape domain	Whole City	Whole City	District level
Spatial resolution for grid meshing	1–10 m	1–10 km	0.2–10 m
Temporal resolution (time step)	Hour	Minute	Second
Computational load	Medium	Relatively high	Very high (depending on the turbulence model applied and grid size)

Although these assumptions may cause deviations of predictions in comparison with measurements (if available), it has been extensively demonstrated in simulated, measured data comparative studies in real-scale cases that the produced deviations (even when applying the RANS model) are considered acceptable at least for practical engineering purposes [114–116]. It has been pointed out, however, that it is still a research challenge to bridge the gap between micro-scale and meso-scale modelling techniques [117] towards perhaps integrated models utilizing the respective benefits of high-resolution analysis and large urban scales, in order to achieve more accurate predictions at simulation environments.

2.2.4. Urban Microclimate Simulation Tools

This section summarizes research-based, commercial, or freely available simulation tools of each method discussed above. It is true that today's scientific literature contains a plethora of field modelling tools, which are mainly products of mathematical interpretation of the physical phenomena encountered in the urban environment. Since this paper focuses on the physical analysis within the urban canopy layer, meso-scale models are beyond the scope of this review, and the present section describes energy balance models (UCM mainly) and micro-scale CFD tools (excluding the FEM-based ones, since they are not so commonly used in urban microclimate analyses). Respective common modelling developments and tools used worldwide (but there are many more) are the following [107,118]:

- Energy balance models
  - UHSM
  - TEB
  - SOLWEIG
  - Rayman
- CFD tools
  - ENVI-met
  - ANSYS-Fluent
  - ANSYS-CFX
  - Phoenics

A summary of strengths and weaknesses of simulation tools is provided in Table 4.

Table 4. Strengths, weaknesses, and special features of computational urban microclimate simulation models and tools.

Model or Tool/Method	Strengths	Weaknesses	Special Modelling Features		Most Common Applications	CPU Load	Availability
			Evaporation and Evapotranspiration	Radiation			
UHSM/UCM	>Solution of heat transfer equations at representative heights (ground, building, atmosphere) >Anthropogenic heat >Spatial discretization of equations >Distribution of temperature and relative humidity >Hourly temperature results	>No thermal comfort indicators are incorporated >Very simplified geometry >Wind speed decoupled from heat transfer equations >Simple roughness equation for wind speed >Turbulence is dealt with simple drag equation >High urban physics expertise and computer skills are required >Lack of documentation and tutorials	>Since it is a customized model, User-defined models only are assumed	>Short- and long-wave radiation models are included	>Assessment of UHI intensity and implications by means of physical parameters only (temperature, relative humidity, incident radiation)	Low	Research-based; The user must reproduce the model

Table 4. *Cont.*

Model or Tool/Method	Strengths	Weaknesses	Special Modelling Features		Most Common Applications	CPU Load	Availability
			Evaporation and Evapotranspiration	Radiation			
TEB/UCM	>Full 3D modelling >Solution of heat budget at three surfaces (ground, walls, and roofs) >Turbulent fluxes are simulated in the PBL/Canopy layer interface >Roads of any orientation may be placed >Conduction fluxes through solid surfaces >Monin–Obukhov conditions for the surface layer >Human comfort index included >A comprehensive Building Energy Model (BEM) is included in tool's latest version	>Relatively simplified geometry >Wind speed decoupled from heat transfer equations >High urban physics' expertise and computer skills are required >Scattered documentation and examples (some information included in SURFEX tool documentation)	>Water interception and evaporation as well as snow mantel evolution models are included >User-defined evapotranspiration models for plantations are required	>Short- and long-wave radiation models are included	>Simulation of urban fluxes' impacts on the atmosphere >Investigation of UHI intensity >Co-simulations with future climate forecast models towards the assessment of future urban canopy microclimates >Calculation of building thermal loads, taking into account external microclimate	Medium	Free (open source available in http://redmine.cnrm-game-meteo.fr/projects/teb)
SOLWEIG/UCM	>Modelling of 3D radiation fluxes >Relatively accurate geometry >Solves for mean radiant temperature (thermal comfort) > Interconnected to QGIS open platform > Well-structured documentation and guides >Ability for the user to integrate own models/codes, e.g., boundary conditions	>Velocity pattern decoupled from heat transfer >Turbulence is not modelled >Plantation evapotranspiration is ignored >Relatively high knowledge of urban/building physics is required	>By-default models for Evaporation >Evapotranspiration is not included	>Short- and long-wave radiation models are included >Direct calculation of the mean radiant temperature	>Calculation of mean radiant temperature >Estimate radiant effects of UHI	Medium	Free (Open source)
Rayman/UCM	>Modelling of 3D radiation fluxes >Relatively accurate geometry >Solves for radiant heat fluxes from solid surfaces and from human body >Solves for thermal comfort indicators (PET, SET*, and PMV) > User friendly > Average expertise in urban physics is required	> Velocity pattern decoupled from heat transfer >Turbulence is not modeled >Limited documentation and tutorials	>Evaporation is included >Evapotranspira-tion is ignored	Short- and long-wave radiation models are included	>Calculation of mean radiant temperature >Estimate radiant effects of UHI	Medium	Free
ENVI-met/microscale CFD	>Urban microclimate-dedicated tool >Full 3D simulation >Compilation of prevailing urban physics phenomena >Most reliable thermal comfort models and indices are included >Average expertise in urban physics is required for simple case studies >Compatibility with BES software >Widely used and validated in a plethora of case studies >Excellent documentation and user guides	>Restricted to Cartesian geometries >Structured grids only >Limited turbulence modelling options >Very high CPU load	>Models for evaporation and evapotranspiration of trees are included	>Short- and long-wave radiation models are included >Mean radiant temperature calculation code is included	>Simulation of UHI > Calculation of thermal comfort at pedestrian level >UHI mitigation strategies >Building energy performance when coupled with BES tools	Very high (depend-ing on grid size, time step, physical models, and available CPU resourses)	Commercial (Only its Lite version is still free, but only for limited domain size and reduced out-put/analysis options)

Table 4. *Cont.*

Model or Tool/Method	Strengths	Weaknesses	Special Modelling Features		Most Common Applications	CPU Load	Availability
			Evaporation and Evapotranspiration	Radiation			
ANSYS-Fluent/microscale CFD	>General purpose CFD platform >Many options of turbulence models and radiation models >Flexibility and easiness of grid generation >Parallel-processing supported >User friendly >Extensive documentation with tutorials >Applies the so-called multigrid solver, which means faster convergence compared to other CFD software	>Since it is a general CFD platform, the user has to develop and incorporate user-defined models in terms of boundary conditions; thus, it requires high expertise in urban physics >The high purchase cost limits its use by practitioners >High CPU load >Thermal comfort indicators not included. User-defined functions are required. >No database of vegetation properties	>User-defined models for evaporation and evapotranspiration should be prepared and compiled	>Short- and long-wave radiation models are included >User-defined function for mean radiant temperature is required	>Simulation of UHI >UHI mitigation strategies >Building energy performance when coupled with BES tools	High (depending on grid size, time step, physical models, and available CPU resourses)	Commercial
ANSYS-CFX/microscale CFD	>General-purpose CFD platform >Many options of turbulence models and radiation models >Flexibility and easiness of grid generation >Parallel processing supported >Extensive documentation with tutorials >Particularly useful for wind-comfort assessments	>Since it is a general CFD platform, the user has to develop and incorporate user-defined models in terms of boundary conditions; thus, it requires high expertise in urban physics >Not so extensive verification/validation exists in literature specifically for urban microclimate assessments >High CPU load >Thermal comfort indicators not included. User-defined functions are required. >No database of vegetation properties >Less grid-meshing flexibility compared to Ansys Fluent	>User-defined models for evaporation and evapotranspiration should be prepared and compiled	>Short- and long-wave radiation models are included >User-defined function for mean radiant temperature is required	>Simulation of UHI >UHI mitigation strategies	High (depending on grid size, time step, physical models, and available CPU resourses)	Commercial
Phoenics/microscale CFD	>General purpose CFD platform >Many options of turbulence models and radiation models >Parallel processing supported >Extensive documentation with tutorials >Includes the Foliage module to account for evaporation phenomena from vegetation	>Since it is a general CFD platform, the user has to develop and incorporate user-defined models, thus it requires high expertise in urban physics and computer skills >Thermal comfort indicators not included. User-defined functions are required >Limited flexibility in grid generation (e.g., tetrahedral meshing is not included) >High CPU load	>The Foliage module simulates evaporation from vegetation	>Short- and long-wave radiation models are included	>Simulation of UHI >UHI mitigation strategies	Very high (depending on grid size, time step, physical models, and available CPU resourses)	Commercial

UHSM

The Urban Heat Storage Model (UHSM) enhances the Oke's urban energy balance equation and it was developed by Bonacquisti et al. (2006) [119]. The model is founded on four-equation energy balance at the ground level and building level, namely:

- Energy balance equation at building surfaces
- Energy balance equation at the ground level
- Sensible heat balance equation
- Latent heat balance equation

It involves three simulation sections, i.e., atmospheric layer (maximum height above building heights) and building and ground levels. The aforementioned equations formulate a system of linearized algebraic equations to relate four major unknown variables, i.e., building surface temperature, ground surface temperature, air temperature, and relative humidity. Ground and building aerodynamic roughness are evaluated as function of drag coefficients of soil and of wind speed in the canopy layer. Wind deceleration within the urban canopy was evaluated as a function of buildings' density, drag coefficients, and wind speeds within the atmospheric layer section. Anthropogenic heat is also taken into account, using expressions representing heat releases by buildings (produced mainly by electricity and fuel consumption), by transportation (vehicles exhausts), and by human metabolic rates. The equations are spatially discretized in the domain (sub-domains) and based on the heat storage within the urban canopy an iterative solution procedure is followed towards the calculation of the unknown variables in each sub-domain.

The main data used as inputs in the model are the thermo-physical and optical properties of urban surfaces as well as atmospheric parameters. The main output of the tool is the spatial distribution (in hourly basis) of ground and building surface temperature, air temperature and relative humidity, the mean surface temperature, and mean temperature at the pedestrian level height. The tool was applied by Bonacquisti et al. [119] in the case of Rome, Italy, and air temperature was used as a validation parameter, i.e., it was compared with in situ temperature observations. Using this tool, the same authors concluded UHI intensities (temperature increase compared to rural areas) of 2 °C and 5 °C, for winter and summer, respectively.

TEB

The Town Energy Budget (TEB) tool [120] was developed in the Centre National de Recherches Météorologiques, Toulouse, France, and it was presented by Masson [121]. The TEB tool is canyon-based but generalized to capture large horizontal scales. Due to the complex shape of the cityscape, the urban energy budget is divided into three parts, i.e., for roofs, walls, and roads. The model simulates turbulent fluxes into the atmosphere at the surface of the meso-scale atmospheric model covered by buildings, roads, or any other artificial material. Heat fluxes are computed for each land type by the appropriate scheme, and then they are averaged in the atmospheric model grid mesh, with respect to the proportion occupied by each type. The fluxes calculated are Latent and sensible heat fluxes, upward radiative fluxes, and component momentum fluxes.

Cityscape geometry is normally represented by buildings that have the same dimensions. Buildings are located along identical roads, the lengths of which are considered far greater than their widths. Finally, any road orientation is possible, all existing with the same probability, and this hypothesis allows the computation of averaged imposition parameters for road and wall surfaces. In order to treat the conduction fluxes through solid surfaces, TEB discretizes each surface type into several layers. The equations applied to represent temperature evolution in these layers are based on energy budget considerations and several prognostic equations for the surface layers of roofs, walls, and roads emerge. The set of equations describing heat transfer mechanisms and turbulent fluxes is similar to that of the UHSM tool. The main difference is that the surface layer is represented by the Monin–Obukhov equations. Its latest version includes a Building Energy Model

(BEM) suite mainly for thermal loads' predictions. Ren et al. [122] integrated TEB into a climate change air quality model and demonstrated improvement of predictions of NOx, PM2.5, and ground-level O_3 in four major north American Cities. The tool was used by Reder et al. [123] towards the suggestion of climate resilience strategies and measures by means of UHI mitigation. As documented by Pigeon et al. [124], the software, enhanced with the BEM suite, allows reliable predictions of buildings' heating and cooling demands in comparison with the more detailed model, EnergyPlus, for various building types. Lately, and in view of recent trends referring to assessments of future climate change impacts on the development of energy policies, TEB has gained interest in the prediction of impacts of climate change scenarios on UHI and urban energy performance [125–127].

SOLWEIG

SOLWEIG is a radiation-dedicated module of the Urban Multi-scale Environmental Predictor (UMEP) [128], which was developed by the Earth Sciences Department in Gothenburg University, and it is extensively described by Lindberg et al. [129]. UMEP is a climate service plugin for QGIS. It is an open-source tool and can be used for various applications related to urban metabolism processes such as thermal energy balance, energy consumption, etc. UMEP consists of a coupled modelling system, which combines "state-of-the-art" 1D and 2D models related to the processes essential for scale-independent urban climate estimations. SOLWEIG, together with the energy balance model SUEWS available in the UMEP QGIS plugin, simulates spatial gradients of 3D radiation fluxes and the mean radiant temperature (T_{mrt}); therefore, it is particularly useful for the assessment of thermal comfort indicators in the cityscape. Mean radiant temperature is derived by modelling short- and long-wave radiation fluxes in six directions, i.e., upward, downward, and from the four cardinal points (horizon) taking into account angular factors. The model requires a relatively limited number of inputs, such as irradiance components (direct, diffuse radiation), air temperature, relative humidity, urban geometry, and geographical coordinates. The output refers mainly to radiation components' fluxes and T_{mrt} distribution.

The framework theory, based on which the mean radiant temperature is calculated, is that one introduced by Hoppe [130] in which radiation fluxes in all six directions are considered. As an energy balance model, it presents the general shortcomings of this certain family of models; e.g., it disregards the velocity pattern in the domain of interest as well as its fluctuations (turbulence). Another shortcoming is that SOLWEIG does not account for evapotranspiration from vegetation. Lindberg et al. (2008) [129] demonstrated its usefulness by performing mean radiant temperature simulations in an urban area of Gothenburg and validated numerical results through comparisons with field measurements. Using SOLWEIG, Chen et al. [131] investigated the spatial variation of mean radiant temperature in different urban settings in Shanghai towards the detection of "hot-spots" with the highest thermal discomfort within the cityscape. In terms of its accuracy, it has been proven that SOLWEIG is equally useful with the microscale ENVI-met model referring to the modelling of the radiation field; however, it presents higher discrepancies because of its less comprehensive calculation model of diffuse radiation [132]. Hosseini-Haghighi et al. [133] developed a systematic approach to upgrade the outdoor thermal comfort using ArcGIS CityEngine for 3D city modeling and SOLWEIG as the climate assessment model, in view of the warmest forecasted year, 2047. The suggested workflow revealed the heat-stress areas and facilitated the efficient intervention regarding tree placement as a passive strategy for heat mitigation.

Rayman

The Rayman [134] software was developed in the Meteorological Institute of Albert Ludwigs University of Freiburg. The capabilities of the tool are described by Matzarakis et al. [135]. Similarly to SOLWEIG, it is a variant of energy balance models, and it mainly computes radiant heat conservation between human skin and its environment. It focuses on the calculation of the mean radiant temperature towards the prediction of thermal comfort conditions. The most important inputs required are Geographical coordinates, meteorological data (temperature, relative humidity, and cloud covering), personal parameters (clothing and activity level), Geological morphology, and urban features (buildings, trees). The results obtained by the model include, among others, Distribution of mean radiant temperature, radiation fluxes, and thermal comfort indices (PMV and PET). In contrast to SOLWEIG it computes more thermal comfort indicators and comprises a more user-friendly environment. However, it should be mentioned that Rayman disregards evapotranspiration from vegetation, while it treats trees as simple obstacles to radiation fluxes. Wind-induced effects and turbulence flow are also ignored. In comparison to SOLWEIG, RayMan has a higher calculation sensitivity and faster simulation speed, while it achieves the best accuracy at high solar altitudes on clear summer days [132]. Battisti [136] used both Rayman and ENVI-met tools to study the impact of using cool materials enhanced with more vegetation and permeable surfaces and demonstrated dramatic improvements regarding summer thermal comfort. Using both ENVI-met and Rayman, Peng and Jim [137] verified that green-roof cooling effects are not restricted to rooftops but extend to the ground to improve neighborhood microclimate.

ENVI-Met

ENVI-met [138] is a three-dimensional, non-hydrostatic model for simulating a microclimate, especially within the urban canyon, taking into account the physical interactions among solid surfaces (e.g., ground and building surfaces), vegetation, and air. It is based on the theoretical background of Computational Fluid Dynamics. It applies the FDM discretization scheme, and it makes use of advanced numerical algorithms for solving the airflow-governing equations, i.e., conservation of mass, momentum, thermal energy, chemical–species' concentration, and turbulence parameters, as well as particle dispersion.

The main input of the model includes, among others, the properties of the incoming wind of the urban domain (wind speed, direction, temperature, relative humidity), a simplified geometry of the urban domain (since only structured grids and cartesian geometries are supported), thermo-physical properties of ground and building materials and of vegetation, and personal parameters of pedestrians (such as metabolic rates and clothing insulation) when the BIO-met is employed. The simulator then executes an iterative solution procedure and produces Distribution of temperature, relative humidity, pollutant concentration, turbulence parameters, wind speed, and thermal comfort indicators (e.g., mean radiant temperature and PMV modified for outdoor conditions), at different heights throughout the urban area of interest.

The background of the ENVI-met system includes sub-models solving for the following special physical mechanisms:

- Long- and short-wave radiation fluxes, accounting for shading
- Radiation reflection from building facades, ground materials, and vegetation
- Evapotranspiration and sensible heat fluxes from vegetation
- Evaporation from water surfaces
- Chemical–species' propagation
- Particles' dispersion
- Heat and water transfer within soil mass
- Body/skin–airflow interactions (e.g., heat transfer, wettedness effect) towards the calculation of thermal comfort indicators

ENVI-met is a useful micro-scale model for the prediction of UHI effects within the urban canopy with acceptable accuracy provided that the model settings are correctly defined. In the case of complex geometries, radical simplifications may be required (such as building merging) in order to comply with grid-mesh restrictions. In addition, mesh possibilities are limited to structured grids with large grid cells (typical spatial resolution: 0.5–10 m). Hence, the effect of viscous sublayers (near solid surfaces) may be seriously underestimated. Another drawback is that only the Standard k-ε model is available for turbulence modelling. Due to the large number of computational nodes, it presents normally very high CPU time until full convergence.

Wania et al. [139] used the ENVI-met system to study the influence of different vertical and horizontal densities of street vegetation on particle dispersion. It was demonstrated that vegetation reduces wind speed, which limits a canyon's ventilation and, therefore, leads to an increase in particle concentration. Vegetation was also found to reduce wind speed at crown height and to disrupt the flow field in close vicinity of the canopy. Szucs [140] highlighted that comfortable and healthy public open spaces encourage people to spend more time outdoors, socialize, exercise, and participate in re-creational events. In this framework, Szucs (2013) used ENVI-met to examine whether climatic conditions in Dublin boost long-term outdoor activities during summer and investigated the extent to which urban planning and the resulting urban morphology of the built environment influence the microclimate created by means of the wind profile. It was confirmed that areas of limited long-term outdoor activities are subjected to high wind speeds, often at the windward sections and around corners of buildings. Compared to the UCM tools SOLWEIG and Rayman, it presents a much better accuracy in comparison to actual measured data regarding radiation parameters [132]. Wai et al. [141] developed an integrated methodology including both ENVI-met and the Weather Research and Forecast (WRF) to explore the cooling performance of a water-spraying system in a sub-tropical compact and high-rise cityscape in a future-climate summer (2050) condition. It was indicated that the spraying system may provide cooling of 2–3 °C for ambient air temperature at the pedestrian level, improving significantly the thermal comfort conditions. In general, it has been widely used for urban planning purposes combating microclimate extremes worldwide; for example, in MDPI one can find 69 research articles with the keyword "envi-met" in their abstract. It presents good compatibility with BES tools; for example, its interconnection with EnergyPlus is now a well-established method [55,142] towards assessments of local climate impacts on building energy performance, especially when building-envelope measures are tested (green roofs, cool materials, insulation materials, PCMs, etc.).

ANSYS-Fluent

Ansys Fluent [143] is a FVM-based, general-purpose CFD platform that provides comprehensive modelling for a wide range of incompressible, compressible, laminar, and turbulent fluid flow problems, under steady or transient conditions. In the software, a wide range of mathematical models for transport phenomena (e.g., heat transfer, momentum, chemical reactions, etc.) is combined with the ability to model complex geometries with high flexibility in grid meshing. Among a wide variety of applications, the platform has been widely used for assessing microclimate conditions in open spaces. In such cases, Fluent has been frequently used to simulate turbulent airflow within urban canopies. To "relax" modelling complexity of fluid flow and related transport phenomena in porous media (i.e., vegetation), various useful features are provided such as porosity functions and others.

Fluent solves for the majority of physical phenomena encountered in urban systems. In addition to those simulated by ENVI-met, it includes:

- A wide variety of turbulence models (RANS, DNS, and LES) providing the user the opportunity to choose (according to the available computational resources and expertise) among different turbulence models aiming to capture the desirable spectrum of turbulent-length scales.
- A wide variety of two-phase flow models to capture particles dispersion.
- A wide variety of radiation models to simulate short- and long-wave radiation.
- A pluralism of grid-meshing options including structured and unstructured grids to build grids with the minimum computational cost, ensuring adequate resolution of results.
- Access to input user-defined functions.

In general, ANSYS Fluent is the one of the most complete platforms existing in the CFD industry including well-known and the latest developments of fluid flow-related models. In terms of computational requirements, Fluent envisages solutions using multiple parallel processors, thus reducing computational costs. The latter, however, is a matter of the user's desires of resolution level; i.e., if a large urban area with a high level of geometrical detail is considered, then the computational cost can be very high, similarly to the most micro-scale CFD tools. The main limitation of the platform is that, since it is not targeted for specific problems, it requires relatively high expertise on fluid flow and transport phenomena for the user to formulate a specific problem. In this sense, the software does not include evapotranspiration and thermal comfort models, which means that, for microclimate modelling, the user should provide him/herself the models via user-defined functions. Nonetheless, it can be easily used to produce the results of parameters required to compute thermal comfort indicators (wind speed, relative humidity, temperature, turbulence intensity) externally.

Numerous CFD studies of the UHI by using Fluent exist in the scientific literature. For example, Stavrakakis et al. [103] used Fluent for the assessment of thermal and wind comfort of pedestrians in an urban area in Crete, Greece. Special physical models, such as evaporation from water surfaces and evapotranspiration from vegetation as well as thermal comfort indicators, were incorporated and compiled in the CFD platform (through user-defined function) towards the formulation of a holistic model that solves for UHI effect on pedestrians' perception of thermal comfort. The micro-scale model developed was then used to assess the pre-renovation situation and to indicate the optimum interventions including vegetation, shading devices, and cool materials in proper locations of the urban domain. Saneinejad et al. [144] studied the evaporative cooling effect on air temperature and thermal comfort within urban street canyons. They took advantage of Fluent capability to incorporate user-defined physical models and they developed a coupled CFD model that solves for vapour and heat transfer in the air, heat and moisture transfer within the porous building walls, and radiative heat exchange between building walls. The effect of evaporation of building surfaces on temperature was adequately quantified and a substantial impact of this phenomenon on pedestrian thermal comfort was shown. Recently, Fluent was used as a reliable database generator for validating a novel energy balance-based model, undertaking the calculation of spatially averaged air temperature within the urban canopy [145]. In terms of its prediction accuracy regarding urban microclimate assessments in real-scale cases, Antoniou et al. [116] applied CFD unsteady RANS modelling and computed an average absolute difference of 1.35 °C, of 0.57 m/s, and of 2.31 °C regarding air temperature, wind speed, and surface temperatures, respectively. As demonstrated in the international scientific literature, Ansys Fluent is particularly useful to test and verify UHI mitigation strategies in cityscapes provided that the designer is familiar with urban physics and possesses computer skills.

ANSYS-CFX

CFX [146] is a FVM-based, general purpose CFD tool that possesses similar capabilities as the ANSYS-Fluent software reported above, at least for airflows within urban canopies. The main differences are focused on mesh-generation algorithms and solution algorithm as well as differences in functionality and operability of available GUIs related to user's actions during pre- and post-processing. By means of spatial discretization, Fluent uses a cell-centered approach, while CFX uses a vertex-centered approach; hence, Fluent can handle polyhedral mesh and cut-cell meshes, while CFX is limited to the traditional tetra- and hexa-mesh topologies. Concerning the comparison between the results obtained by CFX and Fluent, they present similar accuracy; however, Fluent has presented a slightly better accuracy for incompressible flows, although it requires more computational time to converge. This happens due to the fewer computational nodes in CFX grids in comparison to Fluent grids. Fluent has a more functional pre-processor and, thus, it requires less time to prepare the grid and work on available GUIs. Fluent has post-processing capabilities of its own while CFX needs a dedicated post-processor.

Priyadarsini et al. (2008) [147] used CFX to investigate the UHI effect on temperature rising in the urban canopy in Singapore. They determined the key factors causing the phenomenon and investigated the possibilities of improving heat release rate by optimizing airflow in selected hot spots. The main parameters put to the test were building geometry, materials of façades, and the location of air-conditioning units and their impact on the outdoor air temperature. Although a simple model was used (evapotranspiration from vegetation was ignored), good agreement between the computed and the measured results was obtained. It has been demonstrated that the software is particularly useful for urban morphology optimization in terms of acceptable wind speeds within the urban canopy [148], as well as to verify the performance of several bioclimatic interventions (e.g., cool materials) with respect to the reduction of urban surface temperature on hot summer days [149,150].

Phoenics

Phoenics [151] is a FVM-based, general-purpose CFD platform, which, at least for airflows within the urban canopy, provides similar modelling features and capabilities as CFX and Fluent. As the other CFD programs, Phoenics can solve for the most important conservation equations of mass, momentum, heat, chemical species, and turbulent parameters, towards the provision of results of microclimate parameters such as relative humidity, wind speed, turbulence intensity, and temperature. Similarly to the other CFD platforms, it provides access to the user to incorporate special physical models, such as evapotranspiration from vegetation. A substantial advantage of Phoenics over the other CFD tools is that it provides access to the source Fortran-based code rather than only offering the opportunity to incorporate user-defined models. Like previous tools, it possesses a wide variety of models to simulate turbulence, heat, and radiation transfer and, due to its wide validation, it can be confidently used to study microclimates in urban areas. Since it is not just a microclimate-oriented tool, expertise above average on computing and transport phenomena is required in order to develop a reliable microclimate model. The major difference is that it does not implement tetrahedral grids, and either a Body-Fitted or a hexahedral-unstructured grid option is available for complex geometries. The software includes a plant canopy module called FOLIAGE, which accounts for vegetation evaporation phenomena.

Fintikakis et al. [152] used Phoenics to study the urban microclimatic conditions in the historic centre of Tirana. They developed a microclimate model and incorporated it into the CFD platform towards the estimation of pedestrian thermal comfort in order to decide the best retrofitting measures (e.g., trees' kind and orientation, high albedo ground materials, earth-to-air heat exchangers) that ensure the best comfort conditions in strategic locations of the urban domain. Although a simple model was developed (evapotranspiration and radiation were neglected in the mathematical model and they were imposed as temperature boundary conditions taken from field measurements, instead), it provided adequate results at least for practical design purposes. Maragkogiannis et al. [153] combined Terrestrial Laser Scanners (TLS) and aerial ortho-photography with computational fluid dynamics (CFD) to study the thermal conditions of a public square in Chania, Greece. Yang et al. [154] reported that the software presented good structure for developing modular applications but required powerful computer or cloud computing to speed up simulations.

3. Discussion

3.1. Building Energy/Urban Microclimate-Coupled Simulations

As presented in the above sections, currently there is a tremendous availability of computational tools and methods that can be used to conduct urban energy planning studies, even in completely simulated environments. The obvious opportunity that emerged is the ability to predict the energy performance of a group of buildings, taking into account microclimate variations in the vicinity of buildings, at least at a district level. Apparently, the designer may have all the necessary computer tools to conduct joint simulations of urban microclimate and building(s) energy performance, which, however, requires knowledge of building physics, specifically regarding indoor–outdoor interactions. The main question is how the practitioner can really develop such kind of co-simulations. The answer, of course, simply resides on the energy conservation of the control system building/outdoor space. The energy balance equation for a building may be expressed as follows: The heating/cooling load of the building equals the sum of the internal heat gain from lights, occupants, equipment, the convective heat transfer between building's interior surfaces and internal air, and the convective heat transfer due to air infiltration and the change of energy stored in the internal air. On the other hand, the energy balance equation for building exterior surfaces may be expressed as follows: The conduction heat flux through the wall equals the sum of the transmitted solar radiation, the absorbed solar radiation, the net long-wave radiation heat flux, and the convective heat flux exchanged with the outdoor air.

The above description of the heat exchange between indoor and outdoor spaces reveals the physical influences of the external environment to the internal space and vice versa. These influences may be described as follows:

- The incident solar irradiance on building walls.
- The convective heat flux at the external surfaces, which is represented by the Convective Heat Transfer Coefficient (CHTC) and by temperature differences between the ambient air and external surfaces.
- The intensity of long-wave radiation.
- The heat and water-vapor transfer through infiltration.

Ideally, all the above influences should be adequately captured and participate in appropriate boundary conditions of the building energy simulation (BES) model. The last, however, often present some deficiencies in capturing all the impacts described above, such as the following:

- They disregard the non-uniformity of the CHTC in the vicinity of the building. They rely only on a mean value of CHTC based on climate data time series, usually of the wider climate zone (data from remote meteorological stations).
- Infiltration is handled by empirical formulas rather than a more precise representation (accounting for velocity fluctuations through openings, for example).
- Surrounding trees are treated like simple obstacles on incident radiation rather than contributors of moisture and obstructions to outdoor airflow; thus, CHTC and air infiltration rates are underestimated.
- Evaporative cooling effect emanating from water surfaces is ignored.
- Surrounding buildings' (other than being treated as obstacles on incident radiation) effect on airflow pattern and, therefore, on CHTC is not normally taken into account.
- Outdoor climate data are most commonly taken from default libraries of wide climate zones available in the tools' background, which are, however, different from the actual ones especially during summer season due to the Urban Heat Island effect.

On the other hand, as presented in previous sections, the UCM or CFD tools seem very promising towards the simulation of the urban microclimate. The CFD micro-scale models can simulate physical mechanisms that comprise the urban microclimate and by these means they can quantify all the influences of outdoor physical environment to indoor energy consumption. Consequently, the drawbacks reported above can be eliminated under the perspective of CFD/BES tools' coupling. Indeed, numerous authors in scientific literature succeeded to couple these methods based on information exchanging between the two tools in each given time interval as follows [55–57,155]:

- An initial value of external wall temperature in the CFD model is adopted as a wall boundary condition. Air properties of the incoming wind are taken from the nearest

meteorological station and they are set as inflow boundary condition in the CFD model. Boundary conditions for physical features, such as trees and water surfaces, are also set as boundary conditions.
- The CFD model is executed and provides a preliminary prediction of the microclimate in the vicinity of the building(s) of interest, i.e., air temperature, convective heat transfer coefficient, and relative humidity.
- These climate parameters are then passed to the BES tool as climate data (i.e., instead of using the default data from the BES tool libraries) and the BES tool calculates, apart from Energy-related indicators, external walls' temperature.
- The new updated value of building external walls returns to the CFD model as a wall boundary condition, which is executed again towards the update of a microclimate surrounding the building. The updated microclimate is then passed to the BES tool, which is executed again towards the update of the energy-related indicators and the wall temperature.
- And so on.

The iterative process above ends when the wall temperature computed by the BES tool, taking into account its pass from the CFD tool, presents a really small change from one loop to the other (convergence of solution). Then the solution is obtained and the building energy-related indicators are finally calculated.

As stated by Kato [21], the full coupling is practically absurd and sometimes impossible because of its enormous computation amount, especially when similarly small time-step scales over long periods are adopted in the two models. Alternatively, he suggests a coupled CFD network model in building energy (heat) and airflow simulation. However, the suggested approach again requires quite advanced knowledge of transport phenomena and computer skills; hence, again it may be considered difficult to use by practitioners, especially professionals conducting studies for compliance purposes with regulations, e.g., energy audits or energy studies for new or renovated buildings. Focusing on that target audience, an alternative practical, although less accurate, approach (let it be called "semi-coupled approach") would rely on the use of an urban microclimate model responsible for producing local climate data, and then automatically (or manually) passing them as input conditions to the BES tool. Essentially, this semi-coupled approach resides to only insert a weather file to the BES tool, which, instead of a default file of the wider climate zone, is now being produced in a control volume close to the district/building of interest from the micro-climate model. In such an approach, normally a UCM tool is preferred due to its simplicity and fast calculation [156]. To date, the main steps of such semi-coupled approach are the following:

- Incoming-wind properties are taken from the nearest meteorological station or from the weather file of the climate zone and they are set as boundary conditions in the urban microclimate model.
- Appropriate boundary conditions to account for urban physical phenomena, e.g., radiative heat fluxes, evaporation, and evapotranspiration, are set to water and vegetations' surfaces of the microclimate model.
- Estimations of the incident solar radiation on solid surfaces may emerge, utilizing a solar ray tracing model, taking into account albedo and emissivity values of materials.
- The microclimate model is then executed and provides the local microclimate in the vicinity of the building, quartier, or district.
- The microclimate provided by the microclimate model can then be transformed in the format of weather files of the BES tool and compiled in the BES tool.

Obviously, the tactic above is a one-way approach, i.e., the microclimate model is executed first and the climatic conditions that emerged are then passed to the BES tool in the format of the default weather file. It should be mentioned that, since this method treats field and zonal models separately, an average expertise is required by the user in order to obtain correct estimations of initial parameters used as boundary conditions. This means that the user should apply external or incorporated special models that solve for these parameters in order to provide boundary conditions, e.g., a correct "guess" of internal temperature and solution of conduction equations to estimate external surface temperatures, taking into account incident solar radiation. It may be concluded that BES/CFD coupling provides a more accurate prediction of energy-related indicators, hence, a more accurate selection of retrofit measures. Through this coupling procedure it becomes clear that energy-related indicators are only a "symptom" of the mathematical interpretation of building and urban physics and, more specifically, of indoor–outdoor interactions. It should be highlighted, however, that further research is required to confront the challenge of high CPU loads and time required for fully coupled approaches. Fortunately, the dramatic improvement of CPU technologies and resources promises such reliable studies in simulation environments.

3.2. Perspectives on the Use of Advanced Simulation Methods

Provided that the ideal physical model for built environment and energy performance assessment is available, it could be integrated to a decision-making procedure in the context of a retrofitting strategy. Building design optimization is indeed a complex task, since the optimal solution should satisfy many criteria, e.g., energy saving, emissions' avoidance, and cost-efficiency indicators (NPV, payback period, etc.). Scientific research has already presented advanced optimization methods and tools to respond to the aforementioned challenge. For example, Nguyen et al. [157] reviewed simulation-based optimization methods in the building sector. They provided an overview on the subject focusing on discontinuous multi-modal building optimization problems, the performance of optimization algorithms, multi-criteria optimization, surrogate models, stochastic optimization, and the propagation of optimization techniques into real-world design challenges. The paper is recommended as a good source of studies and approaches for building energy optimization. Handling of large databases that emerge by extensive parametric simulation analysis towards the identification of optimal solutions is a cutting-edge issue, especially in the context of recent energy regulations. For example, the EU directive 244/2012/EU suggests the exercise of extensive parametric analysis in the scope of identifying the cost-optimal minimum energy performance requirements of buildings and, furthermore, the identification of the nearly zero energy building (NZEB) levels. Responding to the NZEB challenge, Cao et al. [158] reviewed the feasibility of categorized state-of-the-art technologies, namely, passive energy-saving technologies, energy-efficient building service systems, and Renewable Energy Sources. Based on data derived from international energy reports for the US, China, and the EU, they introduced a ZEB concept.

Although new developments regarding advanced physical modelling have flourished during the last 20 years, it is true that they lack acceptance by the wider engineering and architects' community. An extensive survey presented by Fernandez-Antolin et al. [159] showed that one of the main reasons for limited preference on using advanced simulation tools by recent graduate architects is that they consider them inconvenient and challenging to learn. The study suggests that a key driving force to boost the use of such simulation tools in practice is to integrate related education courses, even at the undergraduate level, e.g., in design courses and in building system courses. In the same study, recommendations to software vendors to improve user-friendliness of the problem setup (geometrical model and input conditions) are also reported. Emphasis on bridging the gap between the use of building energy simulation tools and architectural design is given by researchers of the same team [160]. The study raises the dilemma of suggesting the use of energy simulations in the early design stages and concluded that modern architects should be capable to understand simulated results in the context of suggesting design solutions. To that direction, it is acknowledged that teachers in higher education institutes should bring and exercise advances of simulation tools to the attention of students (future architects and engineers). From the software vendors' side, it is expected that no further increase in cost is presumed in case of providing additional information and guidelines when requested. In addition, the administration of educational institutions should also encourage their use in a constructive way, envisaging subsidies and incentives to boost their adoption, and being responsible for reviewing the projects before granting a license.

The usefulness of utilizing reliable simulation tools in the architectural design stage has been highlighted and demonstrated in many studies (refer, for example, to ref. [161]). In this context, Xie and Gou [162] exploited two case studies (a Sports' Centre and a Hotel) that compare building performance simulation as an early intervention and a late verification tool in the architectural design process, contextualizing the building simulation research in real building practices. In the first case study, a simulation tool was integrated in the early-design stage, while, in the other one, the simulation tool was used at the post-design stage, mainly to verify the results obtained by the suggested architectural design. Through collating technical results with those of designers' perceptions regarding the usefulness of simulation tools via questionnaire surveys, it was concluded that a design team must not only provide quantitative results to obtain accredited building design but also provide documentation of at least two design strategies towards the confirmation of the schematic design. This suggests that the focus of green building rating systems is shifting from simply obtaining accurate quantitative goals for the decision-making process. The present focus is to encourage the selection of multiple design plans and optimize the design solutions.

4. Conclusions

This work intended to inform building designers, engineers, and urban planners on the state of the art regarding tools and methods that may be used in practice in the framework of energy efficiency and climate mitigation and adaptation technical studies. Current energy policies, as regards transition to low-carbon economies in future sustainable Cities, necessitate putting advanced study techniques into practice. The comprehensive overview of tools and methods provided herein may guide the target audience through the ongoing design challenges as well as through practical solutions to respond in their studies. To summarize, the following major conclusions may be drawn:

- Informed decision making on building energy renovation and urban rehabilitation through the reliable quantification of energy, cost, and environmental and comfort indicators is becoming increasingly important, even at practical engineering levels, to meet ambitious goals and trends of policies regarding energy efficiency and climate change resilience.
- To respond in meeting minimum energy performance requirements, especially for nearly zero energy buildings, more accurate building energy performance simulation is required. To that direction, studies in simulation environments should take into account systems' operation schedules, occupancy schedules, and external local microclimate effects.
- A plethora of building energy simulation (BES) tools is available, including powerful tools that are still freely available such as the EnergyPlus and the eQUEST software (among many others).
- Urban microclimate and BES tools presented herein are verified and validated.
- All the UCM models presented herein are freely available (open source).
- A coupled BES/urban microclimate simulation method facilitates more reliable predictions of impacts of external microclimate on buildings' energy performance; hence, it quantifies the energetic impacts of external bioclimatic interventions on buildings.
- Most common BES/CFD-coupled methods refer to:
    - EnergyPlus/Envi-met
    - TRNSYS/Fluent
- Further research is required regarding the reduction of CPU loads and time of coupled building energy and urban microclimate simulations.
- Complexity of physical phenomena in urban planning suggests that the modern designer should acquire know-how in building physics and better computer skills. In parallel, further work by software vendors on improving user friendliness remains a

crucial factor that can boost such simulation approaches and practices from research to practice.

- Higher education institutes play a key role in providing the necessary knowledge and expertise to their students in order to respond to evermore required informed decision making at the design stage. It is admitted that simulation tools and practices should be integrated into educational courses in order to ensure a good readiness level of the modern designer to be able to understand better the impacts of alternative design strategies and to work in teams with other experts, e.g., engineers, building physicists, IT experts, etc.

Author Contributions: Methodology, G.M.S. and M.D.; investigation, G.M.S. and D.A.K.; writing—original draft preparation, G.M.S.; writing—review and editing, D.A.K. and M.D.; supervision, M.D.; project administration, G.M.S. and M.D. All authors have read and agreed to the published version of the manuscript.

Funding: Part of this research was funded by the PROGRAMME MED EUROPEAN TERRITORIAL COOPERATION 2007–2013, project: REPUBLIC-MED, grant number: 1C-MED12-73.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Acknowledgments: Part of the work was conducted in the framework of the lead author's former position as a scientific collaborator in the Centre for Renewable Energy Sources and Saving (CRES) and in the framework of the REPUBLIC-MED (1C-MED12-73) project (project duration: March 2013–June 2015). CRES was the Lead Partner (LP) of the project.

Conflicts of Interest: The authors declare no conflict of interest.

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