Journal of Building Engineering 80 (2023) 107973

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

A modelling framework for modern heritage buildings energy simulation

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A R T I C L E I N F O

Keywords:
Modelling framework
Building thermal simulation
Model validation
Building retrofit
Modern heritage preservation
Existing building stock

A B S T R A C T

The latest European polices highlight the urgent need to rehabilitate the existing building stock, responsible for 40 % of the EU's total energy consumption. In this process, a key role is played by thermal simulations, assessing the effective energy performances. However, significant discrepancies between real and simulated consumptions are frequently outlined. Inaccurate results are particularly dangerous for modern buildings, which, rarely protected, are often altered by invasive retrofitting solutions, with little regard for their heritage and cultural value. This paper introduces a comprehensive framework for the building energy simulation, ensuring the necessary model credibility. It consists of dynamic modelling, calibration and validation, enhancing the usefulness of the final results. A validated model is in fact the premise to propose a well-balanced retrofitting scenario, improving the current energy performances, reducing the operational costs, and preserving the historical values of existing buildings. As operative case-study, Chauderon administrative building in Lausanne (1969–1974), designed by the *Atelier AAA* in collaboration with Jean Prouvé, has been selected. Today, the complex is well-preserved in its original materiality and represents an iconic example of the modern aesthetics, with an expressed need for retrofitting. Following the proposed framework, a reliable model in WUFIplus has been created and validated according to ASHRAE 14, allowing to reliably test the efficacy of future retrofitting scenarios. The final aim of this process is to minimize the risk of inappropriate interventions. For high-quality or recognized post-World War II building stock, the use of a calibrated and validated model is justified and recommended over the static or simplified modelling approaches still commonly employed today.

1. Introduction and background

The existing building stock is today responsible for 40 % of European energy consumptions [1,2]. Within this stock, the buildings realized between 1945 and 1990 accounts for 45 % [3], making of modern architecture the primary focus of contemporary energy-saving policies [4–6]. Regulatory approaches encourage energy conservation measures (ECMs) targeting above all the envelopes, such as external insulations, more efficient glazing, and solar shading [7–9]. In this context, the integrity of modern buildings'

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https://doi.org/10.1016/j.jobe.2023.107973
Received 28 June 2023; Received in revised form 29 August 2023; Accepted 18 October 2023
Available online 22 October 2023

aesthetics is at risk, at a time when their recognition as heritage objects is the topic of an exciting debate around the world [10]. Thus, it becomes crucial to recognize their cultural and historical values [11,12], avoiding disruptive ECMs and integrating energy efficiency with heritage preservation aims [13]. Effectively, in modern architecture fully glazed façades or wide curtain walls are at the same time the most iconic components and the main sources of thermal dispersions, with transmittance values which are often up to three times higher than recommended by current standards [14]. Accurately assessing the effective energy performance is a key factor to prevent unbalanced interventions [15]. For this reason, the energy modelling and the thermal simulation are two essential - but often underestimated - phases [16,17] to outline the most appropriate retrofitting scenarios.

Today, researchers are increasingly concerned about modelling credibility and recognize significant discrepancies between simulated and measured energy use in buildings, reaching up to three times the predicted consumptions [18–21]. Several factors contribute to this disagreement, among them two recognized sources are [22,23]: (1) the widespread preference for simplified building models based on static energy simulation tools; and (2) the presence of input uncertainties [24]. When dealing with historical buildings, dynamic methods are strongly recommended [12], since they consider the comprehensive building's response to the real changings of the outdoor environment [25]. On the other side, static methods, based on standard libraries, present a poor flexibility and insufficient information in terms of technical properties for historical building elements. Considered user-friendly by many practitioners and admitted by several building regulations [26,27], excessively simplified models are often the reason for consistent energy gaps [12], extremely dangerous in the preservation field, where material authenticity and minimal intervention are two leading concepts.

Regarding the input uncertainty, it is recognized by researchers as an inherent feature of modelling. Buildings are in fact complex systems, where many times generic values are used, resulting in large confidence intervals of data [28]. Reliable energy models are achieved when the uncertainties are assessed, and the output discrepancies are minimized through a calibration and validation process [16,19]. Roberti et al. [29] demonstrate that the risk to work with uncalibrated models is particularly high for heritage buildings, since uncontrolled performance gaps may justify invasive and unnecessary renovations.

Although an accurate assessment of the energy performances is highly recommended, the performance gap remains a significant issue in the current practice [16] and methods for achieving a high accuracy in thermal modelling have not been systematically explored yet [19]. Firstly, few papers focus on the model calibration of historical buildings, and even fewer address 20th century realizations. The diffuse difficulty in recognizing the historical values of modern architecture may be a plausible reason for this lack. Pernetti et al. [30] focused on the indoor air and surface temperature for calibrating a 19th century building model; Cardinale et al. [31] studied the energy assessment of two Italian vernacular buildings. Secondly, as noted by Westphal et al. [32], calibration and validation, although available in various simulation tools, are often considered complex processes requiring specific knowledge, avoided since rarely required by building standards. As a result, these important phases still fail to attract practitioners' attention at a large scale, remaining confined to research centres and universities. Roberti et al. [28] underline the necessity to simplify these approaches, developing more user-friendly tools.

To address these challenges, new and appropriate workflows are needed. This paper aims to outline a comprehensive modelling framework to reduce the performance gap in thermal simulations, mainly addressing modern architecture. The method focuses on the two recognized sources of errors, involving dynamic evaluations coupled with calibration and validation phases. The calibration relies on real monitored data and Sensitivity Analysis (SA), to recognize the most influential inputs. The validation phase follows national standards and official guidelines [33], to ensure the necessary model credibility. In this way, the proposed approach assesses the real energy performances, helping in minimizing the performance gap and allowing to predict more realistic retrofitting scenarios. The final aim is to design balanced renovations, capable to reduce the energy needs, to respect the original materiality and to preserve the modern heritage aesthetics.

2. Material and methods

The whole framework integrates the multiple aspects emerged from the literature review into a single coherent process. These aspects include dynamic modelling [12,34], sensitivity analysis [24,28,35], model calibration and validation [16]. The overall approach, as depicted in Fig. 1, is structured into six major phases: (1) building audit, to collect the essential data for the energy simulation; (2) Initial Model (IM) definition, based on the data gathered in the previous step; (3) Initial Model validation, to compare the simulated outputs with the real data, assessing their accuracy; (4) sensitivity analysis – performed when the IM is not validated - to

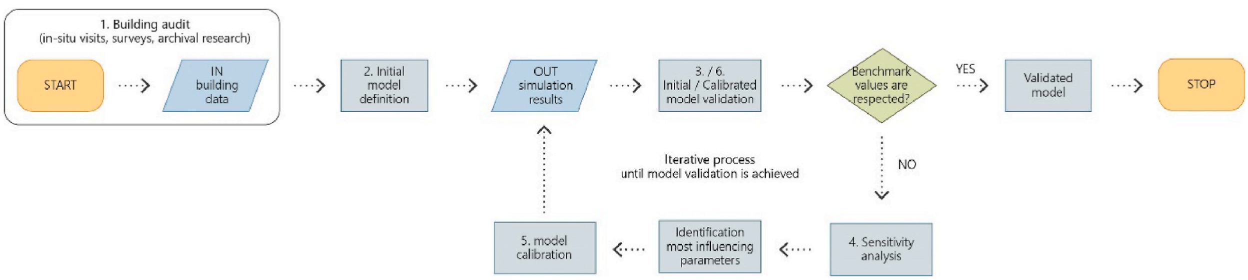

Fig. 1. Methodological process developed for the existing building model validation. The process is intended as an iterative approach.

identify the most influential inputs; (5) model calibration, to create a Calibrated Model (CM); (6) CM validation, comparing the simulated outputs with the real data. Steps 4, 5, 6 are iterative, until the final model validation is achieved.

During the validation phase, MBE (normalized mean bias error) and CV (RMSE) (coefficient of variation of the root mean square error), as widely adopted in previous research and recommended by building standards [33,36,37], are the two selected criteria, checking whether there is acceptable agreement between the simulated results and the real monitored data. Equations (1) and (2) present the formulas employed for MBE and CV (RMSE), where $E_{simulated}$ *and* E_{actual} are respectively the simulated and monitored values, n is the number of observations and $\bar{E}$ is the average of the monitored data for n observations.

$$MBE = \frac{1}{\bar{E}} \bullet \frac{\sum_{j=1}^{N} \left(E_{simulated(j)} - E_{actual(j)}\right)}{n} \times 100 \quad (1)$$

$$CV(RMSE) = \frac{1}{\bar{E}} \bullet \sqrt{\frac{\sum_{j=1}^{N} \left(E_{simulated(j)} - E_{actual(j)}\right)^2}{n}} \times 100 \quad (2)$$

MBE is a non-dimensional indicator of overall bias in the simulation predictions. Negative MBE value means that the simulation model underestimates the energy consumption, while a positive MBE value

Represents an overestimation. It is noted that MBE can suffer from cancellation between positive and negative values, which may lead to misleading interpretations. On the other side, CV (RMSE) can evaluate how close the simulated results are to the real data and does not suffer from the compensation effect.

The obtained results permit to assess the model accuracy with respect to defined benchmark values. If the validation only focuses on the energy use, the benchmarks specified by ASHRAE 14 (2002) [33] can be used. However, if a higher accuracy is desired, the indoor air temperature for internal comfort is widely considered, relying on values coming from literature [38–40]. It is important to note that existing calibration criteria are primarily based on predicted energy consumption, and there are currently no guidelines that consider input uncertainties related to the simulated indoor environment. In the present paper, as recommended by previous research [28,41], both the validations are conducted. The benchmarks values based on the energy consumption and the indoor air temperature are summarized in Table 1.

2.1. Sensitivity analysis using factorial design

The Sensitivity Analysis (SA) represents a fundamental step. Its aim is to evaluate the influence of the input parameters on the model predictions [42,43]. According to Razavi et al. [35] the SA is necessary in good modelling practices, as also encouraged by existing guidelines [44,45]. Such a technique, beside the particularity of each existing method, basically consists of varying the input values to verify the consequent output variation. Between the different SA approaches, Fürbringer and Roulet [27,46] claim that the Design of Experiments (DOE) tools such as the factorial matrices, even if still rarely used today, provide the possibility of a clear feedback on the effect of the inputs' variation as well as the opportunity to consider interactions in a quite simple way [47,48]. For these reasons, factorial design is proposed and preferred over the more diffused Monte-Carlo or One Factor at a Time methods [38].

Factorial design is a classic DOE method which allows to determine the coefficients α_i, α_{ij}, etc. of a linear model with interactions, as described by Eq. (3).

$$Y = \alpha_0 + \sum_i \alpha_i X_i + \sum_{i \neq j} \alpha_{ij} X_i X_j + \dots \quad (3)$$

The matrix of experiments E includes the elements e_{ij} which are the values of the input parameters X_j for the experiment i. In factorial design the simulations are normally performed at the minimum and maximum values of each of the N parameters, defining 2^N points in the experimental space. Assuming centred and normalized inputs, the matrix of experiments E can be written with $+1$ (maximum) and -1 (minimum) values, as shown by Eq. (4) for a $N = 3$ inputs case.

Table 1
Validation benchmark values based on hourly and monthly energy consumption and indoor air temperature.

		Calibration type	MBE [%]	CV-RMSE [%]
Based on energy consumption	ASHRAE 14 [28]	Hourly	30 %	10 %
Based on energy consumption	ASHRAE 14 [28]	Monthly	5 %	15 %
Based on indoor temperature	Literature review [36–38]	Hourly	2 %–6 %	10 %–15 %

$$E = \begin{bmatrix} -1 & -1 & -1 \\ -1 & -1 & +1 \\ -1 & +1 & -1 \\ -1 & +1 & +1 \\ +1 & -1 & -1 \\ +1 & -1 & +1 \\ +1 & +1 & -1 \\ +1 & +1 & +1 \end{bmatrix} \tag{4}$$

Full factorial design allows to determine the effects of N input parameters with all possible interactions after 2^N simulations. This design has the disadvantage of requiring a lot of runs and it is practicable only for small numbers of input parameters. To solve this issue, it is possible to take advantage of the small probability that all the effects are significant, considering only the most influential input parameters, according to literature review [37,49] or using the *fractional factorial design* [50]. In this case, the fractional matrix is based on aliased coefficients and the literature provides a list of generators to define the most convenient matrix for each specific case.

3. Case study

The proposed framework is applied and validated for Chauderon Administrative building in Lausanne, realized between 1969 and 1974 by the *Atelier des Architects Associés* in collaboration with Jean Prouvé, Figs. 2–3. The building has been selected for multiple reasons: (1) it is nationally recognized as modern heritage, but still not legally protected [51]; (2) there is today an expressed interest in reducing its energy consumptions; (3) the lack of legal protection may represent a risk in case of erroneous thermal evaluations, since it can lead to heritage-disruptive renovations; (4) the building is well preserved, especially in terms of its original materiality; (5) it represents an iconic example of 20th century architecture, characterized by a peculiar architectural design, materiality, and pioneering construction techniques. The building is composed by two parts: an upper suspended volume which covers an open space platform and a concrete basement. Only the suspended volume has been considered in the present research, the relevant data are summed up in Table 2.

3.1. Building audit

The first step aimed to provide a precise building description. It involved site visits, historical and archival research, as well as interviews with technicians, engineers, and facility management personnel. In general, when archival information is missing or lacking, on-site surveys coupled with the creation of a BIM model may be helpful in defining the building geometry and its thermal properties. In the present case, a complete building survey, supported by historical documentation [52], allowed to precisely define the architectural features. Among several building components, particular attention was paid to the façade prefabricated panels, which represent one of the few remaining examples of Prouvé's lightweight envelope systems [53–55]. The opaque portion consists of an exterior aluminium sheet (2 mm thickness), an intermediate layer of polyurethane foam insulation (10 cm thickness), and an interior metal sheet (1.5 mm thickness). The windows are equipped with double insulating and reflecting bronze glass, type Stopray by Glaverbel (6/9/8 mm), with neoprene joints, Fig. 4.

The thermal transmittance of the external walls, windows, roof, and first-floor slab has been assessed using Wufi2D [56], while the influence of thermal bridges is calculated in Flixo [57]. The thermophysical properties were derived both from archival documentation

Fig. 2. Aerial view of Chauderon Administrative Building. Historical photo 1974.

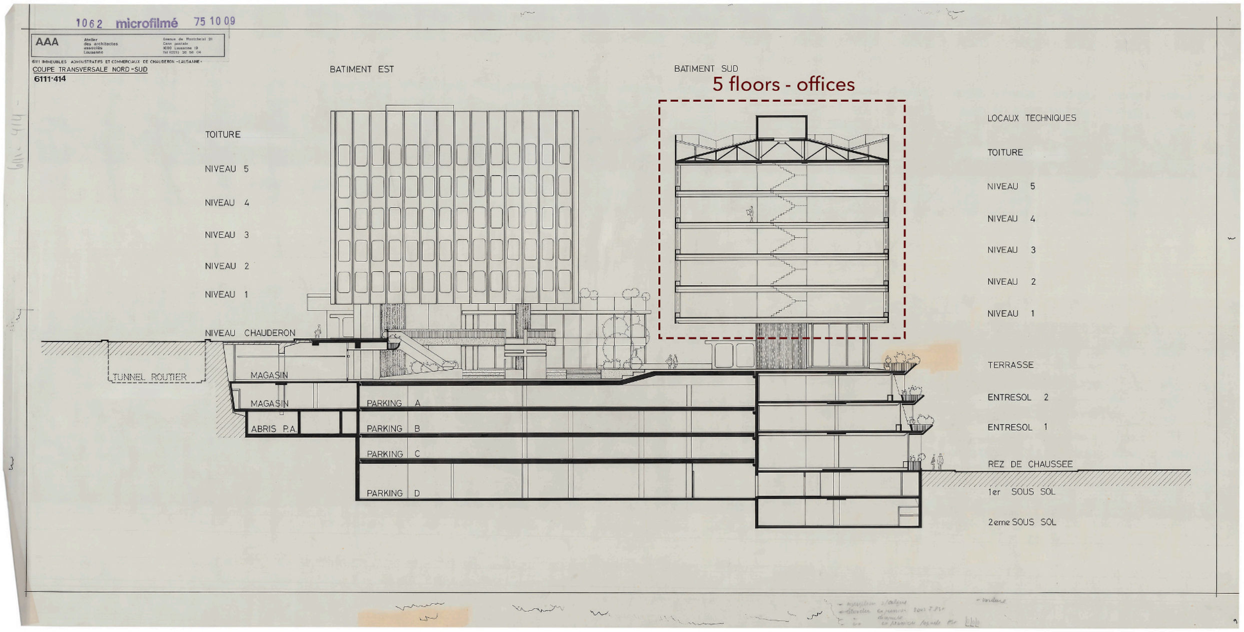

Fig. 3. Chauderon Administrative building, transversal section. In the red box the five office stories analyzed in the present paper. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Identifying data of the case study building.

Name		Chauderon Administrative Complex
Year of construction		1969–1974
Designers		Atelier des Architects Associés, Jean Prouvè
Localization		Place Chauderon 9, Lausanne, CH
Functional destination		Administration/Offices
Protected building		No
Site Altitude	m	495
Floor number	m	5
Tot. neat floor area	m^2	7070
Tot. neat volume	m^3	21832
Total façade area	m^2	2856
Glazing area	m^2	1032
Glazing ratio	%	60
Roof area	m^2	1414

[52] and *in-situ* measurements. Thermography [58] was employed to identify specific areas of concern, such as the absence of thermal insulation beneath the first floor, the insufficient insulation of the original neoprene elements, and the significant thermal losses caused by the windows. Notably, thermal bridges were observed at the vertical joints, as depicted in Fig. 5.

The schedules for indoor temperature profiles were established based on the property's specifications and national thresholds outlined in SIA 380/1 [26]. To determine the air infiltration rates, a blower door test was conducted. Differential pressure measurements and tracer gas analysis revealed that the rooms maintained overpressure, resulting in a negligible infiltration rate. Technical data regarding air flows and other aspects of the HVAC system were obtained from the operational and maintenance manuals of the air handling units. Finally, weather data were obtained from Lausanne-Pully weather station, with mean hourly values considered from the past 15 years of records. At this stage, in case specific inputs lacked available evidence, default settings or values coming from Swiss standards [26,59] were temporarily employed. The main data coming from the building audit are presented in Table 3.

3.2. Initial model definition

The gathered data enabled the creation of the IM, used to perform dynamic simulations in WUFIplus [60]. In accordance with ISO 13790 [25], the building was divided into thermal zones. Specifically, two thermal zones were established to distinguish the south and north offices. The attic and utility rooms were considered to be unconditioned, while the adjacent ground floor was assumed to have the same temperature as the offices above. The thermal zone classification is summarized in Table 4.

After running simulations in WUFIplus, the annual energy demand for space heating in the actual state was 125 KWh/m^{2}y. To provide a basis for comparison, energy simulations were also performed using Lesosai2022 [61], the official Swiss software, based on

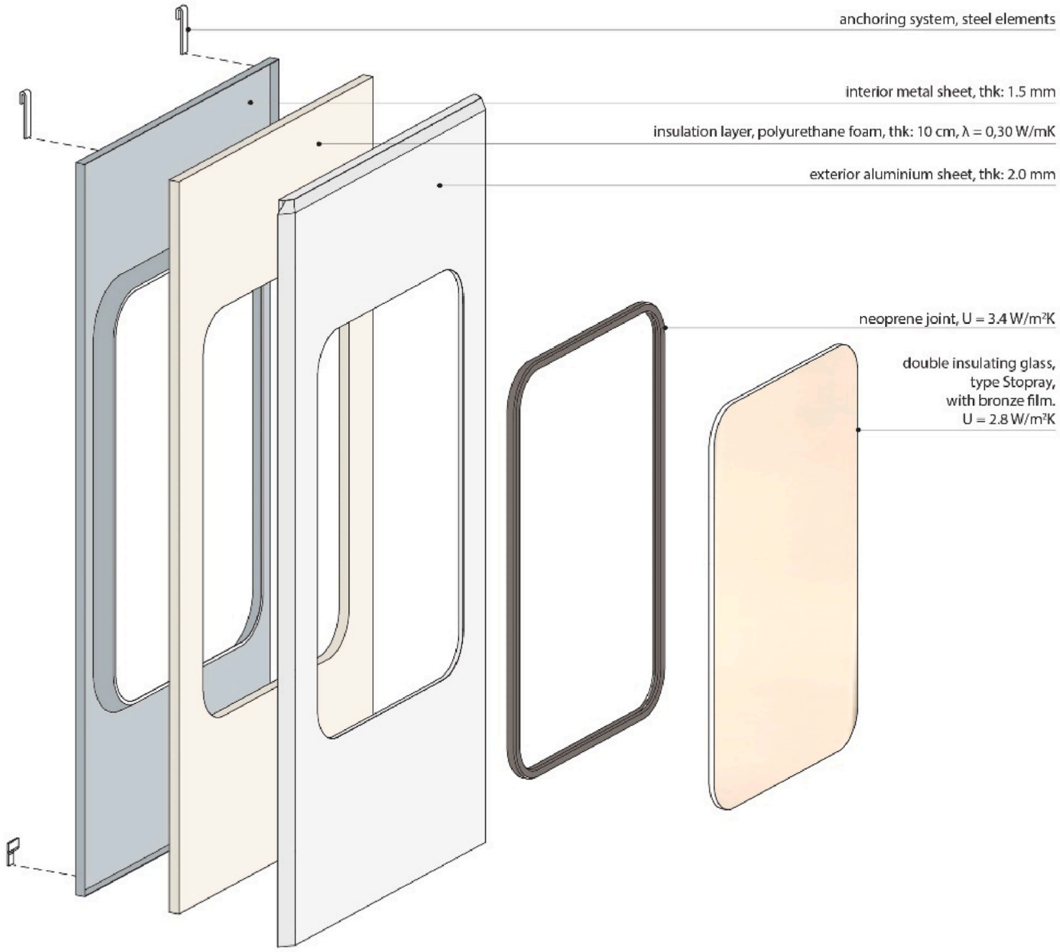

Fig. 4. Exploded view of the façade prefabricated panel and its different components.

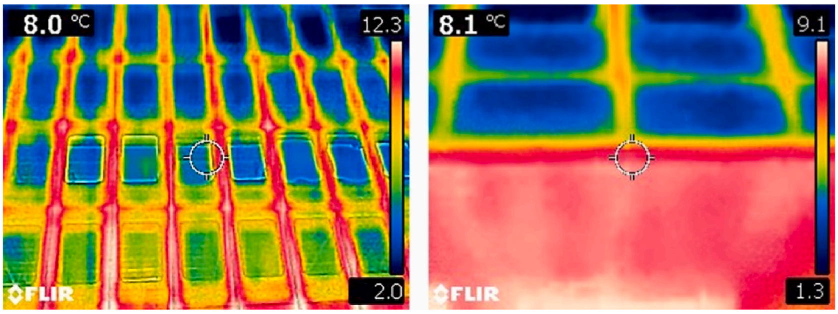

Fig. 5. Thermography results underline the relevant thermal losses through the panels' joints (left) and in correspondence of the porch slab (right).

monthly (quasi-static) calculation, following the norm SIA 380/1 [26]. In this case, the energy demand was 187 KWh/m^2y. Both the results were compared with the historical heating consumptions obtained from monthly supply contract invoices. These data allowed for the determination of an average monthly energy demand based on typical usage of the years 2004, 2011, 2016, and 2021, with an average yearly energy demand of 154 KWh/m^2y. The comparison revealed a consistent performance gap between the predicted and real consumptions, with a deviation of −19 % in the case of WUFIplus and +21 % in the case of Lesosai2022. This finding aligns with previous research [12], indicating that the quasi-static calculation slightly increases the energy gap.

3.3. Initial model validation

Once the IM has been created, the 3rd step has been to assess its accuracy. A validation process was needed, comparing the

Table 3
Main parameters used for the initial model definition coming from the building audit.

Element	Parameter	Source for initial model value	IM value
Exterior pref. panel	Area [m^2]	Archival research/measurements	1850
	Thermal transmittance [W/m^{2}K]	Archival research/in situ analysis/simulations Archival research	0,28
	Elem. thickness [m]		0,30
First slab towards the external porch	Area [m^2]	Archival research/measurements	1122
	Thermal transmittance [W/m^{2}K]	Archival research/in situ analysis/simulations Archival research	3,76
	Elem. thickness [m]		0,12
Last slab towards the unheated attic	Area [m^2]	Archival research/measurements	1414
	Thermal transmittance [W/m^{2}K]	Archival research/in situ analysis/simulations Archival research	3,07
	Elem. thickness [m]		0,22
Internal slab	Area [m^2]	Archival research/measurements	1414
	Thermal transmittance [W/m^{2}K]	Archival research/in situ analysis/simulations Archival research	3,91
	Elem. thickness [m]		0,12
Windows	Area [m^2]	Archival research/measurements	1032
	Glass transmittance [W/m^{2}K]	Archival research/historical documentation	2,79
	Frame transmittance [W/m^{2}K]	Archival research/historical documentation	3,40
	Global transmittance [W/m^{2}K]	Simulations	2,91
	Air infiltration rate [ACH]	Measurements	0,05
	External shading factor [%]	Data sheets/tables	0–15
Thermal bridges	Horizontal [W/mK]	Simulations/in situ analysis	0,5
	Vertical [W/mK]	Simulations/in situ analysis	1,0
Internal loads	Number of people [−]	Measurements/interviews	250
	Electricity consumption [MJ/y]	Bills/number and type of appliances	120
Design conditions (the values vary according to schedules)	Heating temp. range [°C]	SIA 380/1/interviews	20–21
	Cooling temp. range [°C]	SIA 380/1/interviews	25–27
	HVAC air flows [m^3/h]	Manuals/comparison with similar buildings	25k - 32k
	Humidity range [%]	Measurements/Existing data	40–70

Table 4
Thermal zones definition inside the building.

Thermal zone	m^3	Level	Space
Offices north exposed	720	1–5	Heated
Offices south exposed	720	1–5	Heated
Distribution/stair	4160	0–5	Heated
Entrance hall	370	0	Heated
Attic	3600	6	Not-heated

simulation outputs with the measured data. Hereinafter only the results coming from the dynamic calculation are considered, since they present the lowest performance gap. The model validation has been performed following the MBE and CV (RMSE) criteria, as recommended by ASHRAE 14, monitoring the monthly heating consumptions along the year and the indoor air temperature during summer. In particular, the actual air temperature has been detected with hourly measurements made in six different offices in the period from 4th to July 10, 2022. In these regards, Roberti et al. [28] demonstrated that validating a model over two or more different periods of the year definitely improve the confidence in the input parameters. Concerning winter energy consumptions, the MBE value was −19 % and the CV (RMSE) value 29 %, while considering summer air temperature the MBE value was 15 % and the CV (RMSE) value 16 %. Since both the results did not meet neither the ASHRAE 14 standards neither the literature benchmarks, the IM was not validated, indicating the need for a model calibration phase. Effectively, only in rare cases the IM can be expected to yield an acceptable output accuracy, since the lack of necessary inputs' evidence strongly affects the output.

3.4. Sensitivity analysis with factorial design

Thus, the Sensitivity Analysis (SA) was conducted using the IM as a starting point. Usually, in building modelling there are numerous parameters with uncertain values and running lots of simulations to determine their influence with an equal priority can become an extremely time-consuming process. For this reason, starting from a range of selected parameters, the sensitivity analysis helps in defining which inputs are more significant than others, prioritizing them for the model calibration and validation. As a general rule and if needed, the number of the selected parameters can be increased during the iterative process, until the model validation is finally reached.

Beyond the specificity of each case, the research by Cozza et al. [19] states diffuse causes and solutions to reduce performance gaps and the literature review by Chong et al. [37] presents a list of the most commonly selected inputs. In addition, the meticulous historical and technological research conducted by the authors [62] coupled with the detailed energy audit, combining in situ measurements with archival documentation, allowed to identify five parameters for the screening through SA. In particular, they are: (1) indoor air temperature schedule for heating, (2) indoor air temperature schedule for cooling, (3) occupant schedules and behaviour, (4) fresh air supply, (5) unheated attic temperature. To estimate the effects of the input variations a SA via factorial design is proposed, comparing the yearly energy consumptions. As done in previous research [27], the range of inputs' variability has been defined through a positive and negative percentage change, starting from their initial value. The matrix of experiments E, defined in Eq. (4), was computed in Excel and shown in Fig. 6, where $+1$ represents the maximum value of each input parameter and -1 the minimum one. In this case, conjugate effects due to inputs interactions have been considered till the first level, second and further levels were assumed as negligible.

Given that the number of screened parameters N is 5, $2^N = 32$ simulations have been required in order to determine the relative effect of inputs' variation on the output value.

3.5. Model calibration

According to the SA, the indoor air temperature for heating was the most influencing input. Therefore, a first calibrated model (CM1) was created, focusing on precise set point temperatures, usage times, and the operation tables of the heating system. In CM1, the

X =

	a	b	c	d	e	a;b	a;c	a;d	a;e	b;c	b;d	b;e	c;d	c;e	d;e	Y [kWh]
1	1	1	1	−1	1	1	1	−1	1	1	−1	1	−1	1	−1	1'017'551
1	1	1	1	−1	−1	1	1	−1	−1	1	−1	−1	−1	−1	1	983'935
1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1'054'023
1	1	1	1	1	−1	1	1	1	−1	1	1	−1	1	−1	−1	1'021'654
1	1	1	−1	−1	1	1	−1	−1	1	−1	−1	1	1	−1	−1	1'066'753
1	1	1	−1	−1	−1	1	−1	−1	−1	−1	−1	−1	1	1	1	1'038'445
1	1	1	−1	1	1	1	−1	1	1	−1	1	1	−1	−1	1	1'103'951
1	1	1	−1	1	−1	1	−1	1	−1	−1	1	−1	−1	1	−1	1'076'569
1	1	−1	1	−1	1	−1	1	−1	1	−1	1	−1	−1	1	−1	1'927'310
1	1	−1	1	−1	−1	−1	1	−1	−1	−1	1	1	−1	−1	1	1'717'960
1	1	−1	1	1	1	−1	1	1	1	−1	−1	−1	1	1	1	1'360'053
1	1	−1	1	1	−1	−1	1	1	−1	−1	−1	1	1	−1	−1	1'250'978
1	1	−1	−1	−1	1	−1	−1	−1	1	1	1	−1	1	−1	−1	1'882'867
1	1	−1	−1	−1	−1	−1	−1	−1	−1	1	1	1	1	1	1	1'652'214
1	1	−1	−1	1	1	−1	−1	1	1	1	−1	−1	−1	−1	1	1'409'750
1	1	−1	−1	1	−1	−1	−1	1	−1	1	−1	1	−1	1	−1	1'298'343
1	−1	1	1	−1	1	−1	−1	1	−1	1	−1	1	−1	1	−1	663'312
1	−1	1	1	−1	−1	−1	−1	1	1	1	−1	−1	−1	−1	1	607'057
1	−1	1	1	1	1	−1	−1	−1	−1	1	1	1	1	1	1	688'777
1	−1	1	1	1	−1	−1	−1	−1	1	1	1	−1	1	−1	−1	632'782
1	−1	1	−1	−1	1	−1	1	1	−1	−1	−1	1	1	−1	−1	703'211
1	−1	1	−1	−1	−1	−1	1	1	1	−1	−1	−1	1	1	1	647'946
1	−1	1	−1	1	1	−1	1	−1	−1	−1	1	1	−1	−1	1	728'931
1	−1	1	−1	1	−1	−1	1	−1	1	−1	1	−1	−1	1	−1	673'993
1	−1	−1	1	−1	1	1	−1	1	−1	−1	1	−1	−1	1	−1	663'311
1	−1	−1	1	−1	−1	1	−1	1	1	−1	1	1	−1	−1	1	607'057
1	−1	−1	1	1	1	1	−1	−1	−1	−1	−1	−1	1	1	1	672'386
1	−1	−1	1	1	−1	1	−1	−1	1	−1	−1	1	1	−1	−1	616'230
1	−1	−1	−1	−1	1	1	1	1	−1	1	1	−1	1	−1	−1	703'211
1	−1	−1	−1	−1	−1	1	1	1	1	1	1	1	1	1	1	647'946
1	−1	−1	−1	1	1	1	1	−1	−1	1	−1	−1	−1	−1	1	728'931
1	−1	−1	−1	1	−1	1	1	−1	1	1	−1	1	−1	1	−1	673'993

	α_0	α_1	α_2	α_3	α_4	α_5	α_{12}	α_{13}	α_{14}	α_{15}	α_{23}	α_{24}	α_{25}	α_{34}	α_{35}	α_{45}
relative effects $\frac{\alpha_i}{\alpha_0}$ [%]		32.37	13.02	1.75	4.88	3.89	13.23	0.51	5.98	1.07	0.60	6.48	1.71	0.77	0.03	0.71

a: indoor temperature H	b: indoor temperature C	c: internal gains	d: fresh air supply	e: ΔT unheated attic
-1 = 20 °C	-1 = 23 °C	-1 = 150 people	-1 = 18'000 m^3/h	-1 = 10 K
1 = 24 °C	1 = 27 °C	1 = 350 people	1 = 32'000 m^3/h	1 = 15 K

Fig. 6. Matrix of Experiments E as computed in Excel. In black the five main input parameters and in red their combinations. The values of yearly energy consumptions in the last column have been used for the evaluation of each relative effect. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

internal temperatures were only based on the real profiles, as provided by the building technicians, without considering any standard value.

Going beyond, to further reduce the performance gap and the output' discrepancies, an additional model calibration (CM2) was performed. CM1 was used as a simulation base for CM2 creation, where all the parameters screened through the SA were meticulously defined. Similarly to CM1, the indoor air temperature for cooling was defined according to the real building usage. The unheated attic temperature was defined according to surveys in situ monitoring. Fresh air supply has been calculated relying on interviews with the engineers who designed and installed the Air Handling Unit (AHU) systems and the technicians charged for their use. Finally, occupant schedules were defined considering the real working hours, workers per square meter and daily presence in the building were considered.

3.6. Calibrated model validation

CM1 and CM2 are validated following the same steps described for the IM validation. In both cases the annual energy demand is considered as well as the monthly energy consumption and the indoor air temperature. The MBE and the CV (RMSE) errors have been firstly calculated and then compared to the ASHRAE 14 standards and the literature benchmarks.

4. Results and discussion

4.1. Sensitivity analysis

Fig. 7 illustrates the main and conjugate effects of the five screened parameters. The results indicate that the indoor air temperature for heating has the highest influence at 32.5 %, which is a plausible outcome considering the building's age and the cold climate of Lausanne. The indoor air temperature schedule for cooling (13 %), fresh air supply (5 %), and unheated attic temperature (4 %) have lesser but still significant influences. Also, conjugate effects due to the combination of indoor air temperature and fresh air supply, should be taken into account. Notably, the impact of the indoor air temperature schedule for cooling (6.5 %) during summer is slightly higher than in winter (5.5 %), indicating its importance in terms of internal comfort during the warmer months. Other conjugate effects with an impact lower than 2 % were deemed negligible for the calibration purposes. In contrast to several other cases [63–65], occupancy in Chauderon seems to play a minor role (2 %). This finding is not an absolute result, but it is due to o the fact that occupancy was already defined with good accuracy in the initial model and a relatively small variation range was used.

Also, the process demonstrated that the model calibration via DOE techniques requires an almost basic knowledge of statistics,

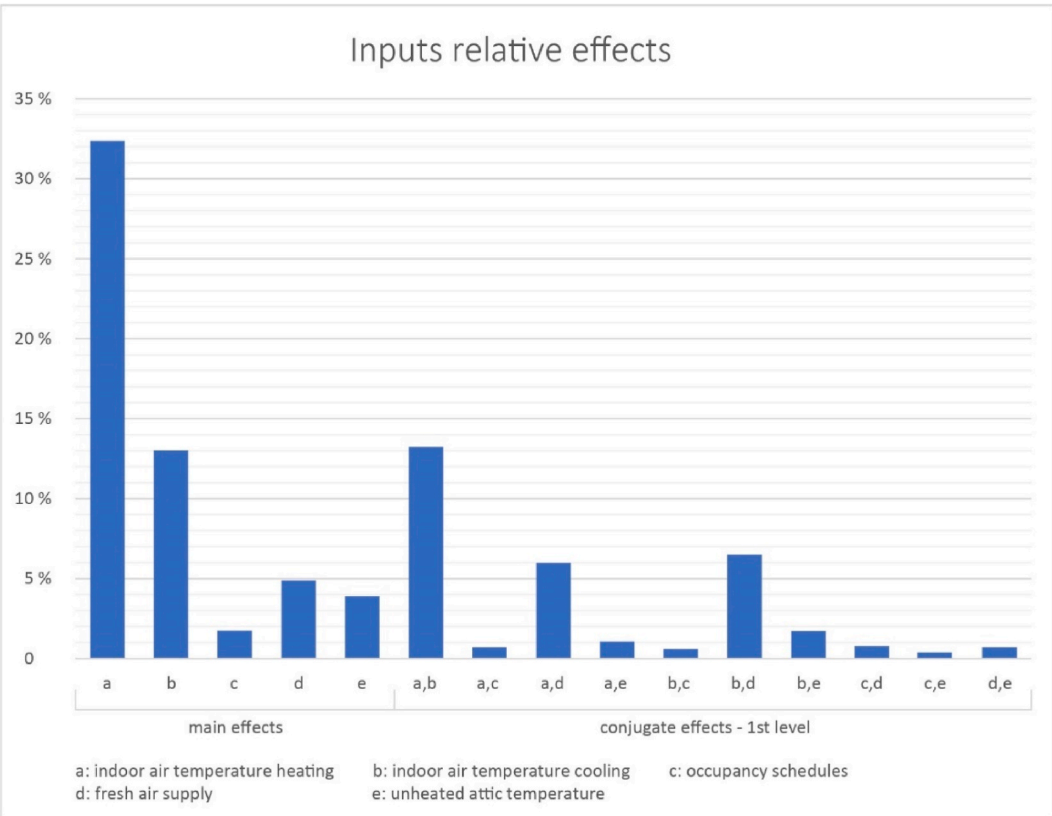

Fig. 7. Final Sensitivity Analysis results with the relative effects of each input parameter. Main effects on the left and conjugate effects on the right.

concretely making of the proposed framework a practical tool, accessible even to non-expert practitioners. The matrix of experiments *E,* in fact, has been fully computed in Excel, without resorting to specific tools as Matlab to solve sophisticated algorithms.

4.2. Calibration and validation

As could be expected, the IM presented unacceptable results, reason why a calibration process was needed. CM1 was created after one simulation, adjusting only the indoor air temperature schedule for heating, while CM2 asked for 13 iterative runs with subsequent inputs calibration before its final definition. Table 5 reports the total energy consumption, as well as the MBE and CV (RMSE) results for the actual state AS, the Initial Model IM and the two calibrated models CM1 and CM2.

Fig. 8 is a comparison of the monthly energy demand of the actual state AS, the IM, CM1 and CM2, while Fig. 9 compares the indoor air temperatures, as measured on site, with the simulated values for the IM and CM2.

Firstly, CM1 had an annual energy demand for space heating of 145 kWh/m^{2}y, resulting in a reduced performance gap from −19 % to −6.1 %. As expected, the calibrated winter schedule with the higher internal temperature actually set in the building (22 °C instead of 20 °C, as suggested by the Swiss standard SIA380/1 [26]) led to a notable increase in the energy consumption. The MBE value for the monthly energy demand was −6% and the CV (RMSE) value 31 %, while for the indoor air temperature the MBE value was 11 % and the CV (RMSE) value 13 %. These results emphasize the complex nature of buildings as systems with multiple interdependent external factors. Somewhat unexpected, CM1 presented a higher CV (RMSE) value, if compared to the IM, even if the MBE value was strongly decreased and the annual performance gap sensibly reduced. The reason is that the MBE was affected the cancellation effect between positive and negative values, resulting in a misleading outcome. While the annual energy consumption in kWh/m^{2}y appeared consistent with the real values, a notable gap still existed in the monthly consumptions, particularly during summer.

On the other hand, in CM2, the annual energy demand for space heating was 149 kWh/m^{2}y, reducing the performance gap to −4%. The MBE value for the monthly energy demand was −3.5 % and the CV (RMSE) value was 14.6 %, while for the indoor air temperature the MBE value was 6 % and the CV (RMSE) value was 7.5 %. In this second case, the calibration of the remaining parameters allowed to solve the issues encountered with CM1. Effectively, the low summer temperature settings (22 °C instead of 26 °C, as suggested by the Swiss standard SIA380/1 [26]) increased not only the energy demand for cooling - not considered in the proposed validation process - but also the heating demand during the months from May to August, due to heating air for drying. Summer temperatures' calibration also permitted to obtain indoor air temperatures coherent with those measured *in-situ*, validating the model even in terms of internal comfort. It is worth noting that several studies [66,67] have highlighted the correlation between windows' characteristics (e.g., orientation, dimensions, usage, and opening system) and indoor air temperature. However, in the case of Chauderon, the impact of the fixed windows on the natural air changes is limited. The IM and CM1 underestimated the air flow rate, and its improvement, based on the effective settings, slightly increased energy consumptions, especially during the mid-season periods, yielding a more realistic output. Lastly, the calibration of the unheated attic temperature also reduced monthly discrepancies, as reported by the CV (RMSE) value. Based on *in-situ* measurements, the unheated attic can be considered a useful buffer zone that generally limits heating or cooling needs.

Although CM2 exhibited an annual energy consumption closer to CM1 than to the real building, the model was significantly improved in terms of monthly behavior. The still existing performance gap is considered not to undermine the overall model credibility. CM2 was finally validated, as all its values met the benchmarks presented in Table 1. Based on the dual validation during two different periods of the year, CM2 is considered a robust representation of the energy performance of Chauderon building in its current state. This result provides a reliable premise for proposing future and heritage-respectful retrofitting scenarios. For example, the importance of correct temperature settings for energy saving is clearly demonstrated, leading to thermal improvements which rarely affect the original materiality. Also, the archival research coupled with energy simulations, allowed to identify valuable elements, as the extremely rare façade's panels, and more common components which can be easily insulated, as the unheated attic space or the first exposed slab, reducing the global consumptions without altering the historical image of the building.

In addition, the experience highlighted the importance of detailed monthly and hourly energy simulations based on dynamic methods. Unfortunately, up to now, several building standards still refer to global consumptions, admitting simple per cent difference calculation. This attitude often led to inaccurate assumptions, particularly dangerous for the rarely protected 20th century buildings, where the cultural values linked to the original materiality should be preserved.

It is finally reported that heavy renovations are not only regrettable from a preservation point of view, but they frequently cause users' discomfort, a significant waste of money and they are not sustainable in terms of grey energy preservation.

5. Conclusions

The present paper presents a framework for calibrating and validating building energy models, focusing on a modern building located in Lausanne. Differently from previous research, the proposed framework is primary tested on 20th-century architecture, as it represents a significant target in current energy-saving policies and constitutes a substantial portion of the existing building stock. At the same time, the scarcity of research in the field and the diffuse lack of legal recognition constitute an additional threat in terms of heritage preservation. Nevertheless, the outlined method can be applied to several other historical buildings, being general enough to cover a wider range of cases. While the framework does not provide specific design actions, it establishes good practices in energy modeling that can extended or adapted by analogy, according to the project needs. For example, different inputs can be screened by SA and alternative benchmarks can be used for validation. In this view, further methodological applications and practical tests on additional case-studies are ongoing, intended as the following research step, exploring a larger scale applicability.

The framework aims to create a dynamic model that not only aligns with the current monitored data but also realistically represents

Table 5
Energy consumption, MBE and CV (RMSE) comparison (a. values for monthly energy demand, b. values for indoor air temperature in Summer) between the Actual State, IM, CM1 and CM2.

	Actual State (AS)	IM	CM1	CM2	IM/CM1 %	IM/CM2 %	AS/CM2 %
Energy consumption [kWh/m^{2}y]	154	125	145	149	+14	+16	−4
MBE[a] [%]	–	−19	−6	−3,5	−69	−82	–
CV (RMSE)[a] [%]	–	29	31	14	6,5	−52	–
MBE[b] [%]	–	15	11	6	−27	−60	–
CV (RMSE)[b] [%]	–	16	13	7,5	−19	−53	–

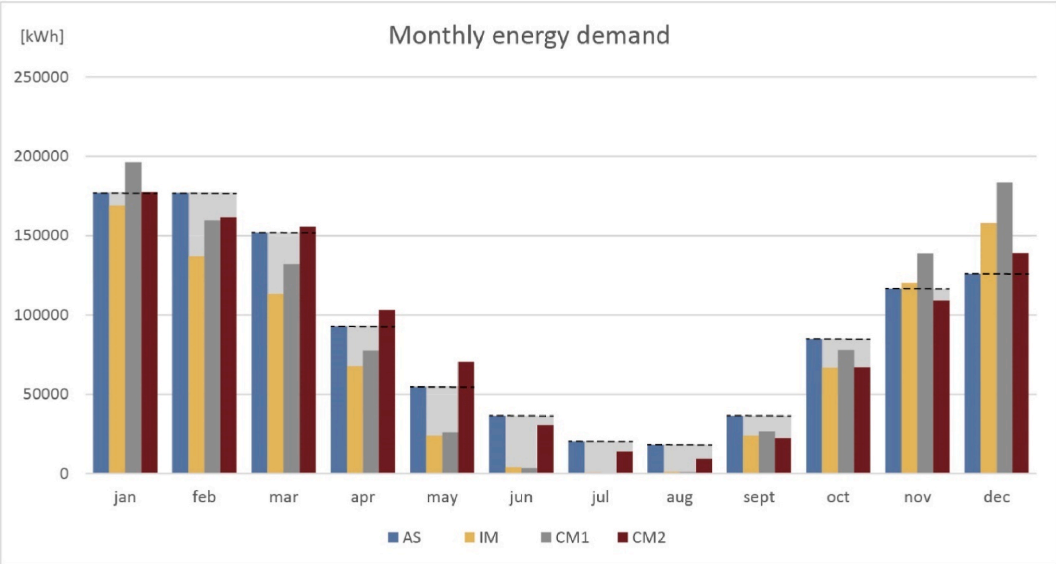

Fig. 8. Monthly energy demand comparison between the Actual State (AS), IM, CM1 and CM2.

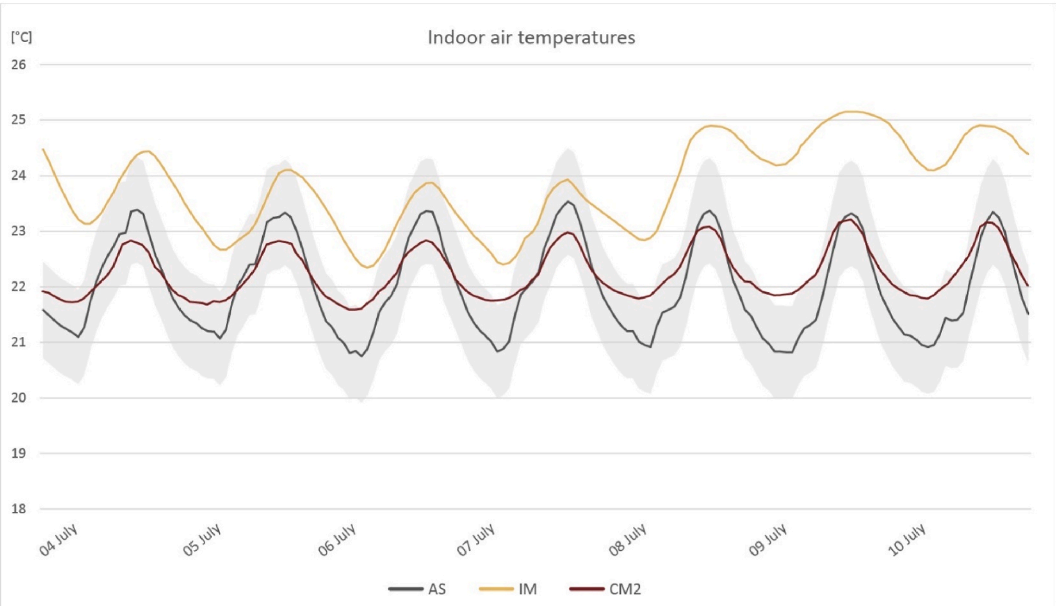

Fig. 9. Indoor air temperature comparison between the Actual State (AS), IM, CM1 and CM2. In light grey the validation range of ±5 % according to literature review.

the building as a complex system of several and interdependent interactions. Historical or modern buildings retrofitting requires, in fact, an interdisciplinary research that goes beyond the sole thermal analysis. It asks for recognizing the valuable building components, the physical and chemical properties of materials, the construction techniques, and the current usage patterns.

The above-mentioned aspects are often neglected by practitioners or led to complicated methodologies, rarely diffused outside universities. Hence, the presented model is based on a calibration process via sensitivity analysis and design of experiments, resulting in a relatively simple and precise approach. Since the building modeling strongly depends on subjective know-how, it appears difficult to objectively define an effort-to-accuracy balance between the existing and the proposed methodologies. For this reason, the framework integration into national guidelines and its concrete dissemination among architects and practitioners is intended as a further research steps, helping in assessing the methodological impact and its practical usage. While the presented model was created in WufiPlus, other widely used tools such as EnergyPlus are equally suitable [68].

The SA serves as a preparatory step for the model calibration, involving the screening of influential parameters. In the discussed case, five parameters were analyzed, based on a thorough building audit. However, this number can vary, and a broader matrix of experiments E can be constructed, increasing the computational time and the simulations' number. Inputs should be preferably selected according to the nature of the analyzed building, if the selection is hardly feasible, literature reviews [40], previous research [37] or expert knowledge can inform the process.

Another crucial aspect is the dual validation over two different periods of the years. For Chauderon building the models are validated with respect to both monthly energy consumption during the entire year and hourly indoor air temperature during a summer week. The former ensures the model's reliability in terms of actual energy use, while the latter addresses internal comfort. Further research could focus more specifically on indoor comfort, considering the increasing concern regarding the risk of overheating [41]. The double validation process requires considerable effort, which is justified by the importance of relying on a robust model. However, according to literature [28] or the modelling scope, even a single and simpler validation may be admitted. Both MBE and CV (RMSE) criteria are adopted in accordance to ASHRAE 14. It has been outlined that relying on the sole MBE may generate misleading assumptions.

In conclusion, the presented framework aims to be a useful guideline that can be integrated into existing retrofitting methodologies [69]. It promotes: (1) reduced energy demand, (2) higher internal comfort, (3) grey energy conservation, (4) cultural heritage respect. The final objective is to create a reliable energy model to preserve the existing buildings, by minimizing the impact of future retrofitting actions and preserving their historical value. This process requires a dual effort in technical and design aspects, but is considered necessary to effectively address the complex societal needs of today, reaching - in a perspective view - larger sustainability goals.

Credit authorship contributions statement

Giuseppe Galbiati: original draft, conceptualization, methodology, main investigation, editing. **Franz Graf**: supervision, conceptualization, methodology, review. **Giulia Marino**: supervision, conceptualization, methodology, formal analysis, review. **Jean-Marie Fürbringer**: supervision, methodology, software, formal analysis, review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationship that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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