PROTOTYPING A DIGITAL TWIN – A CASE STUDY OF A ‘U-SHAPED’ MILITARY BUILDING

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ABSTRACT

The aim of the article is to cover part of the issues related to develop a process aimed at defining some essential step to correctly plan a ‘smart district’ that could dispatch energy produced in excess to the district’s other buildings. The first step has been to search for a type of building with very similar characteristics, such as geometry, zones, with the obvious variant of the geographic localization and thermal behaviour, on the other hand, a certain computational approach has to be set, in order to achieve a further replicable and scalable approach to a small-scale urban building energy modelling (UBEM). Focusing on various characteristics, a standard ‘U-shaped’ building, belonging to a ‘military district’ in a southern city of Italy (Bari), has been chosen as a case study. In order to obtain energy information, the authors have started investigating first the basic components of the building through measures, thermal imaging, heat flux sensor, borescope, secondly a BIM model has been set and then enhanced to a Building Energy Model (BEM) trying to replicate the energy behaviour of the case study as close as possible. Although many technological innovations are emerging, the ‘BIM to BEM process’ and the ‘BEM analysis process’ itself still depends on too many variables and results on several experiments conducted showed a variation of up 26%, that probably could be improved only by a rigorous/hybrid workflow through a digital twin.
Keywords: BEM, BIM, digital twin, computational approach, military district.

1 INTRODUCTION

Between 1990 and 2018, the EU average energy consumption decreased by 4.8%.

However, at national level, the evolution varies. In Italy, over the period of 2008–2018, primary energy consumption per capita decreased by 1.8% while the final energy consumption climate corrected was 115.6 Mtoe, –6.4% since 2000 [1, 2].

Over the same period residential and services sectors grew by 5.8 and 5.5 percentage points, respectively: the building sector, comprising residential and services sectors, represents 43.5% of total final energy consumption in 2018 as shown in Fig. 1 [3].

Buildings, even if they are not the only contributors, play a central role in the final energy demand estimations; they use 40% of total EU energy consumption and generate 36% of greenhouse gases in Europe [4].

Non-residential buildings are on average 40% more energy intensive than residential buildings (273 kWh/m^2 compared to 180 kWh/m^2).

As for residential buildings, energy consumption per m^2 in services is heterogeneous. Italy, Malta and Estonia use by far the largest amount of energy per m^2 (more than 1.5 times higher than the EU average).

For the other countries, energy consumption per m^2 (Fig. 2) is much more homogeneous: most countries use between 200 and 300 kWh per m^2 [5].

In order to reduce energy consumption and not to overestimate energy savings, existing buildings have to be retrofitted by specific energy conservation measures based on a well calibrated energy model.

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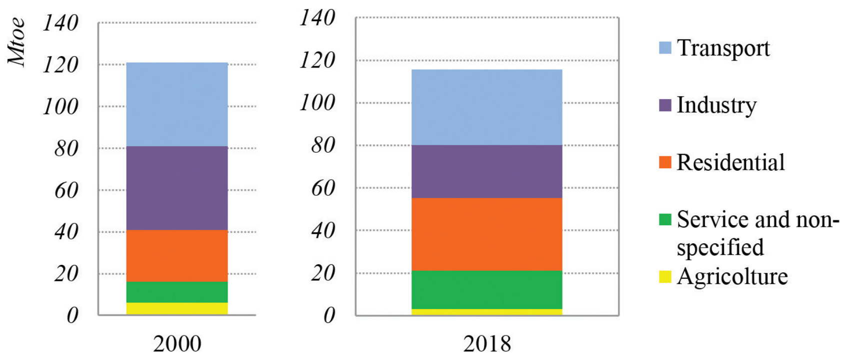


Figure 1: Final Energy Consumption by sector in 2000 and 2018 (normal climate) *(source: Odysee-Mure, 2020).*

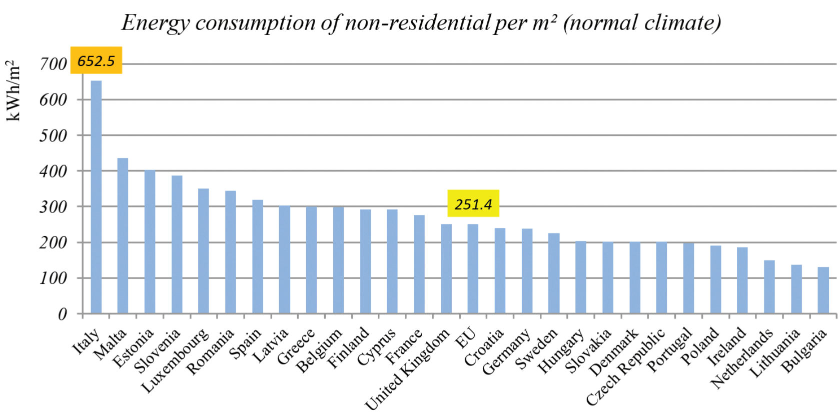


Figure 2: Energy consumption of non-residential per m^2 (normal climate) *(source: https://ec.europa.eu/energy/eu-buildings-datamapper_en, 2020).*

Once a building is geographically localised, its thermal performance (energy consumption) still depends on external conditions (climatic context), specific characteristics (geometry, materials, orientation, HVAC and lightning systems....) and internal conditions (function, occupancy and behaviour). The main 'thermal envelope' could be defined with accuracy all things considered, in fact the way of capturing the geometry and materials of an existing building nowadays bring expert surveyors to a negligible inaccuracy, assuming only few construction errors, the variability is inherent in both the above-mentioned conditions and the subsequent process. With new buildings using generative design tools, simulations and AI, architects can still express their creativity improving, in early stage of a project, indoor thermal comfort while reducing energy demand. Both existing and new buildings could be represented digitally in a time efficient way through Building Information Modelling (BIM) and be energy evaluated with Building Energy Modelling (BEM) with a specific workflow that still requires extensive work experience and professional operator skills.

2 BUILDING ENERGY MODELLING WORKFLOW

In the last few years, 2D simple Computer-Aided Design (CAD) software seems to be not subjected to consistent enhancements and tremendous efforts in order to produce both new and updated drawings are made constantly by professionals, with more or less powerful drafting and design tools at their disposal.

The necessity to store, consult thousands of information and the capacity to let them to be visually more friendly and queryable has changed the way of designing and introduced BIM, scripting and 3D info-visualisation, to reduce and avoid coordination clashes. On one hand, the development of the use of BIM in Europe shows some difficulties in being implemented, because many people still want to use/see traditional drawings [6], on the other hands, BIM authoring, tools and coordination software are moving year by year the project workflow to higher level of digitalization (virtual reality, generative design, etc.). The huge set of appropriate information potentially stored in a BIM model, depending on the maturity level reached, could be used in any virtual simulation reproducing the physical phenomena in the built environment (structural, solar, thermal, human, facilities management, etc.) using an open and neutral format file that contains geometric and non-geometric entity and their combination. Numerous efforts are constantly made to a standardized protocol, in order to gain the best interoperability needed by both professionals and companies but sometimes there seems to be too much convergence between design (BIM) and analysis software, whose components often overlap, and still led to a lack of interdisciplinary coordination between engineers, designers and contractors.

Currently, the Industry Foundation Class (IFC) and Green Building XML (gbXML) are two prevalent informational infrastructures in the architecture, engineering and construction (AEC) industry deeply investigate by Malhotra [7]. To create a building energy model (BEM) in many different ways and automated workflow seems to be one of the most interesting method to reduce the very time-consuming setup part [8].

Regardless on the approaches (statistical or physical) the very first step still remain to gather, analyse and treat input data and create a geometry model usable and compatible with any energy simulation program.

The fundamental steps to run an energy simulation analysis are showed in Fig. 3.

Depending on the level of energy simulation, the basic stages may not constitute a subsequent process, a more detailed design implementation and constant switch across the stages is often required, above all for non-expert users, even many certified software [9] are continuously being developed in order to reduce users' efforts and improve their accuracy. An overview of some different platform workflow to build an energy model that always requires setup, create, analyse and optimize a model are simplified in Tables 1, 2, 3, 4 and Fig. 5.

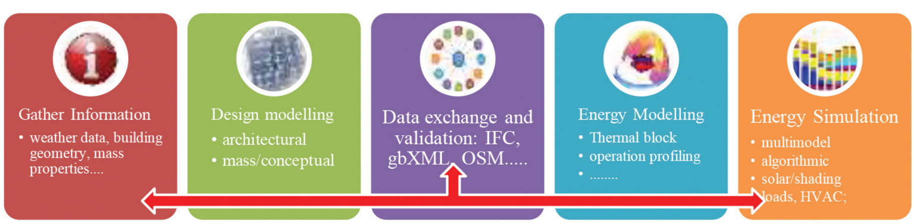


Figure 3: Standard energy study workflow (*by the authors*).

Table 1: Autodesk® 2021 Workflow *(Source: Workflow: Energy Analysis with Revit and Insight – 2021 – Autodesk Knowledge Network adapted by the authors).*

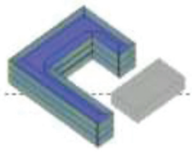
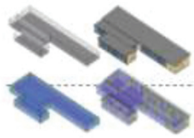
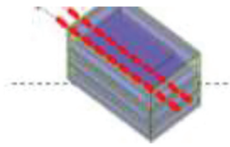
Autodesk Revit® and Insight® [10]			
			
Create the Energy Model: Detailed Architectural Model	*Create the Energy Model: Massing*	*Create the Energy Model: Mixed Design*	*Specify the Location*
			
Create the Energy Model	*Basic and advanced Energy Settings*	*Creating and understanding the Energy Model*	*Generate the Energy Analysis, Optimize and Repeat Energy Optimisation*

Table 2: Graphisoft® 2021 Workflow (*Source: Energy Evaluation Workflow:Overview – Archicad 24 Help and Eco Designer STAR Manual – adapted by the authors).*

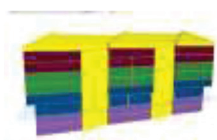
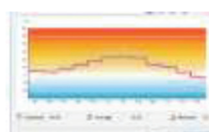
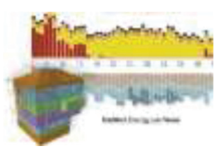
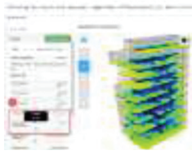
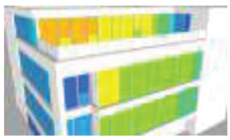
Graphisoft Archicad® and Eco Designer STAR® [11]			
			
Prepare the Architectural BIM for Energy Evaluation	*Define Thermal Blocks*	*Automatic Model Geometry and Material Property Analysis*	*Assign and Input Additional Data to Complete the BEM*
			
Evaluate Building Energy Performance			

Table 3: Trimble SketchUp® and Sefaira® 2021 Workflow *(Source: Energy Efficient Design Software Sefaira – sketchup.com – adapted by the authors).*

Trimble SketchUp® and Sefaira® [12]			
			
Prepare the Architectural BIM for Energy Evaluation	*Analysis Inputs and Settings*	*Model Geometry and Material Property Analysis*	*Assign and Input Additional Data to Complete the BEM*
			
Evaluate Building Energy Performance	*Other Analysis (es. Deluminae Plugin)*		

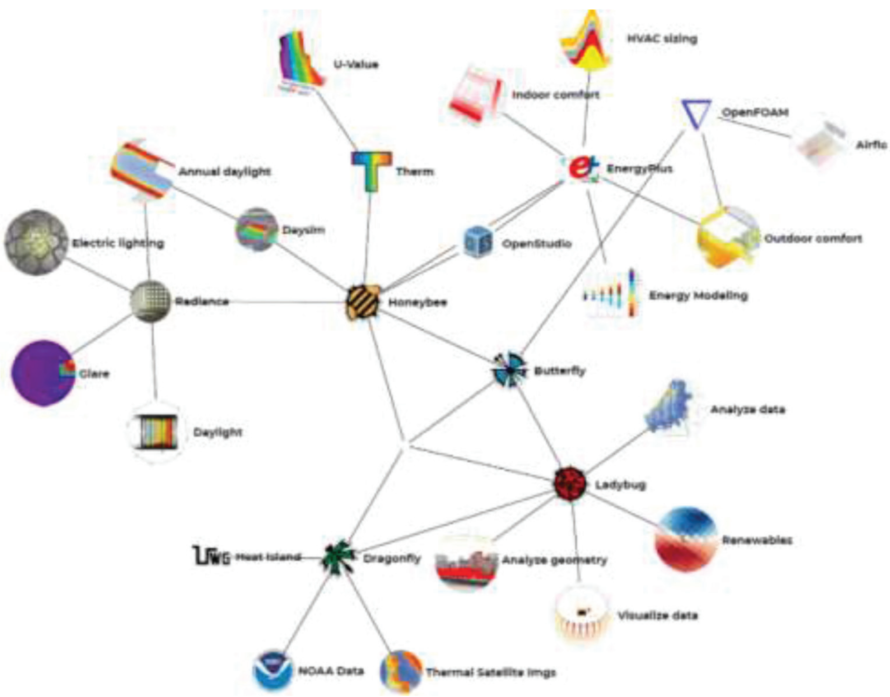
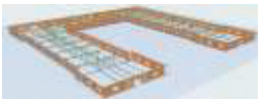


Figure 4: Open Source workflow 2021 – LadyBug tools, OpenStudio and EnergyPlus *(Source: https://www.ladybug.tools).*

Table 4: Elements of the considered building.

Building element representation	Building element	Typology	Thermal transmittance (W/m^2K)	Area (m^2)
	Windows (wood + single glass)	Glazed	3.08	246
	Masonry tuff wall (exterior)	Opaque	0.82	1.154
	Roof slab	Opaque	2.47	2.144,32
	Floor slab	Opaque	3.15	2.144,32

Several other energy modelling and simulation applications, from generic to challenging, are available with pro and cons at various levels of complexity [PHPP, IES-VE, TRNSYS, TERMUS-Plus, Spawn-of-EnergyPlus, ESP-r, IDA-ICE and more]. Depending on conditions and design parameters, they differ from each other in terms of energy simulation engine, optimization algorithm, optimization objective, optimized variables, etc. [13]. Different modelling approaches exist in literature, starting with simple Energy Plus model [14] or white-box/physical/calculation-based models, blackbox/statistical/measurement-based models or hybrid models combining the former two like Kalogeras *et al.* proposed [15] or even simulation workflow using programming language such as Modelica or Python [16, 17].

3 CASE STUDY

3.1 U-shaped military office building model

The target building is located in the Bari suburban area in southern Italy. It has been built during the late 1940s, and identified for further comparison as one of the reference standard shaped buildings of a large stock owned and managed by the Carabinieri Corps (Italian police force having military status). The building has masonry walls with concrete slabs and roofs in the office areas and has a gross floor area of around 2.676 m², a conditioned floor area of 2.420 m^2, a net internal area of 2.170 m², developed on one level with a story height of around 4.4 m and a S/V ratio of 0.55. External walls were built almost entirely using local tuff brick, with plastering.

The most obvious way to organize a building into discrete spaces is by rooms and then four different thermal zones were individuated (offices 58%, archive 5%, circulations 28.45% and restrooms 8.55%).

The windows-to-wall ratio of each side is 28.5% (south-west), 28.7% (north-east), 34% (north-west) and 29.3% (south-east). The building envelope characteristics have been defined through surveys and measuring as average and displayed in Table 4.

The available documentation has been collected (billings from 2015–2020 in Fig. 5). As well, the 'thermal behaviour' of the building occupants has been reported through direct surveys with a paper questionnaire provided by the authors.

In addition, occupancy profiles, with defined separate schedules, communicated by the local Commander, were used to estimate the heat gains due to people, lighting and equipment for each thermal zones. Only real data provided on the number of people and lighting devices inside each zone have been used, the peak occupant density of the office area is 15 m^2/person on workdays. For the simulated period, two meteorological stations (15 km distance) provided local hourly profiles of air temperature, relative humidity, and horizontal global solar irradiation, so test have been conducted with two EnergyPlus .epw Weather file and a Meteonorm calculation [18, 19]. An initial set of values for high infiltration and ventilation rates has been used in the model. Due to the lack of reliable information describing the performance of the cooling system, an ideal air system keeping the indoor air temperature at 20°C during the occupancy time have been modelled.

3.2 BEM convergence

On one hand the authors chose Graphisoft Archicad as the BIM software to be used, as one of the most common software in design stages and helps avoid duplication and conflict, favouring the repetition potential of this investigation, on the other hand, OpenStudio® (EnergyPlus) as BEM software approved by the Green Building Council and is also the most commonly used. Additionally, Acca TermusPlus® [20] (energyPlus core) was tested as an intermediary between, as part of the not simple data exchange process. The model created is not a simple geometric model but included BEM-related information assigned to the attributes of its elements exported through an IFC translator or a gbXML file. The model is transferred to BIMserver, where a serializer developed transforms the IFC file into its equivalent energy model in the OSM format (OpenStudio) [21].

Following the specified data flow process, after correcting some inconsistencies, various BEM software were used to import the basic model for the preparatory experiment, as presented in Fig. 6. The BEM geometry has been automatically generated from the ArchiCAD software including composite structures and openings with all energy-related physical properties enabling energy evaluations for buildings of any size.

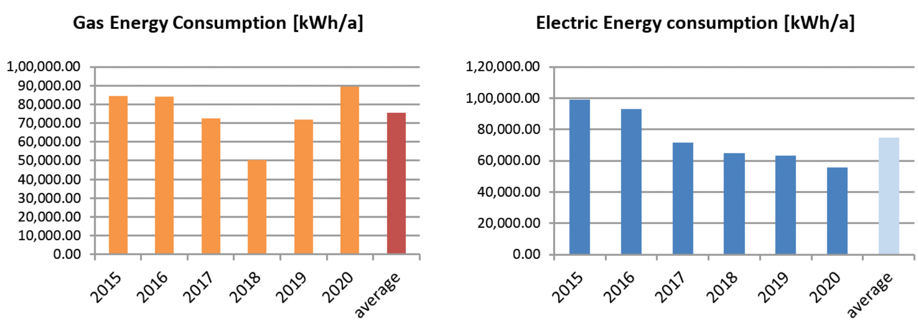


Figure 5: 2015–2020 energy consumption.

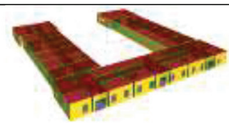
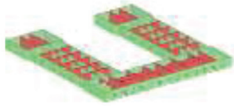
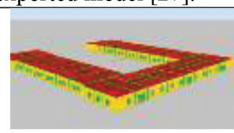
Original BIM model in Archicad®	Analytical energy model in Ecodesigner (Archicad®)	OpenStudio (3.0.0 GNU – EnergyPlus®)
		
Analytical model in TermusPlus®+Energyplus	Satellite view of the case study building (Imagery google earth® view)	Spider gbXML Viewer v2020-10-09 to verify the exported model [27].
		

Figure 6: Tested workflow.

Others authors already compared the capabilities outcomes and some other workflow such as DesignBuilder, TRNSYS 16, IDA-ICE, EnergyPlus, eQUEST, Ecotect, RIUSKA and VIP-Energy [22, 23, 24] or optimization tool [25, 26].

The input boundary conditions for all three simulation approaches made as close to each other as possible are based on the same or similar specified input. In particular, set-point temperatures of the building for the heating and cooling of 20°C and 26°C, respectively, for winter and summer seasons, are assumed.

We then compare the data acquired to pre-calculated values to whether the building achieves the desired energy performance or the simulation match the real energy consumption.

A preliminary sensitivity analysis has identified ventilation rates, infiltration and solar gain as characterized by the highest uncertainty and the greater impact on the eventual differences between simulated and measured energy for space heating and cooling for this case study, then a monthly measured energy consumption (2015–2020) have been contrasted to simulated final uses.

Still few tools are friendly-user, have the right mix of scalability, accuracy and comprehensive feedback for not energy modellers and contains features that helps designers to identify those details responsible for heat loss or inaccuracy at any design stage.

4 RESULTS AND DISCUSSION

Results, summarized graphically (Figs. 7, 8), show that there is a consistent gap in the test 1(+17.70%), 2(+14.80%) and 3(+25.92%) due to a substantial overestimation of the cooling/heating needs, while with OpenStudio workflow the difference is much more limited with the (+5.63%). This is due to many aspect, but the particularly relevant one is the internal solar gains and external air temperature accordingly to the weather data input chosen (.epw file, strusoftclimate or meteonorm calculation) for the climate context. The difference within the geometry (gross floor, net floor, volume, openings) and the set up (zones, schedules, HVAC, lighting, etc.) in the tested software seems to remain under the 5%.

This confirms the sensitivity of input data in building heating energy demand simulation [28]. As regards instead the comparison relative to the heating and cooling energy needs it is clear in Table 5 how all the models present a similar monthly trend.

4 RESULTS AND DISCUSSION

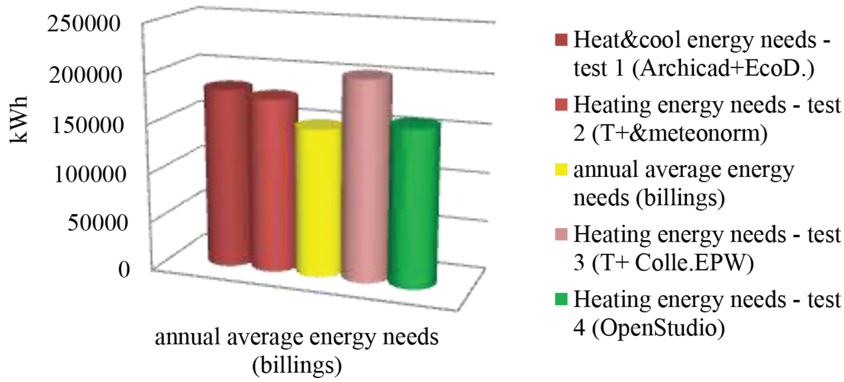


Figure 7: Annual average energy needs.

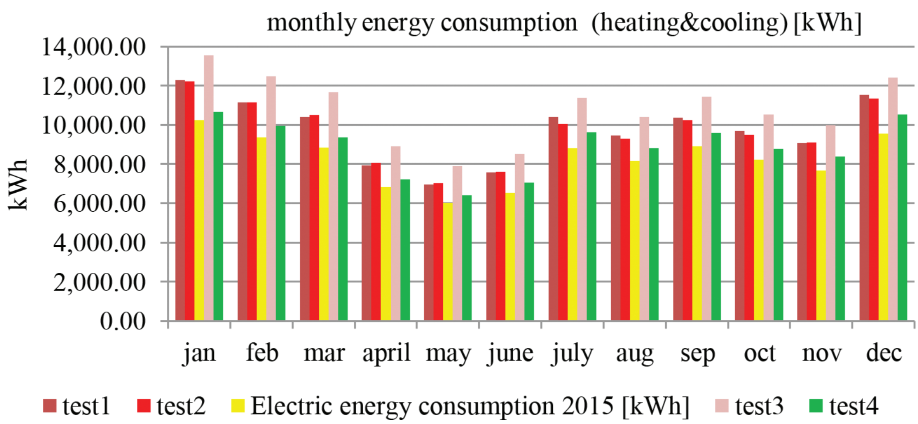


Figure 8: Monthly energy consumption comparison chart.

5 FURTHER INVESTIGATION OF THE PERFORMANCE GAP

In the pilot study, findings are used to identify a number of key issues that need to be addressed within future investigations of the performance gap showed.

1. The methodology of the pilot study will be extended to other five building of the same site with exactly the identical ‘U-shape’, climatic and physical properties, (two buildings with the same orientation and three specular buildings) in order to reduce uncertainties. Even if every single building will have a specific gap, investigation results will mostly show the correlation within the building use and occupant behaviour and could confirm the little discrepancy (<5%) of the case study.
2. In order to calibrate the assumptions of a predictive model and verify the efficacy of the energy simulation, a climatic station and sensors will be installed on one of the building,

or *'should we be using just "Typical" weather data in building performance simulation?'* [29]. The gap will be used to compare a created digital twin based either on sensors or a dynamic algorithm input in order to find a best convergent baseline between digital and real world, using different weather data input [30, 31, 32].

6 CONCLUSION

The inevitable difference between measured and expected performance at a particular existing building, already reported by De Wilde [33] and confirmed with the case study, need mainly not to be bridged only with sophisticated algorithms and time-consuming reviews by thermal experts.

To better reduce the energy inefficiencies and the gap between real and virtual energy consumption, some steps have still to be improved. The process needs a geometry model to be easily converted in an energy model still present some automations to be fixed and some differences (up to the 3% in the case study). In the thermal blocks creation, geometrically based on interior zone, the question remain on how the exterior envelop should be exactly calculated. The meteorological input could represent the first critical issue (up to 25.92% in the case study) to be fixed, so sensors/small weather station with real-time weather data should be implemented as part of an energy survey in existing buildings, because plausible meteorological data are essential for simulations.

To conclude, there is still not an unique and more correct workflow to apply to perform an energy analysis, but an energy evaluation have to be based on what a building does, not only what it is designed to do and whether a building achieves the required energy performance, experts need to monitor various data while the building is in use. So the solutions for the authors is probably to implement and prototyping a digital twin workflow even in the energy domain starting with an hybrid model (BEM + visual scripting/programming) with heuristic input data given by low cost sensor placed on site.

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