Building Energy and Urban Microclimate Simulations

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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.

Keywords: building energy performance ; urban heat island

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.

2. 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, while only a short presentation of their uses for indoor airflows and building thermal simulation is provided.

2.1. 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.

2.2. 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].

3. 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 [28][29][30][31]:

- 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 [32]. 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.

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