The Management of the Energy Performance Simulation of a Complex Building Portfolio. The Case of the School Building Asset of an Italian Municipality

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Abstract

This paper aims at presenting a methodology for the management of multiple energy simulations of complex building assets. The educational buildings of the Milan municipality have been chosen as case studies: several retrofit strategies are tested on hundreds of buildings, evaluating their feasibility and calculating the potential energy savings. The results, obtained with dynamic simulations using SketchUp and the "Intelligent Community Design (iCD)" plugin, are then compared with a static calculation implemented on a regional scale in Lombardy. Besides, a methodology for the collection of the input parameters is proposed, based on the combination of data coming from several sources.

1. Introduction

Due to the increasing risks derived from global warming, proved to be caused by human activities, a dramatic reduction of the greenhouse gas emissions in the atmosphere will be crucial in the near future (Pörtner et al., 2022). The built environment plays a dominant role, since it is one of the largest sources of direct and indirect greenhouse gas emissions (36 %, in Europe) and the share (40 %, ibid.) of energy consumption. In this framework, urban areas play a fundamental role and are deeply involved in meeting the main decarbonization objectives. Educational buildings account for a small percentage of built stock (about 4 % of the European one, in terms of net floor area, and even less, about 3 %, in terms of energy consumption, due to their short time use, (Re Cecconi, 2020), but they represent a critical asset, in particular in Italy (we can refer to the periodic reports edited by Legambiente and the most recent one in particular, Legambiente 2021), because of their age, their maintenance needs and, in general, their social role. Unfortunately, a precise understanding of the energy and carbon footprint of the built asset is rare and often unreliable (this is particularly true for the Italian educational building asset; the Legambiente 2021 report, for example, mentions that the energy-rated buildings are less than ¼ of the total). Data – when easily available – report consumptions only as averages and even their physical description is often unreliable (but improving, see the MIUR OpenData). As a consequence, energy retrofit strategies are usually referred to as one or more "typical" buildings or "archetypes", representatives of the average energy need of the asset and the average retrofit potentials, without defining the real priorities of the asset. This approach is investigated by Mohammadiziazi et al. (2021), who estimated the energy performances of the commercial building stock in Pittsburgh by analyzing twenty building archetypes with a dynamic tool, i.e., EnergyPlus. The same methodology was applied by Caputo et al. (2013), who proposed the estimation of the energy consumption of residential and commercial buildings in Milan, analyzing 56 archetypes different in geometry, construction period, and function. Also, in this case, they use a dynamic tool, i.e., EnergyPlus, whose results were later validated and compared with the energy consumptions reported in the SIRENA (Sistema Informativo Regionale Energia Ambiente) database. Another dynamic tool, i.e., DOE-2.2, was adopted by Krarti et al. (2020) to analyze 54 building archetypes and assess the energy and non-energy benefits in investing in retrofitting existing residential building stock in

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Saudi Arabia. Other authors prefer to assess the energy performances of building archetypes using steady-state methods, using Microsoft Excel (Tuominen et al., 2014) or national energy certification software (Dascalaki et al., 2016). Other methods used for the energy analysis of building archetypes are based on the EN ISO 13790 (Yang et al., 2020; Yang et al., 2022) or multiple regression analysis (Wong et al., 2019). Bottom-up approaches without building archetypes were studied by Costanzo et al. (2019) and Wang et al. (2018). Costanzo et al. (2019) developed a bottom-up engineering approach applied to the Yuzhong District of Chongqing municipality in China, based on EnergyPlus with the Urban Modelling Interface. Similarly, Wang et al. (2018) analyzed the energy demand and the retrofitting potential for three Swiss residential districts of Zurich and Zernez, adopting a bottom-up approach without building archetypes based on EnergyPlus. Other bottom-up approaches investigated are based on statistical methods, e.g., multiple linear regression techniques, as proposed by Mastrucci et al. (2014), Torabi Moghadam et al. (2018), and de Rubeis et al. (2021). These methods can predict the energy consumption on a large scale with reduced computational time and without the need for complex input data as with the physics-based models. The advantages of physical models and data-driven methods are combined and investigated by Li & Yao (2021) and Zygmunt & Gawin (2021), who proposed hybrid approaches based on building archetypes with machine learning and artificial neural network models, respectively. Other analysis methods are based on the energy performance certificates available, as demonstrated by Hjortling et al. (2017) and Gangolells et al. (2016), who respectively mapped the energy performances of existing Swedish and Spanish buildings.

This paper presents a methodology for the assessment of energy retrofit scenarios applied to Italian educational buildings. The energy performances of the school buildings belonging to the Milan municipality were assessed with both dynamic and steady-state tools, testing the effect of three retrofit strategies. The research allowed us to evaluate the energy consumption innovatively; it eliminates the concept of the archetype: the whole urban area of Milan was modeled, assessing the energy performances of each school building. Furthermore, it gave us a clear idea about the available database open sources, cross-checking of the input data, mainly about the buildings' geometry and envelope/plant properties, thus increasing the model reliability and finding a compromise when data were missing.

2. Methodology

2.1 Data Sources and Reliability

This paragraph describes the primary data sources of the modelled school buildings and their related uncertainties. The geometrical models are based on geographic information system (GIS) data, which were later compared with AutoCAD drawings; the buildings' characteristics are obtained from several data sources, such as European projects, national open data, energy performances certificates, etc.

GIS data: OpenStreetMap and Lombardy geographical data

OpenStreetMap (OSM), a crowd-sourcing editable world map, is currently the biggest freely available geodata platform; it provides different kinds of open data, such as building footprints, function, name, height, etc. These maps are based on polylines created with GPS tracks, satellite photos, and various data provided by local governments or volunteers. However, OSM contains two main levels of errors: a systematic one due to the uncertainty of the GIS data, and a casual error, i.e., an unpredictable error due to the inaccuracy of users themselves; besides, for many buildings, we observed an additional lack of information, for example, related to the height of the buildings, which was not consistent with the real values. To overcome these uncertainties, the GIS database of the Lombardy region and the city of Milan was analyzed, visualizing their metadata (shapefile, JSON or CSV format, raster data) on the software QGIS.

AutoCAD drawings

The plans, sections, and elevations for about 20 school buildings, provided as AutoCAD files by the Municipality of Milan, have been analyzed to validate the geometrical information reported in the other data sources.

IEE TABULA project database

The Intelligent Energy Europe Tabula project, published in May 2012 and updated in July 2014, assesses the energy performances of the existing Italian residential buildings, predicting the impact of retrofit measures on both building envelope and plants. This project is chosen as a reference since it contains useful information about the building envelope components: according to the period of construction, it provides a general description of its typical construction elements with their related thermal performances.

Ministero dell'istruzione, dell'università e della ricerca (MIUR) open data

The Italian ministry of education, university, and research provide open data about the whole Italian school asset. For each Italian school, represented by a unique building code, data about location, total areas, and volumes, number of floors, typology of installed plants, year of construction, etc. is provided.

Energy Performance Certificates

The Energy Performance Certificates (EPCs) of the Lombardy region provide more detailed information about the school building asset: heated surfaces and volumes, typology of installed plants, electricity and gas consumptions, envelope thermal transmittances, primary energy consumptions, etc. However, these data are not available for all school buildings, since they refer only to the Italian schools having certified energy performances. Besides, another limitation of these data is related to the certified building unit: in many cases, the energy certificate is provided only for a part of the entire school building, and therefore, in these cases, the data are not representative of the whole building.

EnergyPlus Weather data

The chosen weather data come from the World Meteorological Organization Region and Country and is referred to as a Typical Meteorological Year based on the Milano Malpensa climate. Due to the distance between the airport weather station and the city center, a source of uncertainty arises, since the weather file does not consider the urban heat island effect, which could determine an increased air temperature for several parts of the city.

2.2 Calculation Methods

Two calculation methodologies were chosen: a dynamic one, based on the simulation tool "Intelligent Community Design (iCD)" and applied to 277 educational buildings in Milan, and a steady-state one, based on the UNI/TS 11300-1 and applied to 1036 educational buildings of Lombardy. The first one is a plug-in to SketchUp, a 3D master planning modeling tool able to perform energy analysis scalable from individual buildings up to entire cities. It could be used for both new interventions and retrofit projects, assessing: the heating and cooling energy consumption, the effects of retrofit strategies on the overall performances (i.e., addition of insulation to the building envelope, replacement of the HVAC systems, etc.), energy produced with renewable sources, accessibility to transport and amenities, total building water consumption, etc. The building geometries can be drawn manually on SketchUp or imported from the OpenStreetMap database; all the other characteristics of the buildings can be later assigned by choosing from lists of predefined values. The applied steady-state method is a simplification of the procedure described in the UNI/TS11300-1 standard, and it aims at calculating the final and primary energies according to the following equations:

$$Q_U = (Q_L - \eta Q_G)/\varepsilon_P \quad (1)$$

$$EP_H = Q_U \cdot fp_{nren} \quad (2)$$

For the steady-state calculations, the following hypothesis was assumed: an average air change per hour of 0.4 was considered for each school building, without any heat recovery; the transmission losses were calculated starting from the average envelope thermal transmittances, calculated as weighted values. Concerning the total gains, intended as the sum of internal and solar gains, reference was made to the UNI 10349 for the climatic data and the UNI/TS 11300-1 for the applied average internal gains, equal to 4 W/m^2; besides, a boiler efficiency of 0.83 was assumed to consider the possible losses of the building's systems. In the end, a primary energy conversion of 1.05 was used to estimate the primary energy, choosing natural gas as the primary energy source.

2.3 The Building Geometrical Model

Starting from the OpenStreetMap database, the volumes of all the buildings in Milan were modeled. However, the chosen database contains uncertainties and inaccuracies, mainly linked to the footprint area and height of the buildings: for this reason, the geometry of about 20 educational buildings was later checked and compared with detailed AutoCAD drawings; the rest of the school buildings were instead checked with the data, even if approximate, provided by Google Earth, since no architectural drawings were available for those buildings. The geometric GIS data of different layers are metadata containing technical information and are identified by alphanumeric codes. The school's name or its unique identification code is the link between the geometric and the envelope information. Three actions were performed to achieve the input data needed for the steady-state calculations, based on "Scuole Lombardia", "A020101" and "corpo edificato massima estensione" layers:

1) Filtration in Mapshaper Console: the volumetric unit who have "servizio pubblico - istruzione - sede scuola" were considered.
2) Data Process in Qgis: NN Join Plugin, based on the shorter distance, linked the school's name with the geometry.
3) Data transformation: the surface to volume ratio (S/V) was calculated for all the Lombardy schools based on the procedure proposed by Vicentini and Mutani (2012).

Moreover, the calculated volumes of the buildings were used as reference to check the ones provided by MIUR open data.

2.4 The Building Technological Model

The Lombardy Region Database and MIUR provide very useful but generic information, giving a general description of the building envelope (e.g., "double glazing" or "single glazing" as information for the windows). On the contrary, the Certificazione Energetica degli Edifici (CENED) data provide more specific information that could be, however, as stated in the previous paragraph, related to a small portion of the school buildings modeled. For this reason, the envelope properties were estimated starting from the IEE TABULA project database, assigning the material properties according to the buildings' year of construction. The chosen thermal properties are shown in Table 1.

Table 1 – Envelope thermal transmittance [W/m^{2}K] according to the construction year of the buildings (dynamic and steady-state models)

	?-1975	1976-1990	1991-2005	After 2006
Roof	2.02	1.05	0.68	0.3
Ext. wall	1.74	0.79	0.6	0.34
Int. floor	2.28	0.93	0.65	0.36
Windows	5.23	3.17		2.3
Ground floor	0.79	0.79	0.79	0.79
Int. wall	1.06	0.76 - 0.59		

However, not all the building characteristics were defined using the previously cited sources of data, due to their limitations in terms of information provided. For example, the window to wall ratios (WWR), i.e., the ratio between glazed and opaque envelopes was estimated using Google Earth, calculating these quantities for 49 school buildings. Consequently, the calculated average WWR of 23 % was applied to all 277 school buildings.

2.5 The Building Plant Model

A "central heating radiators" system was applied to all the school buildings as HVAC system; no cooling system is considered. The technical data of the modeled building plants of the dynamic analysis, taken from the iCD database, are summarized in Table 2.

Table 2 – Building system characteristics (dynamic model)

SCOP [kW/kW]	0.83
Heating setpoint [°C]	20
SEER [kW/kW]	-
Cooling setpoint [°C]	-
Auxiliary energy [W/m^2]	0.95
Ventilation heat recovery [%]	-
Air supply [l/(s·m^2)]	0.27
Infiltration rate [ach]	0.167
Domestic Hot Water efficiency [%]	0.5
Average Cold Water temperature [°C]	10
Average Hot Water temperature [°C]	60

2.6 The Building Usage Model

iCD contains several predefined usage profiles, specific for each building typology and human activity. The internal gains are thus assigned to the model, selecting, among the available ones, the usage profiles defined as "School or University", which are summarized in Table 3 and plotted in Fig. 1 along with the building system schedules.

Table 3 – Applied internal gains (dynamic model)

Daily average internal gains [W/m²]			Average people density [m²/pers]
People	Lighting	Appliances	
4	3.4	4	6.8

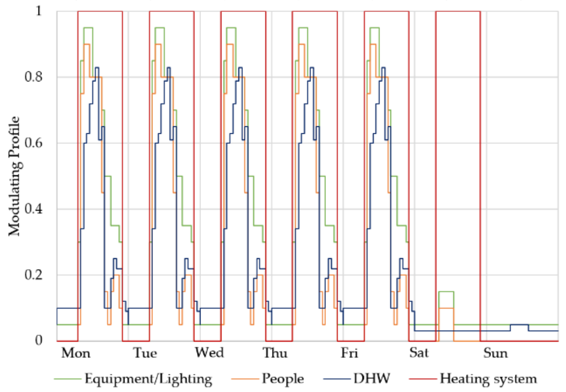

Fig. 1 – Weekly schedules of internal gains and plants (dynamic model)

3. Results and Discussion

3.1 Energy Consumption

The dynamic simulation for all 277 buildings was performed on iCD, analyzing the energy consumption concerning the following: domestic hot water production, auxiliary energy, heating system, equipment, and lighting. These results are plotted in Fig. 2, which summarizes the energy consumption of the school asset as average values. The results show that the highest consumptions, i.e., 69 % of the total, are due to the heating system, probably due to the high heat losses through the envelope and the low efficiency of the installed systems. Therefore, the average total energy of 179.9 kWh/m² is obtained, of which 123.4 kWh/m² are due to heating consumption. This value is consistent with the Italian average heating consumption, estimated equal to 115 kWh/m² (Dias Pereira et al., 2014). Starting from the baseline results, three retrofit scenarios are tested:

1) S1: Replacement of the external windows with double glazing with a thermal transmittance equal to 1.4 W/(m² K)
2) S2: Installation of 10 cm of thermal insulation on the external side of external walls and roof. Fiberglass with a thermal conductivity of 0.034 W/(m K) is chosen for the external walls, while a glass wool panel with thermal conductivity of 0.037 W/(m K) is proposed for the roof.
3) S3: Replacement of the existing boiler with a heat pump with a COP equal to 3.5

The averages and frequencies of the total energy consumption are reported and compared in Fig. 2 and Fig. 3. The replacement of the windows (S1) determines a reduction of the heat losses by transmission, thanks to the reduced thermal transmittance values; in this way, it is possible to reduce the average heating energy consumption, going from 123.4 kWh/m² to 105.7 kWh/m². This solution is optimal for buildings with several floors and a restricted footprint area because the most significant slice of dispersion area will be due to the external area of the wall also influenced by the WWR. The results of the S2 scenario demonstrate the importance of having a well-insulated envelope: we registered a further decrease in the average heating consumption, which arrives at 74.7 kWh/m². Certainly, this solution is more effective than the S1 scenario, due to the larger area of the opaque envelopes. The best results are obtained with the S3 scenario: the replacement of the heat generator determines a reduction of 87 % of the average heating consumption compared with the baseline configuration, decreasing the heating need to 16.5 kWh/m².

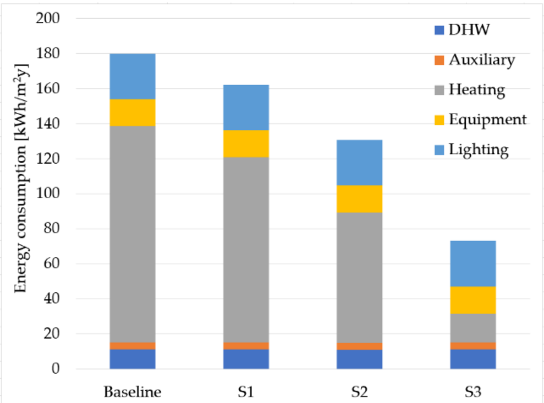

Fig. 2 – Comparison of the average energy consumption

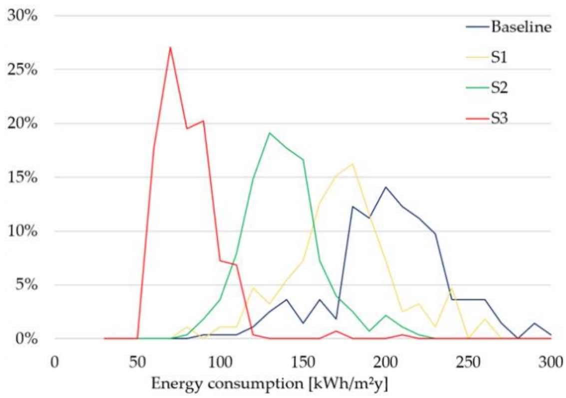

Fig. 3 – Frequency distribution of the total energy consumption

Furthermore, the heating consumption of the school buildings in Lombardy was calculated with a steady-state method: however, to compare these results with those coming from the dynamic model, the initial sample of 1036 schools was reduced to 144 buildings, i.e., the number of buildings common for both steady-state and dynamic models. Comparing the frequencies of several ranges of heating consumption (Fig. 4), we notice that the results of the dynamic calculation do not exceed 240 kWh/m^2, while for the steady-state model we register energy consumption even higher than 340 kWh/m^2. Besides, using the dynamic tool, more than half of the school buildings in Milan are characterized by a heating consumption lower than 140 kWh/m^2; on the contrary, with the steady-state tools, they reach 240 kWh/m^2. Therefore, significant differences between the results compared are presented, which seems higher for the steady-state method. This difference could be related to the methodology itself, highlighting the advantages of dynamic simulation tools, or to the input data and assumptions.

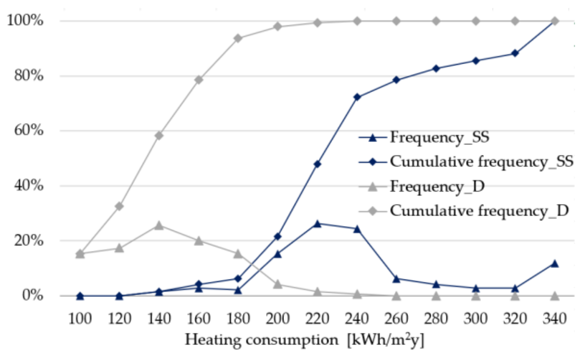

Fig. 4 – Frequency distribution for the steady-state (SS) and dynamic (D) heating consumption

3.2 Limitations and Open Questions

The main limitation of the present methodology concerns the input data needed: several sources have been used to define the buildings' geometries, envelope performances, usage profiles, etc., which might not be consistent with the actual buildings' characteristics. Therefore, the results reported should be compared with measured energy consumption, thus improving and validating the proposed methodology.

4. Conclusion

This paper proposes a methodology for the assessment of the energy performances of urban areas. The educational building asset of Milan was chosen as a case study, calculating its energy consumption with a dynamic tool and obtaining results close to the ones proposed by other authors (e.g., Dias Pereira et al., 2014). Three retrofit strategies were proposed and their effect was assessed: the best results were obtained by replacing the existing heat generators with heat pumps, decreasing the average heating consumption by about 87 % compared to the baseline one. Furthermore, the results obtained with the dynamic tool were compared with steady-state calculations analysing a sample of 144 educational buildings: we registered higher energy consumption with the steady-state method, which could be related to the methodology itself or the different input and sources of data. Hence, future investigations will improve and validate the proposed methodology by comparing the obtained results with actual measured energy consumption.

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Nomenclature

Symbols

ε	Efficiency (-)
η	Utilization factor (-)
EP	Primary energy (kWh)
fp	Primary energy conversion factor (-)
Q	Energy (kWh)

Subscripts/Superscripts

G	Gains
H	Heating
L	Losses
nren	Non-renewable
P	Plants
U	Useful

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