Analysis of the thermal inertia of historic buildings and related advantages for retrofit strategies applied for urban energy modeling

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Abstract

Since the beginning of this century Italian legislation focused on historic and existing buildings' retrofit, as they represent a large part of the national building stock. In this context the most difficult challenge is preserving heritage and obtaining energy saving at the same time. Energy Plus software is used for the detailed dynamic simulation and is compared to simplified resistance-capacitance models. A sensitivity analysis is performed to evaluate the input parameters and their influence on the thermal behaviour of an historic building in Padua (Italy), highlighting the effect of high thermal mass to flatten the temperature trends and optimizing systems' operation.

Key Innovations

- The European and Italian building stocks are mostly historic and need energy saving measures
- The methodology supports the analysis of thermal inertia for historic buildings
- A detailed model and two simplified lumped parameters tools have been compared
- The accuracy of the results obtained from simplified models are mostly related to accurate input data
- Results highlights the importance of investigating and considering thermal inertia for retrofit strategies.

Practical Implications

Results highlights the importance of considering thermal inertia for retrofit strategies avoiding massive actions on protected constructions. Further analysis on the exploitation of the high capacitance of old buildings can reduce the impact of HVAC systems, thus the related energy use and carbon emissions.

Introduction

The retrofit of historical buildings is one of the major challenges to reduce energy use in urban city centers. Recent statistics show that among the 160 million buildings belonging to the European building stock, historical ones are the most important part. About 35% of the building stock in Europe is older than 50 years, among which about 75% is energy inefficient with a renovation rate around 0.4-1.2% every year (European Commission, 2011).

In particular, the Italian building stock accounts of historic buildings (i.e. older than 50 years) for more than 55% (ENEA, 2017). However, historic buildings are subject to conservation principles (Martinez-Molina, 2016) and protected as Cultural Heritage, thus any retrofit action must be carefully designed to deal with architectural and structural importance. Although historic buildings in Europe and United States are mostly exempt from the achievement of minimum energy requirement in buildings (Webb, 2017), in Italy it is not mandatory only for those found in specific lists (Galatioto, 2017). However, a new attitude is shared by policy makers and conservatives defining stricter exemptions in recent regulations (Mazzarella, 2015; Troi, 2014): energy retrofit actions are seen no more as cause of damages and harms to cultural goods, but as an important protection tool to preserve the natural decay due to the progressive aging, thus are allowed when they improve the energy performance without ruining its importance (Decreto Requisiti Minimi, 2015).

Therefore, energy retrofit is extremely challenging because few actions can improve the non-insulated high-mass envelope and the HVAC system, limiting the possibilities to reduce the energy use.

An historical building belonging to the University of Padova, located in the center of the city in northern Italy and built up in four different historic periods has been studied to investigate the possible influence of the thermal inertia for the design of optimal retrofit strategies (Carnieletto et al., 2019).

The first construction belongs to the XII century and completed during the XVI century, while other blocks were built during the centuries, until the last part that was built during the Fascist regime. Energy Plus has been used for the detailed dynamic simulation and was compared to Resistance-Capacitance (RC) models developed for urban building energy simulations. The RC models were applied firstly to the single main zone of the building as 4 air nodes, and later to the whole construction as a single air node, to study the influence of thermal inertia with multiple approaches and to approach the modelling of historical buildings in urban building energy simulations. Since historic building are commonly present in urban city centers, it is important to consider the high thermal mass when modelling historic buildings to evaluate the accuracy of the results, as pointed out by Akkurt et al. (Akkurt et al., 2020).

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Results will be compared to a detailed dynamic model of the whole building implemented with the software Energy Plus, analysing the hourly profiles. This study will help the development of more efficient strategies for historic building retrofit, taking advantage of high thermal mass and related inertia to flatten the temperature trends and peak loads, and optimizing systems' operation exploiting the heat that can be stored and released by the structures. For example, the peak load reduction can positively influence the performances of heat pumps that have been demonstrated to be suitable for increasing the energy efficiency in historical buildings. In fact, new technologies allow the rising of the supply of high temperature at the condenser side, despite the low thermal insulation and high thermal capacitance of historic buildings (Emmi, 2017). Moreover, heat pump technology recently gained increasing interest because of the new regulations that rise the possibility to obtain economic incentives by recognizing the heat exchanged with the heat source as a fraction of renewable energy (Directive 2009/28/EC).

Case study

Building Layout

The implementation of an energy model requires as fundamental input the building characteristics such as envelope properties and HVAC systems, other than internal loads and typical end use. The Palace investigated is one of the main buildings of the University that was built in different historical periods; therefore, several documents reported that its construction was not homogeneous. In the early sixteenth century, the main structure was expanded to adapt it to the increasing academic activity, as explained by the green area in Figure 1. Later in the XVIII century the Palace was further extended as shown by the red area, and finally the current configuration has been settled during the early 19th century (blue area) and the fascist period (yellow) when it has been further expanded to take on today's appearance.

Figure 1: Summary of the different periods and types of construction

For this reason, it was interesting to study the thermal behaviour of the building comparing a detailed model developed with EnergyPlus and two simplified models based on EUReCA, a resistance-capacitance tool developed by Zarrella et al. (2020).

Energy model

Energy Plus model

The detailed model of the building has been developed using the Open Studio interface combined with the software Energy Plus. Each floor of the building has been divided into several thermal zones (Figure 2) chosen appropriately according both to the intended use, to make more effective the management of internal loads in the energy analysis, and to the type of construction, to make an accurate comparison with the simplified model.

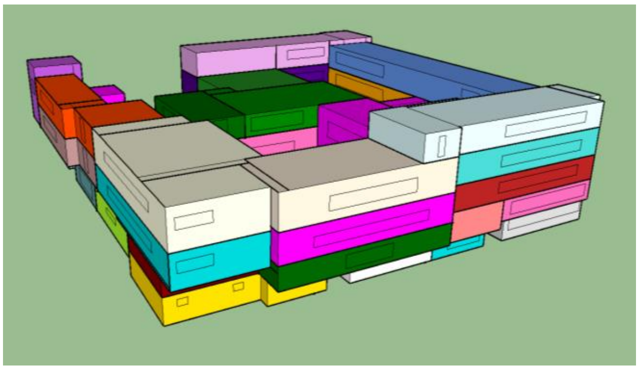

Figure 2: Thermal zone division in EnergyPlus

According to the final use of the building, the internal loads considered are related to the presence of people, lights and typical electrical devices for office and class use. The oldest areas of the Palace are usually occupied for occasional events such as conferences, graduation ceremonies, or guided tours. Thus, the hourly profiles scheduled for occupancy and internal loads depend on the presence of people. The other sectors of the building are mainly used for University offices and teaching activities, therefore with different operating and boundary conditions during weekdays and weekends. The occupancy schedule is based on the typical working time assuming a maximum overcrowding of 70% of the maximum capacity for each zone.

The contributions of lighting and electrical equipment (computers, printers, etc.) have been decided according to EN ISO 18523 Standard (ISO, 2018):

- 10 W/m^2 for specific light loads;
- 150 W for each computer.

Temperature set points were defined for the calculation of the building energy demand, setting 21°C for the occupied hours (9 am - 5 pm) during the winter season, while the value of 18°C has been maintained constant during the night and weekend days to be closer to the real operation of the Palace.

The cooling setpoint temperature is set at 26°C and 60% relative humidity during the occupied hours of the

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summer season, while it is increased at 28°C in the period from 8 am to 9 am and from 5 pm to 6 pm.

The envelope stratigraphy was verified with on-site surveys and information collected from historic documents, assuming four main combinations according to the year of built as presented in Figure 3.

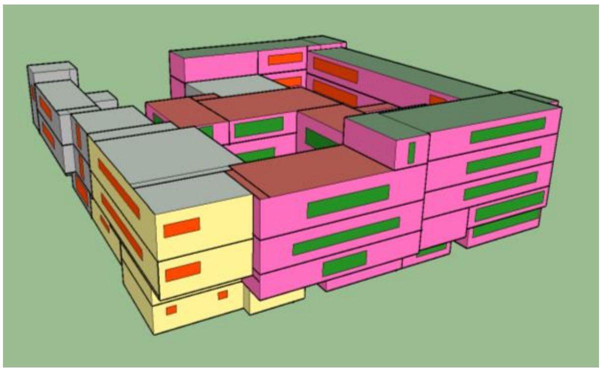

Figure 3: Rendering by construction type

Table 1 presents an example of stratigraphy applied to the oldest walls, whose material properties were taken from UNI 11552 Standard (UNI; 2014). The oldest parts of the building were made of stone masonry with wood slab and roofs, while the most recent construction presents solid brick walls and brick-concrete slabs.

Table 1: Example of wall stratigraphy.

Layer	Capacity [kJ/(m² K)]	Width [m]	Transmittance [W/(m² K)]
1500			
External wall	1512	0.60	2.50
Ground floor	200	0.15	2.15
Slab	80	0.15	1.90
Roof	44	0.05	2.50
1800			
External wall	1512	0.60	2.09
Ground floor	200	0.15	1.88
Slab	117	0.20	1.80
Roof	101	0.15	1.80
Early 1900			
External wall	760	0.50	1.15
Ground floor	240	0.25	1.88
Slab	185	0.20	1.45
Roof	185	0.20	1.60
Late 1900			
External wall	760	0.50	1.15
Ground floor	400	0.25	1.30
Slab	280	0.20	1.10
Roof	280	0.25	1.08

As expected, old constructions were made of massive walls and structures with high thermal inertia that can be exploited to optimize the operating condition of the system, since a significantly high thermal capacity may influence the operative temperature of the thermal zones and, consequently, the overall energy demand. Due to the uncertainty of some information, internal walls have been considered equal for the whole building, with 10 cm of hollow bricks as average value. Single glazing windows with thermal transmittance equal to 4.5 W/(m² K) have been applied.

EUReCA models

According to a previous research (Vivian et al., 2017), simplified lumped capacitance energy models can be suitable to estimate accurately the energy demand of a building. However, the case study presented is not conventional, due to the presence of buildings belonging to different historical periods that were combined to obtain the current layout.

A simplified energy model has been implemented according to the lumped-capacitance approach presented by the ISO 13790:2008 (ISO, 2008) and VDI6007 Standards (German Association of Engineers, 2012) using the tool EUReCA (Energy Urban Resistance Capacitance Approach) developed by the Authors.

In particular, the building thermal characteristics are lumped in a discrete number of parameters using five thermal resistances and one thermal capacitance (5R1C) in the case of ISO 13790 Standard to reproduce the transient building thermal behaviour, as shown in Figure 4. θ_i, θ_s and θ_m represent the building air node, internal surfaces' node, and surfaces' mass node, respectively. $H_{tr,ms}$, $H_{tr,em}$ and $H_{tr,w}$ are the transmission coefficients through opaque and glazed surfaces. $H_{tr,is}$ is the convective/radiative heat transfer coefficient between air and surfaces, and H_{ve} is the ventilation heat transfer coefficient. Finally, θ_{sup} and θ_e are the external and supply air temperature (boundary conditions).

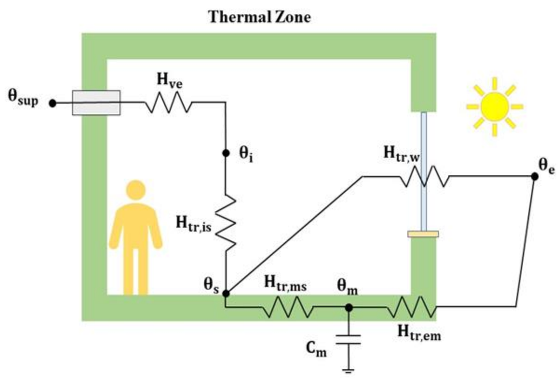

Figure 4: Physical scheme of the 5R1C model

Each thermal resistance and capacitance were estimated according to the specific guidelines of the Standard by means of four main group of input data: (a) building geometry, (b) building structures' characteristics, (c) user behaviours and (d) weather data.

The 7R2C model suggested by the German Standard VDI 6007 (2012) introduces a second capacitance dividing the structures in external ($C_{1,EW}$) and adiabatic ($C_{1,IW}$). The simplified physical model is presented in Figure 5, that shows the thermal resistances associated to adiabatic ($R_{1,IW}$) and non-adiabatic surfaces ($R_{1,EW}$). R_{rad} considers the long-wave radiant heat transfer between the

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two structure's categories while the convective heat transfer between the internal air and the non-adiabatic and adiabatic surfaces is represented by $R_{conv,EW}$ and $R_{conv,IW}$ respectively. The thermal capacitance node of the non-adiabatic surfaces is connected to the external environment through the thermal resistance $R_{Rest,EW}$, while ventilation and infiltration heat losses are considered with R_{ve}.

Both the 5R1C and the 7R2C thermal networks can be considered as white-box physical models. Each parameter is defined by means of the thermo-physical properties of the building, without any calibration or optimization process. They are calculated according to the mentioned Standards.

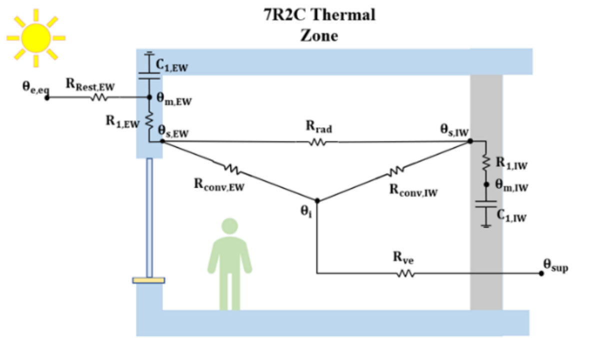

Figure 5: Physical scheme of the 7R2C model

EUReCA can handle both CityJSON and GeoJSON semantic geo-referenced data to import the building geometry, while the structures' set must be compiled for each building, reporting stratigraphy and thermal characteristics of each surface. Table 2 shows the geometric characteristics of the single zones compared to the model of the whole building as a single air node (Whole building).

The total footprint area (Whole building) is around 7% higher than the sum of the single zone, due to the simplified extrusion of the overall footprint times the height of the building; however, results are not significantly affected by the approximation.

Table 2: Summary of the geometric characteristics

Period of construction	ID	Volume	External wall area	Footprint area
		[m^3]	[m^2]	[m^2]
1500	bd500	7834	2330	1641
1500	bd5002	6801	725	850
1800	bd800	8740	1457	2431
Early 1900	bd900e	20694	3879	6868
Late 1900	bd900l	25589	4362	4553
Whole Building	EP	69658	12753	16343

For the case study presented, opaque walls and window properties have been defined according to the Energy Plus detailed model, in order to have comparable results. Appliances and occupancy schedules, temperature and humidity setpoints as well as air change rate are also defined according to the same Standards used for the detailed model. More detailed information about solar heat gains and latent loads can be found in a previous study (Zarrella et al., 2020).

Using a criterion of continuity of materials, the main building has been split in the five areas presented in Figure 1 by dividing the historical part of the fourteenth century from the most modern parts.

Two different cases have been simulated and compared to the whole building modelled with Energy Plus:

- *Case A*: a single air node for the whole building;
- *Case B*: 5 different air nodes corresponding to each main zone.

For the second case, each stratigraphy has been assigned according to the period of construction. The simulation of the overall model has been further simplified assuming as wall properties the average transmittance of the second case.

Results

Previous sections described the case study building and the workflow of the lumped-parameters simulations. The following section shows firstly the aggregated energy demand resulting from the detailed and simplified models, then looks at other additional considerations deriving from the analysis of hourly temperature profiles and Root Mean Square Errors (RMSE).

Energy Results

Results for the entire building (*Case A*) are shown in Table 3. The relative error compared to Energy Plus in the heating season is 14% (1C) and 24% (2C), while the cooling season presents more variable results partially due to the lower energy demand and the more intermittent operating schedule, around 34% (1C) and 25% (2C).

These seasonal results are coherent with a previous work focusing on the validation of the simplified models, and confirm that energy prediction can be slightly affected in buildings with complex geometries, as this case study. Indeed, a simple extrusion can be not acceptable in a single building simulation, but it is necessary to scale-up these models to an urban scenario. However, the annual results highlight how, considering a good quality of input data, the simplified models can reach a decent estimation of buildings energy needs despite the geometrical approximation.

Table 3: Building total heating and cooling demand

[MWh]	1C	2C	EP
Heating	1877 (14%)	2027 (24%)	1640
Cooling	280 (34%)	260 (25%)	209

Figure 6 displays the heating (Figure 6.a) and cooling (Figure 6.b) seasonal demand resulting from the different

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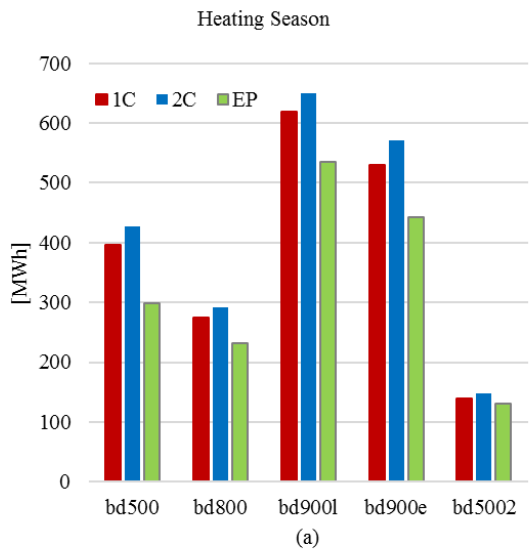
models and building's areas. Looking at the winter season, bd900e and bd900l report the highest heating demand calculated with Energy Plus, i.e. 520 and 440 MWh respectively. Despite its poor insulation level, bd5002 has the lowest value due to its smaller dimensions and high internal heat gains (conference rooms). Another observation regards the performance of the simplified thermal networks, whose results are coherent with the detailed modeling of EnergyPlus also in this scenario. Nonetheless, the heating demand, especially using the 2C model, is overestimated for all building's areas (Table 4). The highest relative error (43 %) occurs in bd500, where the internal heat gains are almost null and this has a greater impact on the lumped modelling. In bd5002 the prediction of the 1 capacitance model is good, reaching an outcome close to the EnergyPlus simulation (6%).

Sensible and latent cooling demand results in lower values with respect to the heating season. Considering this parameter the recent and largest wings of the building (bd900e and bd900l) show the highest values, but in this case bd900e has a higher demand than bd900l, reaching 99 MWh. The cooling demand for bd500, bd5002 and bd800 is really low, between 10 and 20 MWh. Simplified thermal networks outcomes are really good considering bd900e, while in the other cases the prediction is overestimated as in winter season. As previously mentioned, this behaviour of EUReCA model has been already studied in a previous research (Zarrella et al., 2020) and deals both with the simplified thermal zone model, and with the mutual shading of building surfaces. This is not considered in EUReCA, whose solar heat gains are higher than EnergyPlus simulations. Moreover, the low cooling demand density of this case study causes high relative errors between simplified and detailed models. Even so, the error on the prediction of the 7R2C model during summer season is lower than the 5R1C network, showing the higher reliability with respect to the simpler 5R1C: for instance, in bd800 the relative difference with respect to EnergyPlus is 49% and 35% for 1C and 2C models respectively.



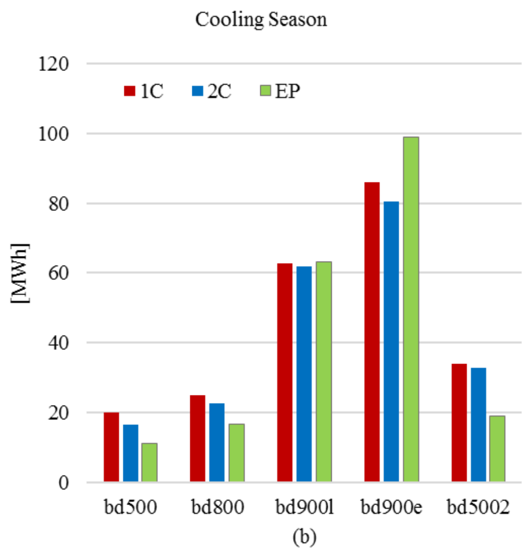


Figure 6: Heating (a) and Cooling (b) energy demand

Table 4: Relative error between simplified and detailed models

Period	Heating		Cooling	
	1C	2C	1C	2C
bd500	33%	43%	80%	50%
1800	18%	26%	49%	35%
Early 1900	16%	21%	-1%	-2%
Late 1900	20%	29%	-13%	-19%
bd5002	6%	13%	80%	73%

Temperature Profiles

The second part of the results focuses on the operative temperature of the different models. Operative temperature in simplified thermal networks is calculated as the average between the air temperature and the surfaces' temperature. Considering the 7R2C model the surfaces temperature is the combination of the adiabatic and non-adiabatic nodes' temperatures, weighted by the total area of each group of structures. Moreover, as far as the zoning approach is different between the detailed simulation and the simplified thermal networks, operative temperatures resulting from the EnergyPlus simulation are combined together. Thus, considering the thermal zones belonging to each building wing, their equivalent temperature is calculated through a volume-weighted average. Figure 7 displays the winter or summer operative temperature for different building wings.

Winter operative temperature ranges between 16 °C and 20 °C in every building zone (air setpoint temperature is set to 18 °C night-time and 21 °C day-time). The lowest value in the heating season is reached in bd500 (Figure 7.a) due to the lower U-value of external walls and roofs, together with negligible internal heat gains. Summer operative temperature reaches its top values during the first week of August (hour 5050-5250) and ranges

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between 28 °C and 34 °C (Figure 7.b) during the weekends or holidays where the system is switched off. Despite these intermittent peaks, the operative temperature stays under 27 °C for each zone during the building opening days, guaranteeing the indoor thermal comfort.

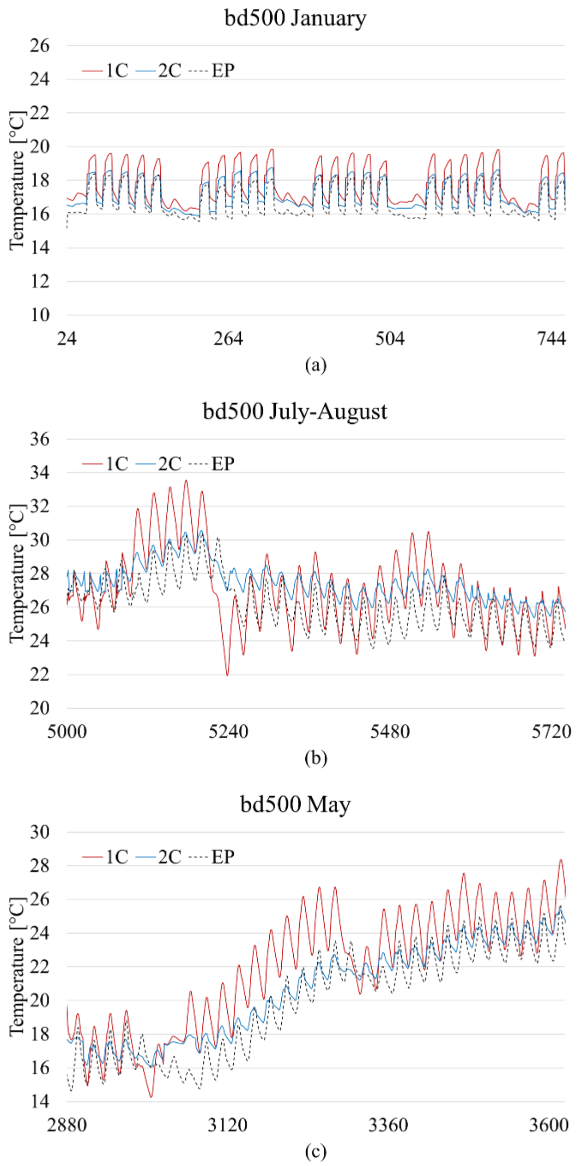

Figure 7: Operative temperature profiles for building 1500: winter (a), summer (b), free-floating (c)

The operative temperature resulting from simplified models is close to the EnergyPlus trend, both in heating and in cooling season. The trend during a free-floating period is displayed as well (Figure 7.c). The simplified models trend follows correctly the EnergyPlus benchmark, especially for the 7R2C thermal network, which is almost always in between EnergyPlus daily peak and valleys. On the contrary, 5R1C network results in a highly variable trend, which causes a difference between night-time and day-time temperatures higher than the 2C model or EnergyPlus. This observation is highlighted by means of a Root Mean Square Error (RMSE) measure. The RMSE is calculated between the operative temperature of the simplified networks and the EnergyPlus trend, considered as a benchmark. Figure 8 shows the results for each building's wing. In any case, the 5R1C model causes higher errors on the operative temperature calculation. The lowest error shows up in bd800 (about 1.4°C), similar to bd900f and bd500, while the worst prediction appears in bd5002 (2.2 °C), clearly affected by the internal heat gains, as previously mentioned. The 7R2C model performs better, reducing the RMSE between 0.2 and 0.6 °C depending on the considered wing. Looking at the global simulation (Case A), the resulting RMSE is 1.6 °C and 1.1 °C for 1C and 2C networks respectively, showing a good performance of these models also on the temperature estimation.

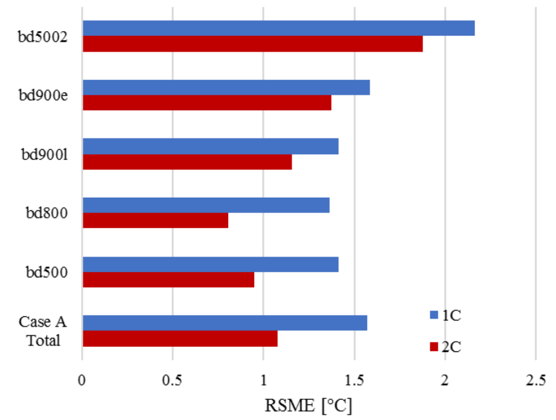

Figure 8: Operative temperature Root Mean Square Error (RMSE)

Control strategy of the setpoint temperature

Two different setpoint controls on air temperature for the heating season have been simulated both with EnergyPlus and the 7R2C model to study the behaviour of the operative temperature and the energy demand. Figure 9 shows the comparison between the different schedules used in the simulations:

- baseline case, with a setback temperature during the night and the weekends of 18°C, and a daily temperature of 21°C
- on/off control with setback temperature of 10°C
- stepwise control with 4 temperature steps before reaching the daily setpoint.

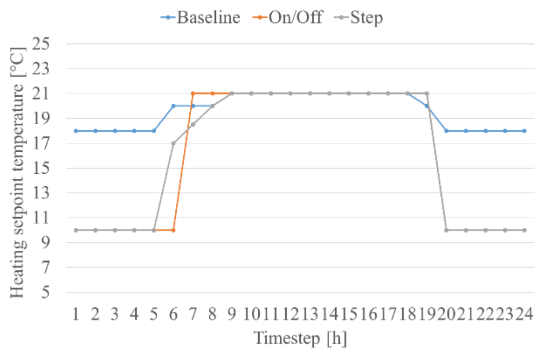

Figure 9: Heating setpoint air temperature for different regulations strategies

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The operative temperatures in Figure 10 show the same trends both with EnergyPlus and 7R2C models, although showing a slower trend when using a stepwise regulation. During the daily operation of the building temperatures range between 18.5°C and 19°C, increasing constantly and ensuring the thermal comfort for the users.

The hourly energy demand for space heating shows that the two strategies assume the same value at 8 am, when the daily operation of the building commonly starts. Figure 11 highlights that the stepwise regulation of the setpoint temperature allows a reduction of the daily peak load required by the heating system (around 40% with EP and 25% with 7R2C) by starting the system slightly before and maintaining an increasing temperature trend.

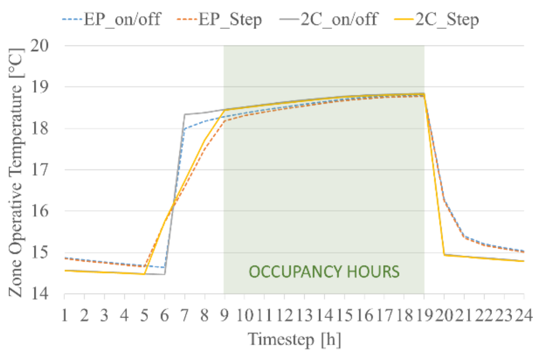

Figure 10: Operative temperature of Bd1800 obtained with Energy Plus and 7R2C models

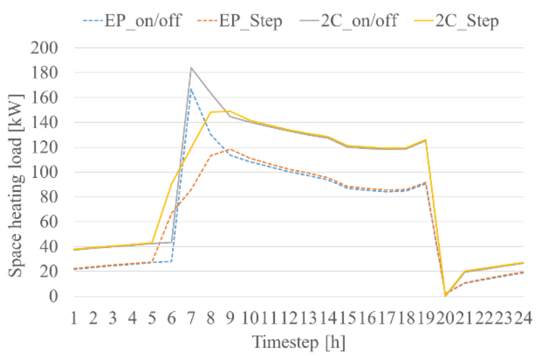

Figure 11: Space heating energy demand of Bd1800 obtained with Energy Plus and 7R2C models

Moreover, the heating demand is slightly overestimated by the 7R2C compared to the EnergyPlus model, as already shown by Prataviera et al. (2021). This gap is mostly due to the different building dynamic behaviour considered in the two simplified models and to the simplified thermal zoning and geometrical assumptions. Furthermore, the stepwise control allows a minimal reduction of the energy demand as shown in Table 5, which presents the relative difference between the two setpoint regulation strategies. The 7R2C model has a better performance compared to the 5R1C showing a lower error, while EnergyPlus presents significantly higher errors but still acceptable.

Table 5: Relative difference

	1C	2C	EP
Whole Building	-0.50%	-0.48%	-2.05%
bd500	-0.39%	-0.40%	-1.40%
1800	-0.45%	-0.45%	-1.90%
Early 1900	-0.50%	-0.53%	-2.43%
Late 1900	-0.51%	-0.48%	-1.95%
bd5002	-0.55%	-0.54%	-2.64%

Conclusion

The comparison between the single resistance-capacitance models for each construction and the overall model of the building with Energy Plus aims at evaluating the influence of massive walls and the related thermal inertia on the energy performance of the building. This approach represents a key phase to model historical building in an urban context, since they usually present peculiar characteristics from the recent constructions. The comparison between a detailed model developed with the dynamic tool Energy Plus with simplified 5R1C and 7R2C lumped-capacitance models shows good results when proper input parameters are used, as can be seen for bd900e.

The results outline that the energy demand of the building is better estimated in the winter season, with an error of 14% with 5R1C model and 24% with 7R2C model; for the specific case study, the cooling energy demand is less accurate, mostly due to the more intermittent operation.

The study remarks the importance of the modelling approach with simplified models that can be used also at urban scale. To proper consider the thermal inertia of the building fabric, a strategy can be to split the building in different volumes, improving the sensitivity of lumped capacitance models in the evaluation of energy demands and air temperatures. However, this operation could require more data availability.

A similar approach can be useful to properly consider historical buildings in urban energy models, especially in Countries like Italy. In these cases, thermal inertia should be considered as an important factor to define energy saving strategies that take advantage of this property, for example using proper insulating materials avoiding the risk of overheating due to the high thermal mass. When wall insulation is not allowed due to cultural heritage protection, the installation of more performing windows applied as envelope refurbishment as non-invasive action, combined with operating schedule modifications can lead to significant results in terms of energy savings, as shown in previous works (Carnieletto et al., 2019). In addition, further optimized developing control strategies for heating and cooling systems can possibly reduce the impact of the systems, exploiting the effect of the thermal inertia. In fact, the application of an on/off control strategy compared to a stepwise control of the heating setpoint temperature allows a peak load reduction of the 40% when simulating the building with EnergyPlus and

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around 25% with the simplified model, thus maintaining reasonable values of operative temperatures.

The developed methodology can be useful to apply new strategies to groups of buildings in historic urban city centers, supporting the reduction of energy use and related CO_2 emissions at wider level while respecting the existing limitations on the possible interventions to protect the historic importance of these buildings.

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