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Multi-step building energy model calibration process based on measured data

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A R T I C L E I N F O

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A B S T R A C T

Building energy models are a key element in regulatory compliance calculations. These energy performance calculations often do not accurately reflect actual operating conditions. Therefore, evaluation of energy performance comparing actual energy use of a building with the outcome of dynamic simulation models can be misleading, this difference is also known as the energy performance gap. The reduction of the gap is an important task aimed to provide confidence in the use of models for evaluation of energy efficiency. This paper is focused on reducing the technical issues (e.g. poorly adjusted thermal parameters in the envelope, inefficient boiler operator or lack of adjustment in parameters of heat pumps, baseboard radiators or air handling units) which are one of the main causes of the energy performance gap. The application of a multi-step, optimization-based, calibration methodology performed in a white-box simulation environment (EnergyPlus) using three months of ten minute time-step data to adjust HVAC parameter values with a genetic algorithm software (Jeplus) is validated on a real test site. Resulting in a BEM that fits the building's hourly performance benchmark into international standards on three key levels: indoor temperature by Thermal Zone (TZ), heat production and electric consumption from heat pumps, which comprise all the components of a building energy model. A batch of 1500 h of heating operation, obtained from the building management system, has been used to calibrate the model. The results complied with the requirements of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14–2002 at hourly interval, with NMBE $\leqslant\pm10\%$,Cv (RMSE) $\leqslant 30\%$ and R2 $\geqslant 75\%$ and with the International Performance Measurement and Verification Protocol (EVO) for Cv(RMSE) $\leqslant 20\%$ and R2 $\geqslant 75\%$ in the three aforementioned levels, which can be considered a step forward in the area of calibrating white box models. In addition, to prove the strength and robustness of the results, the model has been checked in a long testing and independent period of 2.500 h of heating operations with the same level of compliance. The demonstrator is the library of a school located in Denmark. The HVAC system is composed of four air–water heat pumps that deliver heating to the whole compound with the backup support of a gas boiler. The library is heated with baseboard radiators system with the support of an air handling unit used for ventilation purposes.

1. Introduction

Buildings are key elements influencing global energy consumption, they represent around 32% of global final energy consumption and 40% of global primary energy consumption [1,2], contributing to about 19% of energy related carbon emissions [3]. Due to a variety of social, economic and political factors, the current trend in building energy and carbon emissions are expected to increase, doubling or even tripling by 2050. To face this scenario, various energy policies have been developed for building regulations and certifications schemes to ensure minimum requirements, specially when existing building retrofits could derive 50% to 90% of energy savings worldwide [4]. Establishing mandatory in new and retrofit construction projects the inclusion of energy studies that aim to increase energy efficiency and reduce maintenance costs and CO2 emissions [5]. Yet, the assessment of a building's energy behavior proves to be quite an exceptional challenge, turning any building energy study into a complex problem filled with uncertainties, where researchers often have to assume or estimate the values of many parameters in order to simulate its behavior [6]. Where the key question is: how to establish a Building Energy Model (BEM) that captures the behaviour of the

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real building, minimizing the consequences of the gap produced between the simulation environment and reality and therefore, reducing the risk of its results been mistakenly taken as valid or delivering designs that are actually unsuitable in practice.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Guideline 14–2002 [7] in conjunction with M&V Guidelines [8] and the International Performance Measurement and Verification Protocol (IPMVP) [9] structures the procedure to perform energy measurements and calibration of buildings. IPMVP describes four different options to quantify energy performance. Option A and B, labeled "Retrofit Isolation", narrows down the measurement boundary focusing on evaluating the performance of a particular element or component of the building system. Many studies for Heating Ventilation and Air Conditioning (HVAC) calibration are performed akin to this framework, where the component is calibrated separately of the building, or under laboratory conditions. Yasin et. al. [10] focus on the performance of a ceiling panel under experimental laboratory conditions. Monfet & Zmeureanu [11] focus exclusively on a cooling plant, applying a combination of manufacturer data with measurements to adjust the parameters and performance curves of the plant. While Mihal and Zmeureanu [12] and Martin et. al. [13] execute the calibration of an Air Handling Unit (AHU) and its air side loop by benchmarking its air flow, supply air temperature and energy consumption.

In the case of whole building energy performance evaluation IPMVP suggest the use of either: Option C "Whole Facility", which is based on the use of utility meters; or Option D "Calibrated Simulation", focusing on the development of computer BEMs that can predict the building and its systems performance. Under Option D, the BEM is required to capture the actual building heat and energy behavior, minimizing the gap between simulated results and reality. To achieve this it becomes essential to calibrate the BEM [14], allowing the correct evaluation of building energy performance through time and under different external environmental factors [15,16]. A calibrated BEM identifies issues regarding the system behaviour in a non-intrusive way to: test and validate the energy savings and performance of the different Energy Conservation Measures (ECM) [17], assess different HVAC system configurations prior their installment [18], and enables the commissioning of the building and its HVAC system [19].

BEM calibration can be executed manually or with the use of automatic subroutines [6]. There are many strategies deployed to find which parameters within the simulation are influential and achieve calibration of a BEM. Some studies like Y. Heo et. al. [20], J. Yuan et. al. [21], A. Chong et. al. [22], and, H. Lim and Zhai [23] use a Bayesian approach, others like L. Martin et. al. [13], O'Neill and Eisenhower [24] and, Robertson et. al. [25] focus on sensibility analysis. Coakley et. al. uses goodness of fit [26]. Royapoor and Roskilly apply an uncertainty analysis [27]. While, Ruiz and Bandera [16] and Qiu et. al. [28] use different optimization algorithms. Some of this strategies disregard if the parameter is bound to the building's envelope system or to it's HVAC system. Chong and Menberg [29], Qiu et. al. [28], Yuan et. al. [30], and Aftab et. al. [31] are some examples of performing a global calibration procedure where all parameters, regardless of which system they belong to, are calibrated simultaneously. However using this approach may spread the error between the different building systems, generating a BEM that may be unfit for the evaluation of a particular retrofit or ECM.

One solution to avoid this, is to take a multi-step approach where the building's envelope is addressed first before tuning the HVAC system, B. Merema et. al. [32], A. Cacabelos et. al. [33], and Subbarao et. al. [34] are clear examples of addressing the envelope prior the HVAC system. Tüysüz and Sözeret [35] provide a multi-step approach to calibrate the building's energy demand for summer and winter periods. D. Kim et. al. [36] first focus on envelope infiltration, then internal loads and finally calibrates HVAC energy consumption by making a correlation to outside air temperature. Cornaro, Bosco et. al. [37] proceed in a multi-stage strategy, treating each part of the calibration separately, as other authors they first focus on the envelope and then on the HVAC system. The reason is that the buildings energy demand is closely linked to the energy gain and lost through its envelope. (Annex 49) [38,39]. Once the envelope is calibrated, and all thermal loads have been introduced, the specific demand for HVAC systems is set and the next step takes place.

There are multiple ways to approach HVAC calibration, Yin et. al. [40] focuses on calibrating the HVAC system through the equipment performance curves, and suggest that heating and cooling room set-points are key elements to determine the building's energy consumption. H. Lim and Zhai [23], Chong and Menberg [29], J. Chen et. al. [41], and T. Hong et. al. [42] make use of such set-points in company of other energy efficiency related parameters like the Coefficient of Performance (CoP). D. Kim et. al. [36] use outside air set-point temperature depending on the building's particular HVAC system. And others, like Yuan et. al. [30] focus on air flow and CoP to obtain the building's consumption. Yet in all cases, once this is achieved no indoor temperature evaluation is performed. And the fact is, that calibrating HVAC parameters in a BEM while the system is interconnected with the building can be a daunting task. Specially in real test sites given the uncertainties in the delivery of heating and cooling to each one of the building's Thermal Zones (TZ), inter-zonal heat transfer and air flow [34]. The application of a multi-step strategy could address this challenge: by using a load profile object to bypass the HVAC distribution system, effectively disconnecting the building and working directly with it's energy demand like Chong et. al. [22], treating heating and cooling systems independently as Guyot et. al. suggests [43], and finding localized solutions for distributing heating and cooling into multiple TZ [44,45], like Mihal and Zmeureanu when using air flow [12].

It is to be noted that single level bench-marking of BEMs based solely on energy consumption seems to be a common practice. The reason may lie in the close relationship between energy studies and cost-benefit analysis. Where BEM models are evaluated against a local standard established on a yearly resolution [46], or directly cross-checked against building's monthly consumption bills [37]. The fact is that just like Chong and Menberg [29], Tüysüz and Sözeret [35], H. Lim and Zhai [23], Yuan et. al. [30], T. Hong et. al. [42], Qiu et. al. [28], Guyot et. al. [43], Lara et. al. [44], and Lyu et. al. [47] most studies are bench-marked only on monthly metered energy consumption. This practice, of single level benchmark continues when improving the quality of the BEM to hourly resolutions [22,36,40], where the calibration of the HVAC system is performed focusing entirely on energy consumption.

Adjusting the HVAC systems within the framework of IMPVP Option D should aim to generate a BEM that fits into both: temperature and energy criteria. Accurate enough for the application of strategies like Demand Response (DR), Model Predictive Control (MPC) and even provide a reference tool for Fault Detection Diagnosis (FDD). In this regard, Cacabelos et. al. [33], and Merema et. al. [32] express the need of executing a multi-level benchmark. The requirement of at least cross check the building's energy consumption with its indoor climate to capture the building's behavior.

Merema et. al. [32] performed a multi-step manual calibration evaluating energy consumption and the building's average indoor temperatures. Their approach managed to keep temperature within a maximum range of 1 °C, yet the heating coil's energy consumption reached a coefficient of variation of the root mean square error (CvRMSE) of 31.70% close to ASHRAE's standard value. While in Cacabelos et. al. [33] calibration approach the hourly error for simulated indoor temperature was below 2 °C yet their evaluation for energy consumption was kept on a monthly resolution. To be able to analyze the whole building's performance, it is important to keep the relationship between the building's energy consumption and it's indoor climate in the same resolution.

The purpose of this study is to validate a multi-step HVAC calibration methodology performed in a white-box simulation BEM in real test site under normal operation conditions. The main objective is to reach the BEM's hourly performance under international standards, and bring into discussion the requirement of a multi-level benchmark, at least in terms of indoor climate and energy consumption, when stating a BEM model as calibrated. The following study was developed using minor sensor deployment inside Gedved test site, the library building of a fully operational school located in Denmark. Measurement campaigns on 2019 and 2020 focused to obtain indoor temperatures and rely on the BMS data collection for establishing the HVAC system operation.

The novelty of this study is the validation on a real test site of a multi-step HVAC calibration methodology performed in a white-box simulation environment using three months of ten minute time-step data, resulting in a BEM that fits the building's hourly performance on three key levels: indoor climate by TZ, heating energy production and electric consumption into international standards. A high quality BEM that proved stable during the evaluation period, capable of fitting into unseen data, including any non recurrent events, which are stresses belonging to either building operation or weather conditions of specific nature that have low probability of reoccurrence (i.e. an extreme cold day). Something that to our knowledge has not yet been performed.

Fig. 1 displays the paper structure, organized as follows: Section 2 describes the calibration methodology and its principles to be applied to the current case study. Section 3 briefly presents building case study describing its HVAC systems and the development of the baseline BEM that is subject to calibration, including considerations regarding data quality used inside this process. Section 4 details the results obtained from this process for the calibration and evaluation periods, illustrating the benefits of a calibrated BEM when compared to a state of the art baseline BEM. Finally, Section 5 asserts the conclusions and practical implications of reaching this high performance calibrated BEM, which meets within international standard criteria in multiple levels and enunciates future studies regarding the application of this methodology.

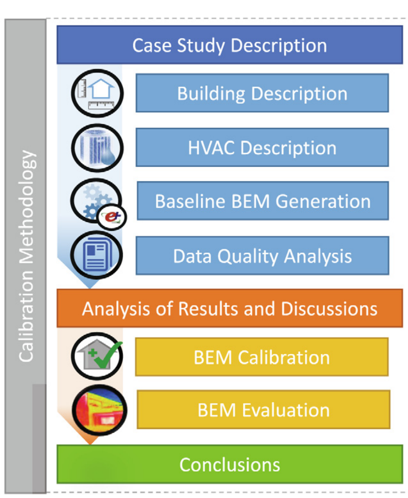

Fig. 1. Multi-Step Building Energy Model Calibration Process Based on Measured Data Flowchart.

2. Calibration methodology

The methodology applied for calibrating BEMs, require continuous data measurement and analysis to capture the buildings heat dynamics and its HVAC systems behaviour. A variety of sensors are deployed inside the building to gather information from multiple sources like: weather conditions, indoor room temperature, equipment operation, air flow, energy consumption, and others. Table 1 shows a list of some of the main variables required for this process:

The main objective of analysing the raw data stream is to clear it from any errors in the measurements, which are flagged and purged from the stream. Only allowing the use of validated data inside the simulation environment, and thus reducing the uncertainty from faulty sensor or equipment malfunction inside the calibration process of the BEM. The first step of this data analysis is to evaluate the quality of the data stream. The collected raw data is filtered through an algorithm that fills with a linear interpolation any small gaps, defined as any 3 h or less blank data gap, and flags major gaps as no valid for use. The resulting data stream is subject to an in depth cross reference evaluation to find possible inconsistencies and/or sensor malfunctions in the stream.

Continuous data analysis is a learning process that allows the development of new filters within the cross reference evaluation to search for sensor malfunctions or suspicious data. Furthermore, additional information for the systems' operation can be obtained from the measurement data stream by means of statistical analysis and calculation. These indirect readings help to establish how each of the HVAC components operate. Once this data preparation process is complete and a quality data stream is assured, then it can be used for simulation purposes. As Fig. 3 shows, the information obtained is divided into: input data, an operation file that represents the history of the building behaviour whose main objective is to stress and stimulate the simulation environment (as an input file in EnergyPlus) for the calibration of parameter values; and control data file, a separate data stream whose purpose is to compare actual measurements of the building and its systems with the BEM results to evaluate the calibration of the parameter values.

When looking into the building's heat dynamics and the relationship between its environment and support systems, as displayed in Fig. 2, the building indoor temperatures are associated with the building's demand response to different loading stress

Table 1
Measurement sensors commonly deployed for data driven BEMs.

Measurement	Units
Weather:	
Outside Temperature	°C
Outside Relative Humidity	%
Global Horizontal Radiation	W/m^2
Diffuse Radiation	W/m^2
Wind Speed	m/s
Wind Direction	deg
Precipitation	mm
Atmospheric Pressure	Pa
Ground Temperature	°C
Indoor Climate:	
Indoor Ambient Temperature by TZ	°C
Indoor Relative Humidity	%
HVAC System:	
Water Inlet Temperature	°C
Water Outlet Temperature	°C
Water Flow	m^3/h
Equipment ON/OFF status	1/0
Electric Consumption:	
Lighting Electric Energy and Power Rate Consumption	Wh - W
Plugs (Outlets) Electric Energy and Power Rate Consumption	Wh - W
HVAC equipment Electric Energy and Power Rate Consumption	Wh - W

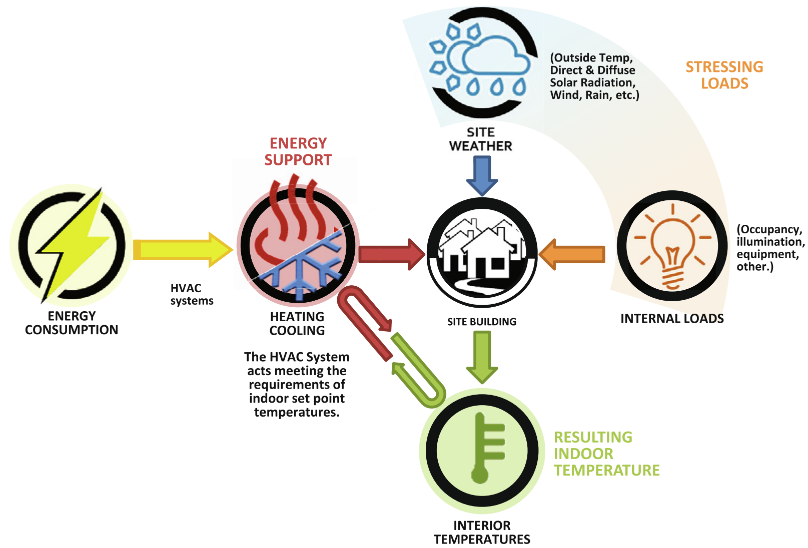

Fig. 2. Overview of building heat dynamics.

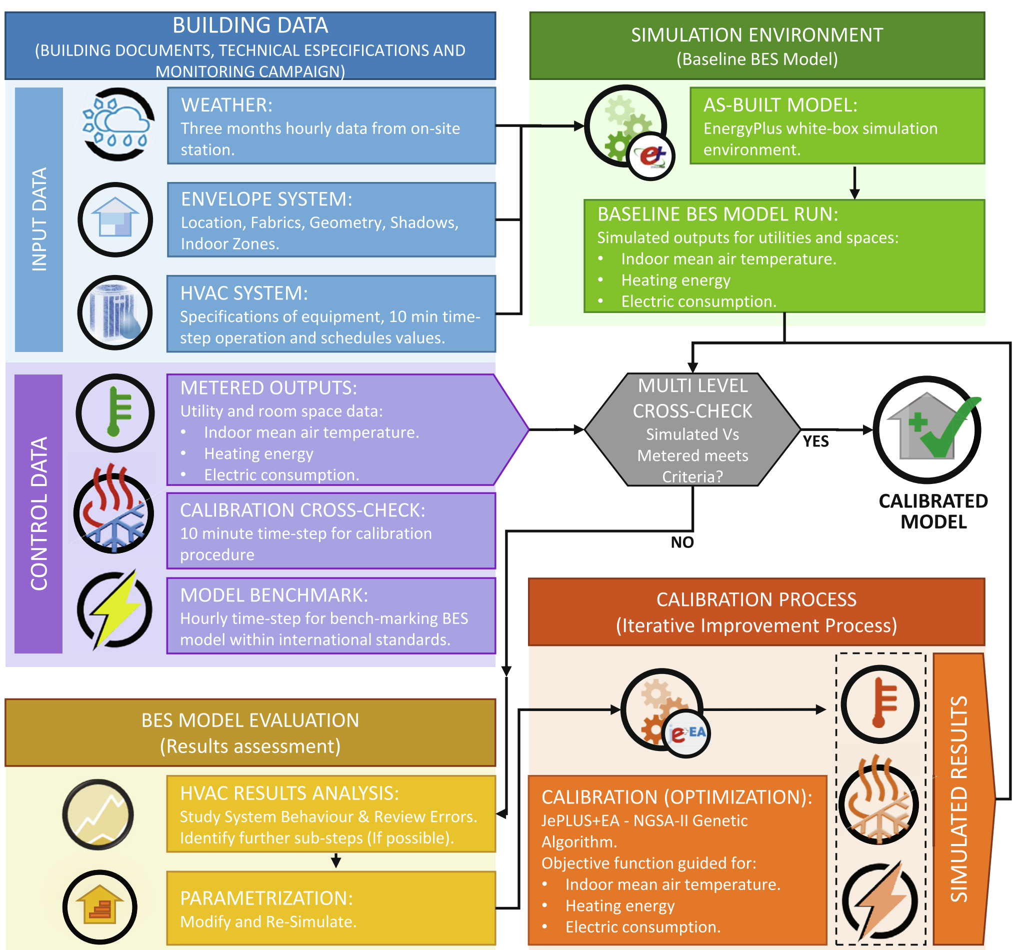

Fig. 3. Overview of Calibration Methodology.

factors. These factors can be external (weather) or internal (as occupancy, lighting or other loads), and their affectation to the building's heat dynamics is constrained by comfort conditions established by the users. Which means that in most cases an energy support system, the HVAC system, is required to meet this demand. The resulting energy balance between the building's different components is in fact a complex undetermined system subject to a great number of variables, some measurable and others inherently unknown. This forces researchers to make educated assumptions when establishing the value in some parameters as they try to represent the building and its systems behaviour inside a BEM. One of the best strategies when facing such challenge is to divide it into smaller, more manageable systems, basically engage the problem through a multi-step process.

Since the building's energy demand is closely linked to the energy gain and lost through its envelope, having indoor temperature as the key measurement value, especially when the building is in free oscillation, allow us to calibrate the values of variables like infiltration, capacitance, and thermal mass that influence the building's heat dynamics. Once we are aware of the amount of energy gain/loss by the building through its envelope, we will have direct access to its energy demand (Annex 49 [38,39]), which is why detailing the HVAC system on a BEM whose envelope had been previously calibrated is a prerequisite for applying this methodology in HVAC calibration. The successful application of this methodology on addressing the calibration of envelope parameter values has been validated and published by the authors in previous works [48]. As an extension of their work, we adapt this inverse methodology applying it into a white box HVAC simulation environment and execute an empirical validation based on a fully operational building case study.

Fig. 3 displays an overview of the calibration process applied for each step in Gedved test site. Where the calibration process initiates after generating a baseline BEM that resembles as closely as possible the actual test site building and its HVAC components. [33] This baseline BEM developed in EnergyPlus simulation environment contains the building's calibrated envelope system which includes: the building's location, shadow details, indoor space geometry, thermal zones classification, constructions and materials. As well as, any required loads for stressing purposes (weather file and internal loads when available) and a detailed model of the building's different HVAC components, whose performance curves and parameters are set to technical specifications. As such, this is the best baseline model possible with the information available for the project.

When modelling a detailed HVAC system, the amount of parameters that can influence each other increases with the level of complexity of the simulation model. Attempting to calibrate the HVAC system as a whole may create an immense search space demanding massive computational resources in terms of run-time and power. It makes sense to split the calibration process and executing a multi-step calibration process, adjusting the building's HVAC components part by part whenever it is possible, rather than doing it as whole. Which is why, the baseline BEM undergoes an initial result assessment where it is studied prior to the parametrization process. The results from this initial run are indispensable for establishing how to split the HVAC system into multiple subsystems and selecting the key parameters that will be calibrated.

In the case of Gedved, the first step taken was the detachment of the building from the HVAC supply equipment by the use of a Load Profile object. This is an EnergyPlus object that specifies the building's scheduled heating and cooling loads when they are already known. Its use can effectively disconnect the building and all HVAC terminal units from the production system when running a detailed HVAC simulation. This meant an important reduction on the amount of parameters involved in the calibration process by solely focusing on the heating supply group, where each key parameter found was limited to 10 possible different discreet values to choose from. Furthermore, the use of a load profile object in EnergyPlus environment, allows us to calibrate the heating supply equipment against the actual measured heating demand of the building.

The parameter optimization displayed on Fig. 3, takes place by running the simulations on jEPlus + EA software. jEPlus is a parametric tool that runs with EnergyPlus software to perform complex parametric simulations [49]. jEPlus + EA adds a particular multi-objective Evolutionary Algorithm to jEPlus running platform, a second generation Non Sorting Genetic Algorithm (NSGA-II). By establishing a series of objective functions, in terms of indoor climate, heating and energy consumption behavior, the NGSA-II genetic algorithm is used to search for the HVAC parameter values that will produce the best fit between the simulated results and the measurement data obtained from the building's system until the error value meets the standard. The functionality of this algorithm and its advantages on spread of solutions and convergence can be explained by [50].

The results for the 26 different key parameters that were involved in this step of the calibration process are shown in Section 4.1 on Table 5. Once the heating supply group was calibrated, we disconnect the load profile and proceeded to reconnect the building. The next step focuses on calibrating the terminal units, that is the baseboard radiators located inside each thermal zone and the AHU that delivers ventilation to them.

The solution of this step must satisfy all three conditions stated in Fig. 4: indoor climate, heating energy and cooling energy production, and finally the equipment's energy consumption. The calibration process takes place in the same way as in the first step, noting that to further reduce the size of the search space, the baseboard radiators were classified by their size generating 3 "type" components (one per each thermal zone). Results obtained for the 13 key variables used in this step are displayed in Section 4.1, Table 6.

The resulting BEM obtained from finalizing this calibration procedure is a whole calibrated building. A simulation model that correlates the building's indoor climate, the heating energy production and distribution from its HVAC systems, and their electric consumption. For this reason, it is important to establish the three level benchmark displayed in Fig. 4 when evaluating the whole BEM performance.

The described multi-step calibration process is versatile, it can focus the search for parameter values that correlate the system's behavior between two or more conditions, for example: indoor temperature or the building's heating demand, with its production systems and energy consumption. The proposed methodology is flexible enough to allow us to subdivide the problem in search for localized solutions. If we focus solely on the buildings energy production systems, specifically the building's HVAC production components, we can eliminate the uncertainties belonging to the buildings envelope by detaching the building indoor climate and attaching directly to the simulation its demand.

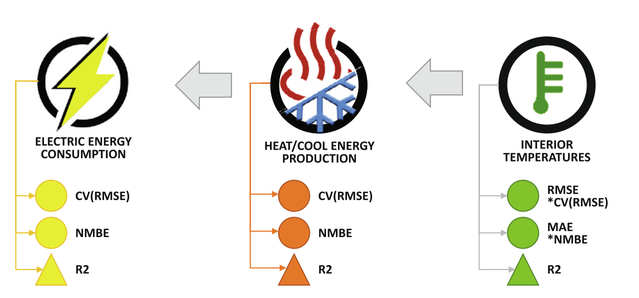

Fig. 4. The calibration process aims to satisfy all three conditions: indoor climate (building's demand), heating and/or cooling, and energy consumption must fit to on-site measurement data. (Note*:The NMBE and Cv(RMSE) index for indoor temperature are calculated for comparison purposes with existing literature.).

2.1. Statistical indices used for calibration

Calibration is an optimization process in which simulation models are corrected, by means of changing certain parameter values, until the simulated results fit into measurable observations. The error produced between the simulation environment results and the real building data is evaluated under the following international protocols: the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) [7], the International Performance Measurement and Verification Protocol (IPMVP) [9], and The Chartered Institution of Building Services Engineers (CIBSE) [51]. In terms of energy consumption, ASHRAE Guideline 14 [7] and IMPVP [9] set boundary limits for: the normalized mean bias error (NMBE) and the coefficient of variation of the root mean square error (CvRMSE).

NMBE calculates the average error between the simulated values and measured values, which is then normalised by the mean of measured values, this is a bias error index that takes into account the sign of the average error vector and may be prone to cancellation errors. Therefore, it must be used in company with other index to measure the performance of the simulated model:

$$NMBE = \frac{1}{\overline{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n-p} \cdot 100(\%) \tag{1}$$

Cv(RMSE) is derived by normalizing the root mean square error with the mean of the measured values. These indices consider only the distance between values, omitting the sign of the error vector and overcoming cancellation errors:

$$CV(RMSE) = \frac{1}{\overline{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \cdot 100(\%) \tag{2}$$

In terms of indoor temperatures, CIBSE's Operation Performance: Building performance modelling and calibration for evaluation of energy in-use TM-63 [51], uses the mean absolute error (MAE) and the root mean square error (RMSE) to compare the simulated model results with measured values. Stating an acceptable limit for indoor temperature MAE of 2 °C based on different studies like the one of Royapoor and Roskilly [27]. While the German standard VDI-6020:2002 [52] provides a maximum value for the RMSE of 1.5 °C. Both indices measure the absolute distance of the vector when comparing simulated versus measured data avoiding cancellation errors.

MAE is the average of the absolute errors between the simulated and measured values:

$$MAE = \frac{\sum_{i=1}^{n}|m_i - s_i|}{n}, \tag{3}$$

RMSE, also known as standard deviation of the differences between measured and simulated values, measures the root of the square error between the simulated and the measured value:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \tag{4}$$

Eqs. (1)–(4) measure the distance between the simulated value and the measured one. Although these bias error indices are important, it is also required to evaluate how the simulation model behaves from time-step to time-step in comparison to real measurements. The quality of this linear relationship between the simulated and observed data is obtained by the use of a goodness-of-fit index, ASHRAE Guideline 14 [7] and IMPVP [9] recommend the use of the square of the Pearson correlation coefficient (R^2) as a measure of this quality.

R^2 measures the linear relationship between a simulated and a measured curve slopes, in other words, how lookalike the simulated model result curve is to the measured one. This relation may be quite good, and still has a substantial bias in terms of error distance, and thus the R^2 cannot be used alone to measure a simulated model performance.

$$R^2 = \left(\frac{\sum_{i=1}^{n}(m_i - \overline{m}) \cdot (s_i - \overline{s})}{\sqrt{\sum_{i=1}^{n}(m_i - \overline{m})^2 \cdot \sum_{i=1}^{n}(s_i - \overline{s})^2}} \right)^2 \tag{5}$$

Where:

$\overline{m}$ = the mean of measured values.
$\overline{s}$ = the mean of simulated values.
m_i = the measured value
s_i = the simulated value
n = the number of data points
p = 1 (According to the M&V methodology for energy calibrated models)

A BEM performance evaluation is determined by the use of at least one bias index in company with one goodness-of-fit index [53]. Since the coefficient of determination R^2 is stated as a recommendation when evaluating energy performance under ASHRAE and IMPVP standards, it can also be applied to assess indoor temperature goodness-of-fit. Thus completing the multi-level error uncertainty analysis of the simulated results in terms of energy and indoor temperature required to benchmark the performance of a BEM. As Table 2 shows, the use of these five uncertainty indices will establish how well the resulting BEM fits into reality.

The resulting building energy simulation model with its calibrated parameters values, represents the thermal dynamics of the building and captures the behaviour of its HVAC systems.

3. Case study description

3.1. Building description

For the practical application of the calibration methodology explained in Section 2, Gedved School was selected. Built on 1979 and renovated on 2007, the site is located in Denmark and it is composed of six buildings whose heating demands are met by one main hot water heating supply system. Of the different buildings that are part of this compound, the library building was selected for this study since it represents the overall architecture of the whole site. This is a one-story highly insulated building situated at an altitude of 248 m, whose envelope mainly consists of two brick layers with 150 mm insulation in between (U estimated value = 0.27 W/m^{2}K). The installed glazing are two-layer double-glazed windows with cold frames. The slopped ceiling is insulated with 200 mm mineral wool while the flat ceiling has a 250 mm mineral wool insulation layer (Estimated U value = 0.07 W/m^{2}K and 0.16 W/m^{2}K, respectively). Finally the floor is made of concrete and contains 150 mm insulation under it (U value = 0.21 W/m^{2}K). [54] It has an effective surface area of 1138.37 m^2 that holds a total volume of air of 3764.97 m^3 with a big central space (the library) from where the different classrooms and serving spaces branch outwards. As Fig. 5 shows it is comprised of 18 rooms which include: 1 library, 9 classrooms, 2 storage rooms, 4 cloakrooms, 1 staff room, 1 teacher's cloakroom.

Of which 16 thermal zones, corresponding to 217.22 m^2 (707.29 m^3 or 18.79% of the buildings total air volume), belong to secondary rooms like: cloakrooms, WC and storage. Although these rooms are either unconditioned, service cavities, or disconnected from the BMS, they must be introduced in the BEM to simulate their effect. The main rooms displayed on Table 3 hold at least

Table 2
Hourly error index limit values for model calibration.

	Energy Consumption		Indoor Temperature	
Hourly Index	ASHRAE	IPMVP	CIBSE	VDI-6020
NMBE (%)	$\leqslant \pm 10$	$\leqslant \pm 5$	–	–
CV(RMSE) (%)	≤ 30	≤ 20	–	–
MAE (°C)	–	–	≤ 2.0	–
RMSE (°C)	–	–	–	≤ 1.5
R2 (%)	$\geqslant 75$	$\geqslant 75$	$\geqslant 75$	$\geqslant 75$

one HVAC equipment installed inside them that will be subject to the calibration process.

To minimize any uncertainty error that the building envelope may introduce in the HVAC calibration process, the HVAC system is detailed in a BEM whose envelope has been previously calibrated using the methodology stated by Ramos et. al. in [16], and validated by Gutiérrez et. al. in their study [48].

3.2. Building HVAC system description

The climate of Denmark is cold in winter and mild in summer with a predominant overcast sky, rain and wind all year round. According to Köppen Climate Classification, the test site is located on a warm summer continental or hemiboreal climate zone (Dfb). This zones are located north of hot summer continental climates, generally between 45° and 58° latitude in central and eastern Europe. Characteristically, this climate maintains significant precipitation all year round with an average monthly temperature above 10 °C for all months during summer. Where its warmest month average temperature does not reach 22 °C, and its coldest month average temperature in winter is below −3 °C [55]. As such it is no surprise that the HVAC systems of the test site were designed only for winter (cold) conditions.

Given the geographical location of the test site, the installed HVAC system in Gedved can be classified as a hot water heating system designed solely for winter conditions. Heating water is produced by a group of four 47 kW air–water heat pumps (HP), numbered as HP-01 to 04, connected in cascade to a 2.0 m^3 buffer tank. Additionally, the building's heat production system is supported by an 460 kW auxiliary condensing boiler with a gas burner that runs into operation only when the HP group is unable to meet peak demands.

Heat is distributed thorough the whole compound by a main heating loop which pipe's branches to each one of the buildings that are part of Gevded School site. Heating inside each one of the buildings is delivered by wall mounted baseboard radiators system while ventilation demands are met by an air handling unit (AHU) composed of a heating coil and a rotary heat recovery system.

3.3. HVAC simulation baseline model

The HVAC system described on the buildings technical documents is introduced into a detailed HVAC model inside EnergyPlus simulation environment by the use of DesignBuilderV6 software. This detailed HVAC model incorporates a number of different predefined simulation components already inside EnergyPlus equipment library. The nodes connecting these components are linked by the means of loops, branches, pipes and ducts, into the buildings thermal zones or other associated components in order to describe the buildings heating, cooling and ventilation system. After the system production, distribution and delivery systems are properly defined, input data like: site weather, HVAC system operation, and availability status for each of its components is introduced into the model prior its simulation. The idea of using a detailed HVAC simulation model is to faithfully translate all the information from the site survey and technical documentation to represent as closely as possible the behaviour of the currently installed HVAC system, aiming to create a digital twin of the building's HVAC system.

Fig. 6 shows the detailed HVAC simulation model for Gedved test site developed in DesignBuilder software and exported to EnergyPlus simulation environment. The generated scheme is composed by four main loops: main heating supply loop, auxiliary heating supply loop, main distribution loop and the library's building loop. The round labeled icons E-H-T in the figure correspond to key nodes in the system: "E" indicates where the electric consumption for the system is measured (HP-01 to 04), "H" are the two heating energy sensors deployed in the water distribution loops, and "T" are the indoor temperature sensors.

3.3.1. Main heating supply loop

The heating supply loop contains four air–water heaters (units HP-01 to 04) each one modelled as a heat pump water heater (HPWH) with pumped condenser element according to EnergyPlus Engineering Reference [56] The water heater tank modelled with the HPWH component does not have an internal heating element

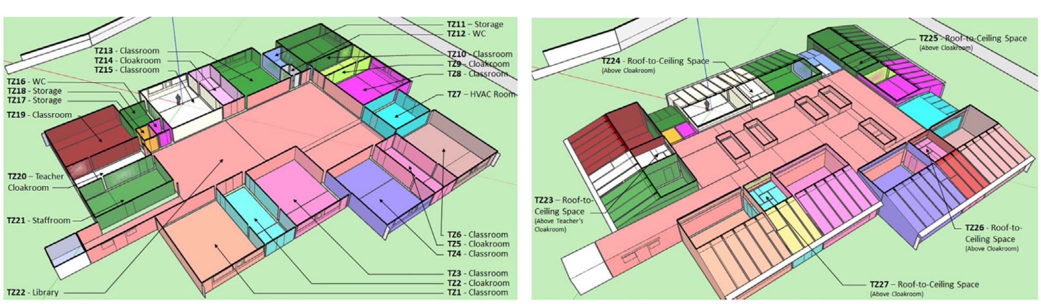

Fig. 5. GEDVED Test Site. On the left, Thermal Zone's Ground Floor Plan. On the right, Thermal Zone's Ceiling Floor Plan.

Table 3
Effective floor area and indoor air volume of thermal zones with HVAC equipment subject to calibration.

	TZ01	TZ03	TZ04	TZ06	TZ08	TZ10	TZ13	TZ15	TZ19	TZ21	TZ22	TOTAL
Area (m^2)	60.57	60.43	60.77	62.34	60.87	60.51	60.89	60.88	60.51	38.78	334.6	921.15
Volume (m^3)	212.69	211.74	213.51	213.62	213.85	212.44	213.90	213.89	212.42	136.19	1003.43	3057.68

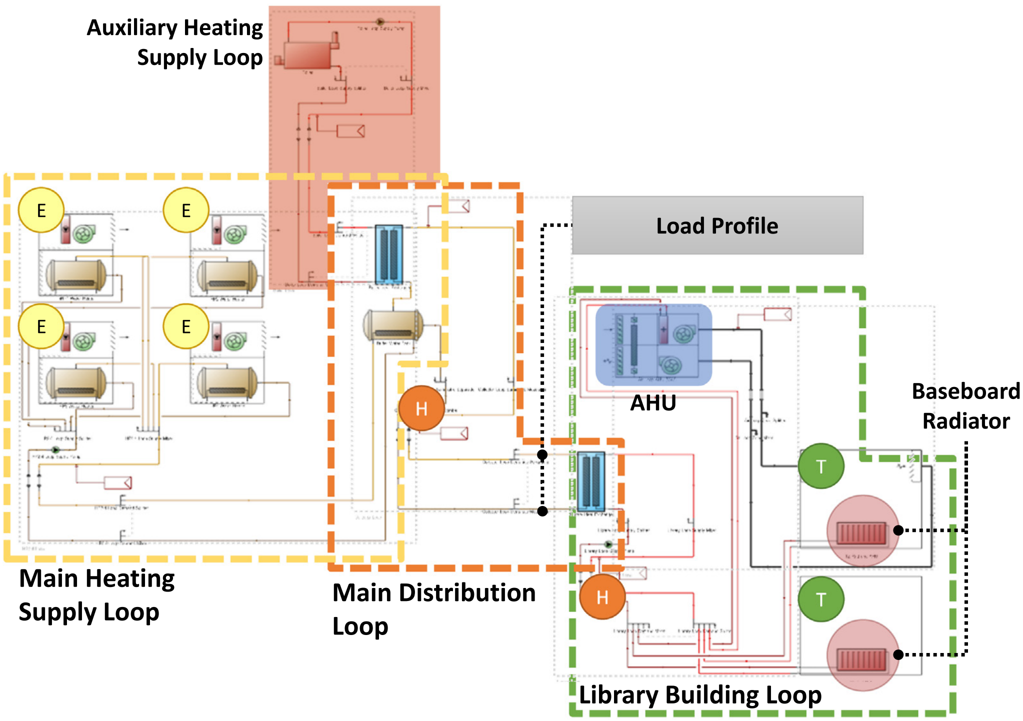

Fig. 6. Gedved HVAC simulation environment.

ensuring that the DX compression system is the only possible source of heat. The coil then "calculates the air-side sensible and latent cooling capacity at the specific operating conditions for each simulation time-step, as well as the condenser's water-side temperature difference at a given condenser water flow rate." [56].

This EnergyPlus component was selected because it is the most similar object to simulate the behavior of an air–water heat pump. The four HP units that form the main HP group are connected through an adiabatic pipping sub-loop with a set-point controller to a water heater tank that represents the building's buffer tank. Furthermore, the HVAC simulation Baseline Model parameters such as: the volume of water in the heater tank, heating capacity, fan and water air flow, and reference fluid temperatures for this component have been set to match the one obtained from the HP technical specifications.

On this regard, HP heating energy performance and electrical consumption are correlated to outdoor and hot water supply temperature conditions. This relation is usually established in the equipment's technical documents and can be introduced inside the simulation environment by the application of a least-squares linear regression model following the example of Hydeman et. al. [57] for performance curve tools and development. Eq. 6 shows the resulting bi-quadratic expression used to define this curves inside EnergyPlus.

$$z = C_1 + C_2 * x + C_3 * x_2 + C_4 * y + C_5 * y_2 + C_6 * x * y, \tag{6}$$

Where:

z = value of either heating capacity or coefficient of performance CoP.
x = stands for outdoor air temperature (°C)
y = is supply hot water temperature (°C)
C_i = coefficients that define the equation.

A linear regression process based on the equipment specifications is used to determine the six parameters Ci (C_1 to C_6) for its heating capacity curve and for it's consumption performance curve. The resulting curves should be as close as possible to the ones stated in the technical documentation. For Gedved heat pumps, the resulting heating capacity curve has a CV(RMSE) of 0.01% with an R2 of 98.75% when compared to the one described in the technical specification documents. While for its CoP, the resulting curve matches the one in the documents with a CV (RMSE) of 0.01% with an R2 of 98.77%, as shown in Fig. 7.

Since the available technical specifications for the equipment curves and the measurements obtained from the BMS include in them the consumption from the HP sub-components like its fans, the modelled equipment only requires the curves mentioned on the previous paragraphs. The HP fan is set as a ON/OFF fan element which performance curves remain set on default values by the simulation environment. Although a similar process like the one described above could be used to obtain the fan's performance curves [58] if the power consumption of the HP would be disaggregated by its subcomponents.

3.3.2. Auxiliary heating supply loop

The purpose of this heating subsystem is to provide auxiliary heating to the main distribution loop. This HVAC subsystem operates only when the main heating group (HP-01 to 04) fails to meet the required demand. The building's condenser gas fired boiler is modelled as a boiler unit in EnergyPlus [56]. Just as with the HP group, all parameters for the auxiliary boiler are set to technical documentation and the boiler is linked to an ideal fluid to fluid heat exchanger, placed to represent the operation of its three way valve with the main heating loop's buffer tank. Whenever this component is running, the data stream is flagged and not taken into account when performing the calibration procedure. This way we achieved to work exclusively with the heating energy and the electric consumption provided to the building by the HP group without losing the thermal history provided by this equipment.

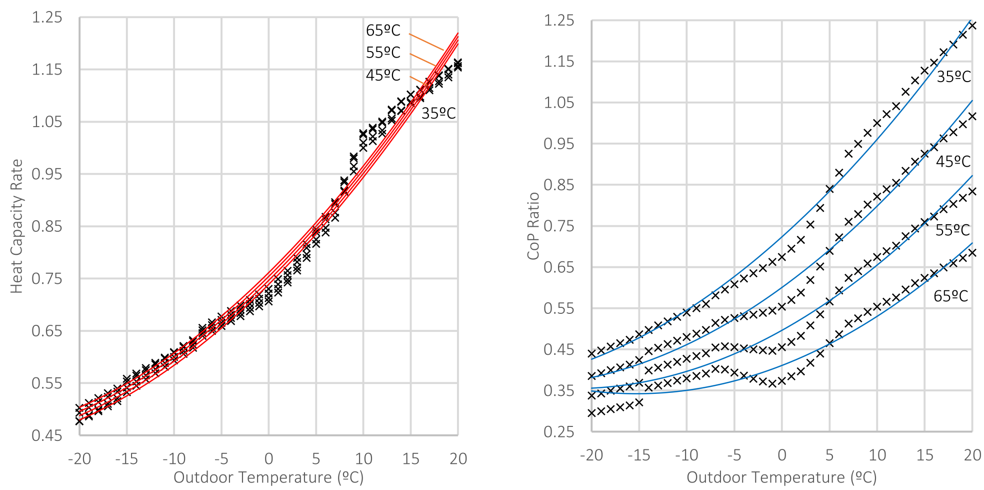

Fig. 7. Calculated Baseline Heat Pump performance curves: Heating Capacity (red) and CoP (blue) generated for supply hot water temperature leaving the equipment and introduced in the HVAC baseline model. Data obtained from technical documentation is displayed in black. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.3.3. Main distribution loop

The main distribution loop is intended to represent the main heating ring that delivers heating energy throughout the whole building compound. It is modelled as a pipe system between two ideal fluid to fluid heat exchangers; one as stated before, represents the auxiliary heating supply loop's three way valve, while the second one represents the pipping derivation to the actual test site building, the school's library loop. A fluid to fluid heat exchanger is a general EnergyPlus component [56], that can serve as a coupling link between two hydronic systems that operate under different conditions if its operation parameters are set to generate an ideal heat exchange.

3.3.4. Library building loop

This is the HVAC end point system, the link between the BEM's envelope system and thermal zone distribution with the detailed HVAC components that are placed inside it. It connects the building's energy demand-response with the HVAC equipment. Since this is a multi-step calibration of the HVAC system, the library building loop detailing the HVAC terminal unit components (i.e. its air handling unit and wall mounted radiators), was replaced on the first step by a data driven load profile representing the whole test site heating demand [22]. This EnergyPlus object can specify a scheduled heating and cooling loads, which is useful when the building loads are already known and its performance is dependent of the main supply loop components. [56] Once the HP group has been calibrated, the system is reconnected to: an AHU unit with a single heating coil and a heat recovery system used mainly for ventilation purposes [56], and a low temperature baseboard radiator system located inside each thermal zone in order to continue the calibration process.

An ever present challenge when developing simulation models lies in computer processing power and the simulation run-time execution [59]. It is to be noted that in order to save computational resources the wall mounted radiators introduced in the simulation environment were defined as baseboard convective water elements. As it is described in EnergyPlus documentation, the objective of this component is "to calculate the convective and radiant heat transfer from water baseboard heaters to the people and the surfaces within a zone so that surface heat balances can take into account the radiant heat transfer to the surfaces and thus enhance the accuracy of thermal comfort predictions within the space." [56] This modification improved nearly three times the simulation run-time of the BEM (from 1957s to 672s), based on a i7 Core processor mainframe with 32 Gb Ram.

3.4. Data quality analysis

As explained on Section 2, the calibration process applied in this study is a data driven process where the quantity and quality of the data will influence the quality of the calibration. When addressing the value of quality in data or information, Yang and Becerik-Gerber [18] suggest to summarize the process of data gathering and its categorization by quality based on classification structures developed on similar studies [60–62]. As such, quality value of data may be classified in five distinct levels.

Values obtained from continuous on-site measurement are classified as data of the best quality, since the measurement process and the equipment used meet standards and are calibrated. This kind of data is regarded as first in line to be introduced into the BEM and can be characterized as: input data, values that are used as external stress (i.e. weather) or system stimulation (i.e. energy load profile) when running the simulation; or control data, measurements used to compare the simulation results with actual performance (i.e. energy consumption).

Surveying is considered the second level of data quality, it may or not be a quantifiable and although it requires cross checking its results allow us to establish directly certain performance values. The third level information is obtained from building documents. Operation and maintenance manuals take preference over As-Built documents, which in turn take preference over design/project documents. When there is no other information, codes, standards and manufacturer handbooks may be used. This is fourth level quality data, research has demonstrated that given the variability of building types, locations, and systems, this kind of data may not be reliable if universally applied.

Finally, the lowest level for quality of data is the default settings for similar type of building or equipment and data gained from experience. In order to represent as accurately as possible real conditions inside the simulation environment, the baseline model becomes a mesh of different quality level data.

In terms of measurement, on-site data obtained from the continuous monitorization campaign during winter season on 2019 and 2020 in Gedved test site, data from the multiple instruments listed in Table 1 is collected every five minutes by the means of an online broker. The obtained stream undergoes an exhaustive health analysis that filters any blank or missing values. As a project rule set for this study, any missing streams above 3 h are flagged and discarded as not valid for use in the calibration procedure. While missing data bellow this time gap is filled with a linear interpolation between two known values.

The resulting stream can then be analyzed for sensor and/or equipment malfunctions, executing a cross check evaluation between sensors. For instance, main distribution loop hot water temperature is cross checked with the auxiliary boiler operation availability. Because the boiler can supply hot water at higher temperatures than the HP group, we can check if either: the availability sensor for the auxiliary loop, or the boiler itself, is working correctly. Cross checking the data obtained from a monitorization campaign is key in understanding the operation of any HVAC equipment or system. As with missing data values, if any data is found to have a suspicious behavior during this cross check evaluation, it is flagged for a further inquire and not taken into account for the calibration procedure.

3.4.1. Data as input

Weather conditions are usually associated with energy stress of a building, affecting directly its energy demand. However, weather conditions also influence the performance of the buildings installed HVAC equipment. [63–65] In the case of HP units, outdoor weather temperature is one of the most important factors linked to its performance. Therefore, Gedved test site has an on-site weather station in its premises, Table 4 lists the station sensors and their accuracy.

The sensors shown in Table 4 deliver data in an hourly format, as such the weather file (.epw) that will stress the BEM was developed in the same time-step format.

Section 3.3.4 introduces a load profile object in the first step of calibration process that represents the whole school's heating energy demand. Data is collected directly from the measurements delivered by an energy meter that complies with the EN 1434:2015 standard installed in the main distribution loop. The instrument used is an energy meter with a temperature differential range ($\Delta\Theta$) of 3 to 178 K and a typical energy accuracy of $\pm(0.15 + 2/\Delta\Theta)\%$.

The BMS contains multiple data regarding the operation of the HVAC subsystems, obtaining and understanding the specific operational schedules can become a difficult task [66]. Cross-checking the data obtained from the Building Management System (BMS) regarding hot water supply temperature, valve opening, fan status, and electric power was used to establish the different equipment's: availability schedules, order of operation (HP group), and supply temperature set-points inside EnergyPlus interface.

As stated in the previous Section 3.4 the data collected from the BMS comes in a five minute time-step. After analyzing the amount of data for the test site, a total of 39302 five minute time-steps were found as valid data. Working with data on this level adds on the simulation run-time challenges, for this reason a project standard of ten minute time-step was established. This means that all of the multi-step calibration processes are executed on this ten minute time-step size. Additionally, to save computational resources and reduce the run-time of the calibration process a period of 3 months, from January to March 2019, was selected as the BEM's training period. Resulting in a total of 1574 h of operation.

Table 4
Gedved Test Site Weather station sensor accuracy's values.

Sensor	Range	Accuracy
Wind Speed	–	1.0 m/s
Wind Direction	–	1.0°
Precipitation	–	0.2 mm
Atmospheric Pressure	–	±1.5 hPa
Temperature	−40° to +60°	±0.3 °C
Humidity	–	±2.5%
Radiation	300 to 2800 nm	0.1 W/m^2

3.4.2. Data as control

Having defined the data that will stress and guide the simulation model, it is required to obtain measurements to contrast the simulation results. Heating energy supply and electric consumption of each one of the heating group HP was obtained by the building's BMS broker system and standarized to a 10 min time-step interval. This information is harvested directly from the HP group interface and classified as Control Data, only to be used for cross checking the results obtained from each run of the calibration process.

Finally, following ASHRAE Guideline 14 [7] and IMPVP [9] standards mentioned in Section 2.1, after the multi-step calibration process is finished, the results obtained from the BEM are benchmarked on an hourly basis.

4. Analysis of results and discussions

4.1. Calibration period

Table 5 shows the parameter value results for the HP group after the first step of HVAC calibration process was completed. The application of the Load Profile object in this first stage enabled us to successfully detach the building envelope from the heat production system while maintaining the building's actual heating demand to stress the simulation. It is to be noted that there is a reduction of the Rated Heating Capacity and CoP values of the calibrated heat pump when compared to the ones from specification documents included in the baseline model. This may signal that the calibrated model has captured the efficiency loss of this equipment either due to natural operating degradation or, the design vs. real operation gap of the equipment.

Once the heating supply system has been calibrated, the Load Profile object is removed and replaced by reconnecting the building to the heating production system. As stated in Section 3.1 the HVAC simulation model is detailed into a BEM whose envelope had been previously calibrated using the methodology stated by Gutierrez et. al. [48]. Since calibrating the envelope as a prior step captures the buildings energy gain and loss through its envelope allowing the process of HVAC calibration to be handled in a more reliable way. Executing this preliminary step minimizes the propagation of the uncertainty from the envelope parameters into the HVAC system, and is one of the keys to success in the application of multi-step methodology in developing high quality BEM.

The results obtained from the second step, for the calibration of baseboard radiators and the AHU parameter values, are shown in Table 6. Since there was no information regarding the baseboard radiators specifications other than its size, the parameters of the radiators in the baseline BEM were calculated to meet the indoor zone heating demand by setting them to "autosize". The main challenge in this step was to distribute the energy delivered by the HP group to the different HVAC components in the building. Since the data available only showed the total water flow of the entire library circuit, the parametrization process for water flow was key to establish how the heating demand for the different zone was met. This required an efficient model in terms of optimization run-time. The developed BEM undergoes significant changes in an effort to improve solution speed time. One example of these changes is the selection of water convectors to represent the baseboard radiators. Another improvement was found by applying a standarized format on the input file, in other words to keep the

Table 5
List of parameter values before (Baseline Model) and after (Calibrated Model) obtained from the calibration process of the HP supply group.

Parameter	Units	Baseline Model	Calibrated Model
Heat Pumps			
Rated Heating Capacity	W	63440	50752
Rated COP	W/W	5.310	4.300
Rated Sensible Heat Ratio	–	0.737	0.788
Rated Evaporator Air Flow Rate	m^3/s	5.193319	3.000000
Rated Condenser Water Flow Rate	m^3/s	0.002175	0.017500
HP-01 Off Cycle Loss Coefficient to Ambient Temperature	W/K	0	750
HP-02 Off Cycle Loss Coefficient to Ambient Temperature	W/K	0	900
HP-03 Off Cycle Loss Coefficient to Ambient Temperature	W/K	0	800
HP-04 Off Cycle Loss Coefficient to Ambient Temperature	W/K	0	850
Use Side Design Flow Rate	m^3/s	0.576974	0.001533
Indirect Water Heating Recovery Time	h	0.0392	0.0175
HP Biquadratic Capacity Curve			
Coefficient1 Constant	–	0.677625613	0.710589968
Coefficient2 x	–	0.015399454	0.018081366
Coefficient3 x^2	–	0.001019225	0.000250611
Coefficient4 y	–	0.001056556	0.000839972
Coefficient5 y^2	–	−0.000002862	−0.000000913
Coefficient6 x.y	–	0.000021313	−0.000002884
HP Biquadratic COP Curve			
Coefficient1 Constant	–	1.281579968	1.301971234
Coefficient2 x	–	0.039121045	0.034475036
Coefficient3 x^2	–	0.000845521	0.000294165
Coefficient4 y	–	−0.020543463	−0.019818080
Coefficient5 y^2	–	0.000106552	0.000094005
Coefficient6 x.y	–	−0.000500116	−0.000392034
Buffer Tank			
Off Cycle Loss Coefficient to Ambient Temperature	W/K	0	200
Source Side Design Flow Rate	m^3/s	0.576974	0.500000
Indirect Water Heating Recovery Time	h	0.2939	0.0400

Table 6
List of parameter values before (Baseline Model) and after (Calibrated Model) obtained from the calibration process of the Air Handling Unit and the Baseboard Radiators.

Parameter	Units	Baseline Model	Calibrated Model
Plant Loop			
Library Building Loop	m^3	0.200	0.400
Air Handling Unit			
Minimum Outdoor Air Flow Rate	m^3/s	2.364000	1.228000
U-Factor Times Area Value	W/K	6058	800
Maximum Water Flow Rate	m^3/s	0.000840	0.000120
Sensible Air-to-Air Heat Recovery at 100% Heating Air Flow	–	0.750	0.850
Latent Air-to-Air Heat Recovery at 100% Heating Air Flow	–	0.750	0.850
Sensible Air-to-Air Heat Recovery at 75% Heating Air Flow	–	0.750	0.850
Latent Air-to-Air Heat Recovery at 75% Heating Air Flow	–	0.750	0.850
Baseboard Radiators			
TZ01 Design Size Maximum Water Flow Rate	m^3/s	0.000234	0.000083
TZ01 Design Size U-Factor Times Area Value	W/K	603	600
TZ03 Design Size Maximum Water Flow Rate	m^3/s	0.000308	0.000083
TZ03 Design Size U-Factor Times Area Value	W/K	853	600
TZ04 Design Size Maximum Water Flow Rate	m^3/s	0.000426	0.000083
TZ04 Design Size U-Factor Times Area Value	W/K	963	600
TZ06 Design Size Maximum Water Flow Rate	m^3/s	0.000601	0.000083
TZ06 Design Size U-Factor Times Area Value	W/K	1323	600
TZ08 Design Size Maximum Water Flow Rate	m^3/s	0.000727	0.000083
TZ08 Design Size U-Factor Times Area Value	W/K	2053	600
TZ10 Design Size Maximum Water Flow Rate	m^3/s	0.000699	0.000083
TZ10 Design Size U-Factor Times Area Value	W/K	1897	600
TZ13 Design Size Maximum Water Flow Rate	m^3/s	0.000453	0.000083
TZ13 Design Size U-Factor Times Area Value	W/K	1140	600
TZ15 Design Size Maximum Water Flow Rate	m^3/s	0.000369	0.000083
TZ15 Design Size U-Factor Times Area Value	W/K	901	600
TZ19 Design Size Maximum Water Flow Rate	m^3/s	0.000502	0.000083
TZ19 Design Size U-Factor Times Area Value	W/K	1006	600
TZ21 Design Size Maximum Water Flow Rate	m^3/s	0.000345	0.000073
TZ21 Design Size U-Factor Times Area Value	W/K	871	180
TZ22 Design Size Maximum Water Flow Rate	m^3/s	0.000664	0.000270
TZ22 Design Size U-Factor Times Area Value	W/K	18197	2500

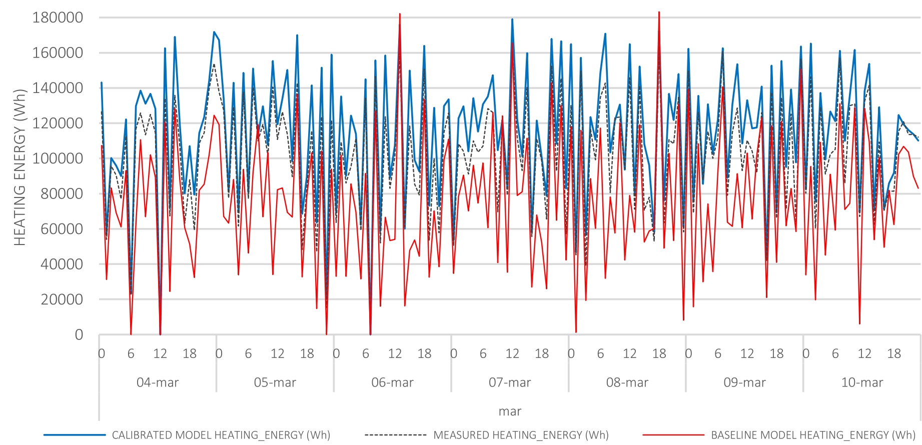

Fig. 8. Week 04–10 of March 2019. Comparison between baseline model and calibrated model results for heating energy production.

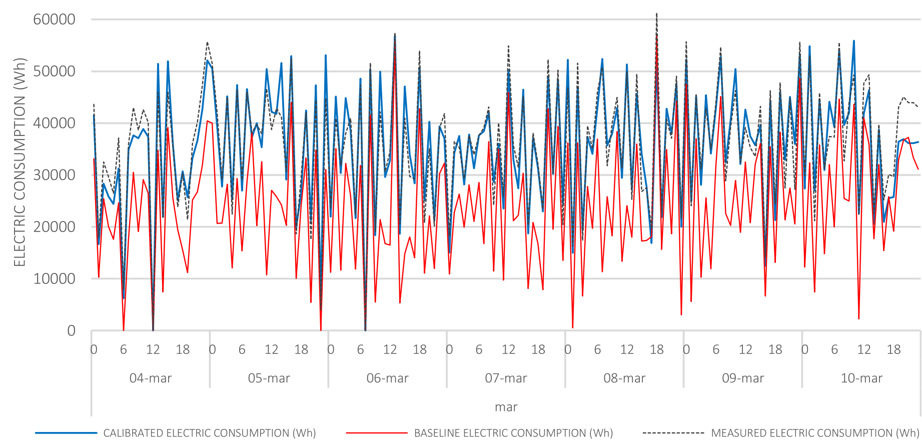

Fig. 9. Week 04–10 of March 2019. Comparison between baseline model and calibrated model results for electric energy consumption.

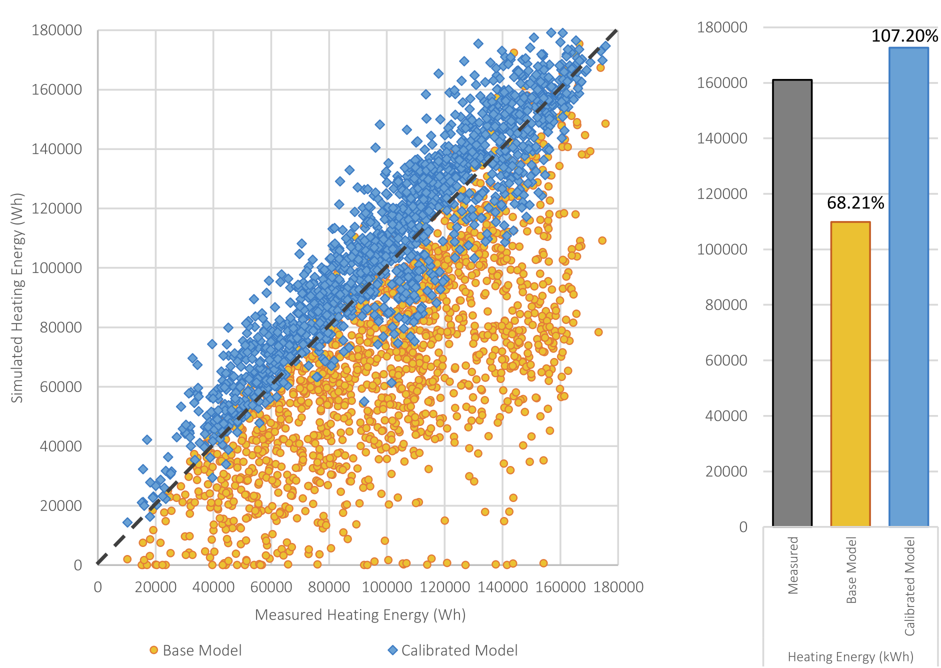

Fig. 10. Heating production results comparison between baseline model (yellow) and the calibrated model (blue) for the calibration period 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

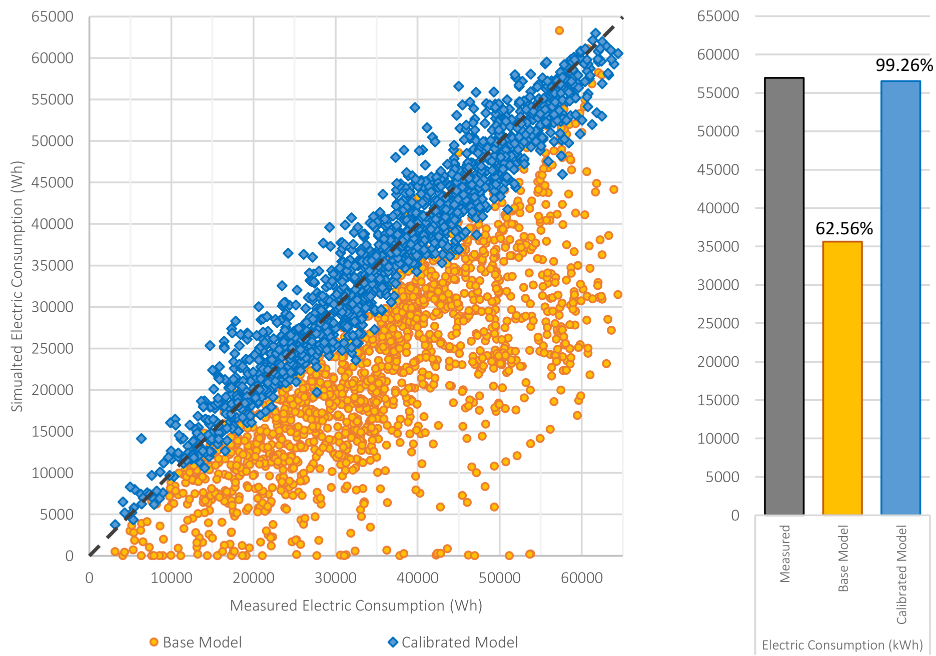

Fig. 11. Electric consumption results comparison between baseline model (yellow) and the calibrated model (blue) for the calibration period 2019. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

simulation environment in a ten minute time-step (except for the weather file) for all calculations and outputs while the optimization process takes place.

There is a relationship between the level of quality of the data obtained and introduced in the BEM and results of the calibration process. The application of this methodology could not be performed without a continuous quality assurance process in the survey of the building systems, its sensors and data evaluation. Cleaning the data stream from uncertainties, errors and or malfunctions while providing vital information to understand the operation of the HVAC system before it is used in the calibration of the model is critical, specially when facing the challenges of using on-site data.

It may be challenging but the benefits of the multi-step process described in Section 2 can be seen in Figs. 8 and 9, where the black curve displays the measured heat production and electric consumption for the HP group. Our study shows that even the most accurate baseline model (displayed in red) based on technical documentation seems to struggle meeting the measurements of the control data stream. The calibrated model (displayed in blue) has found parameter values that allow it to fit better the heat production and electric consumption of the building.

Fig. 10 and Fig. 11 compare measured and simulated heating energy production and electric consumption results between the baseline model (displayed in yellow) and the calibrated one (displayed in blue) for the whole training period from January to March 2019. Ideally, if the simulation model results fit perfectly to the control data, the resulting cloud of points would form an ideal 45° behaviour line. The results from the calibrated model cluster around this 45° line and show less dispersion for both: heating production and electric consumption, which shows how the calibration process improves the results from the baseline model and captures the behavior of the HP group heat supply system.

In terms of overall heating production for the whole training period, the calibrated model differs from actual measurements by just 7.20% while the baseline model heating production just reaches a 68.21% of the measured heating production. The same can be said about electric consumption, the calibrated model nearly matches the reading from the control data measurement consuming 99.26% of electric energy for the whole training period, while the baseline model just reaches a 62.56% match in electric consumption.

The impact of the calibration process applied to Gedved test site becomes evident in Table 7, when comparing the results between models using the hourly uncertainty index stated in Section 2.

The calibrated model shows a clear improvement in capturing the behaviour of the HVAC system. This result is achieved while maintaining the indoor temperature of the buildings spaces, Fig. 12 displays a comparison between measured indoor temperature values and the results obtained from the calibrated model. The process manages to distribute the heating energy into the different

Table 7
Hourly uncertainty index results for electric consumption and thermal energy obtained from the Calibration procedure using 1574 h of operation between January to March 2019.

	International Standard		Baseline Model Results		Calibrated Model Results	
INDEX	ASHRAE	IMPVP	Electric Consumption	Heating Production	Electric Consumption	Heating Production
NMBE	±10%	±5%	37.444%	31.787%	0.745%	−7.200%
Cv(RMSE)	30%	20%	44.735%	41.654%	9.421%	14.230%
R^{2a}	75%	75%	57.370%	49.889%	93.517%	88.074%

[a]Though there is no universal standard for a minimum acceptable R^2 value, 75% is often considered a reasonable indicator of a good causal relationship amongst the energy and independent variables.[9].

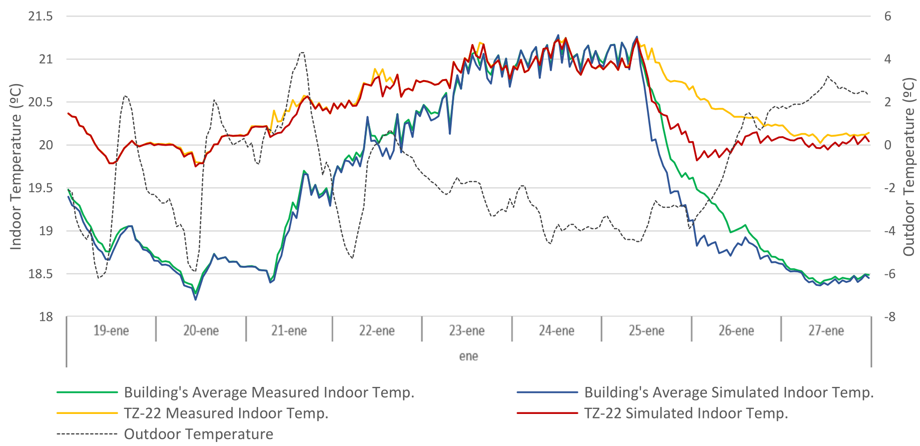

Fig. 12. Week 19–27 of January 2019. Comparison between measured indoor temperature and the calibrated model results.

Table 8
Hourly uncertainty index results for indoor temperature by thermal zone obtained for the Calibration period using 1574 h of operation between January to March2019.

	Indoor Temperature by TZ										
INDEX	Tz-01	Tz-03	Tz-04	Tz-06	Tz-08	Tz-10	Tz-13	Tz-15	Tz-19	Tz-21	Tz-22
MAE (°C)	0.060	0.032	0.099	0.206	0.938	0.542	0.106	0.044	0.109	0.132	0.057
RMSE (°C)	0.167	0.128	0.198	0.364	1.108	0.751	0.228	0.124	0.320	0.323	0.131
NMBE (%)	0.073	0.029	0.398	0.998	4.370	2.572	0.449	0.134	0.461	0.587	0.251
Cv(RMSE) (%)	0.785	0.591	0.945	1.793	5.163	3.603	1.076	0.594	1.668	1.532	0.615
R^2 (%)	97.579	97.355	97.487	93.991	59.644	76.166	95.607	98.579	96.015	94.021	94.735

thermal zones maintaining the indoor temperatures within a maximum value of 0.5°C for the average of the whole building. When evaluating a BEM calibration in terms of its indoor micro-climate, the right tool for the job needs to be used, in this case the right uncertainty index. Wide spread application of NMBE and Cv(RMSE) International Standard thresholds such as ASHRAE and IMPVP which have been developed for energy metering are a common mistake when assessing indoor temperature. Results displayed on Fig. 12 and Table 8 suggest that the use of CIBSE and VDI-6020 thresholds based on MAE and RMSE for assessing indoor temperature seem to be more rigorous and assertive than trying to adapt an energy standard NMBE and Cv(RMSE) limit values to indoor climate.

Furthermore, Table 8 displays the uncertainty error indices for indoor temperature obtained for each one of the conditioned thermal zones, where all thermal zones are well within the suggested limits of MAE 2 °C [51] and RMSE 1.5 °C [52].

When calculating the results for the average of the whole building, we obtain a MAE of 0.174 °C with an RMSE of 0.294 °C and a correlation factor R^2 of 91.897%, well within international standards displayed on Table 2 in Section 2.1. The NMBE and Cv(RMSE) index shown in Table 8 has been added for comparison purposes with existing literature, it is important to note that the values obtained for these indices are relatively small to the ones suggested by IMPVP and ASHRAE Guideline 14 standard. The reason is, this standards focus on energy measurement and comparison and their suggested limits are unfit for temperature analysis. What we have observed in this study is that a NMBE higher than 2% or a Cv(RMSE) higher than 5% will result in simulated temperatures not meeting the ones obtained from measured data.

Finally, it is key to note that focusing on achieving calibration on one single level, either indoor climate or energy consumption is not enough to achieve a fully calibrated BEM. A building's thermal dynamics is a complex system, the results obtained in Fig. 12 require to be cross-checked with energy performance such as the ones displayed in Figs. 10 and 11. This multi-level benchmark is required in order to truly assess the BEM model performance. The resulting calibrated BEM is a solution that states a correct energy supply and consumption for the HVAC system and could be used for future test of additional ECMs scenarios, BMS optimizations, and other energy saving strategies like MPC.

4.2. Evaluation period results

Any calibration is incomplete without an evaluation process. The evaluation of a BEM allows to check the overall stability in time of the calibration results, avoiding known issues such as over-fitting of the parameters values to the calibration data stream stimulus. As such, this evaluation process requires a new unused set of data to stress the calibrated BEM. In the case of Gedved, the 2019–2020 winter campaign was used to evaluate the stability of the calibration results, from November 2019 to March 2020. This unseen data set contains new building operation criteria for example, it includes the school's winter holidays when the system is working on its lowest demand point, and the following days when the system needs to be restarted to full load. While in terms of weather conditions, this period is in average 1.0 °C warmer when comparing it with the BEM training period, with a maximum hourly temperature of 11.4 °C and minimum of −5.5 °C, being January 2020 clearly a warmer month than its 2019 counterpart as Table 9 indicates.

In terms of Heating Energy delivered by the heat pump group, the calibrated BEM manages to stay within ASHRAE international standard hourly limits. While in Electric Consumption, the calibrated model not only manages to stay well under ASHRAE limits, its performance manages to meet IMPVP international standard limits. As seen on Fig. 13 and 14, displaying the week of 09 to 15 of March 2020, set one year after the calibration period took place, we can see that for both: heating energy and electric consumption, the model simulated results closely match the measurements obtained by the building sensors.

Table 9
Difference between training and checking periods in terms of hourly average, maximum and minimum Outdoor DryBulb Temperature by month, for the test site.

Outdoor DryBulb Temperature	Units	Training Period				Checking/Evaluating Period					
		2019			Average	2019		2020			Average
		Jan	Feb	Mar		Nov	Dec	Jan	Feb	Mar	
Average	°C	1.553	4.483	5.434	3.823	5.368	4.493	5.501	4.404	4.481	4.849
Maximum	°C	8.500	14.200	14.600	12.433	9.700	10.100	10.600	11.400	11.200	10.600
Minimum	°C	−6.200	−4.000	−3.700	−4.633	−1.300	−2.800	−1.600	−4.400	−5.500	−3.120

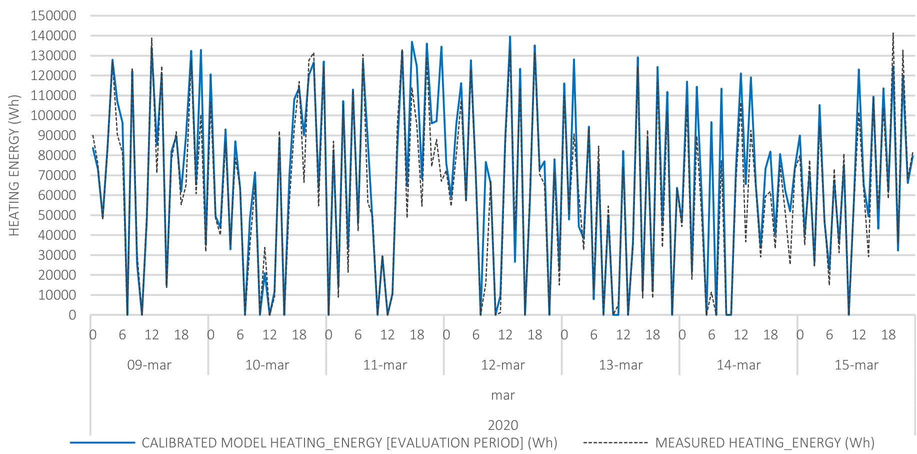

Fig. 13. Week 09–15 of March 2020. Calibrated model evaluation period results for heating energy production.

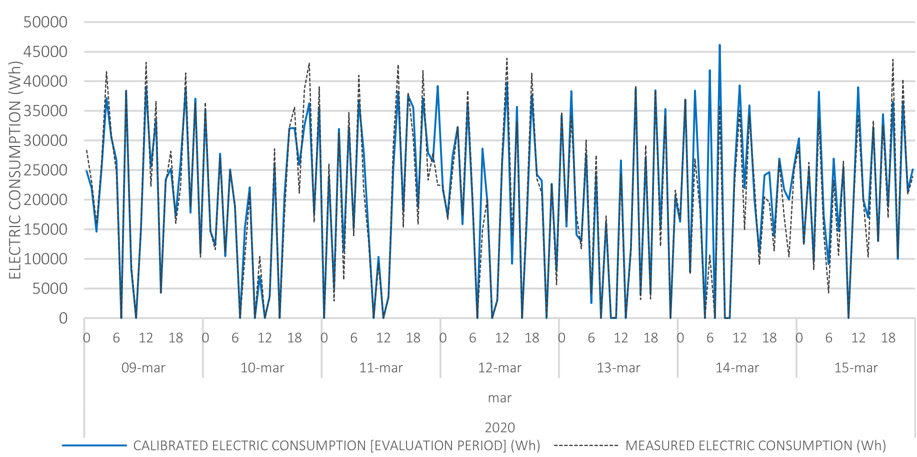

Fig. 14. Week 09–15 of March 2020. Calibrated model evaluation period results for electric consumption.

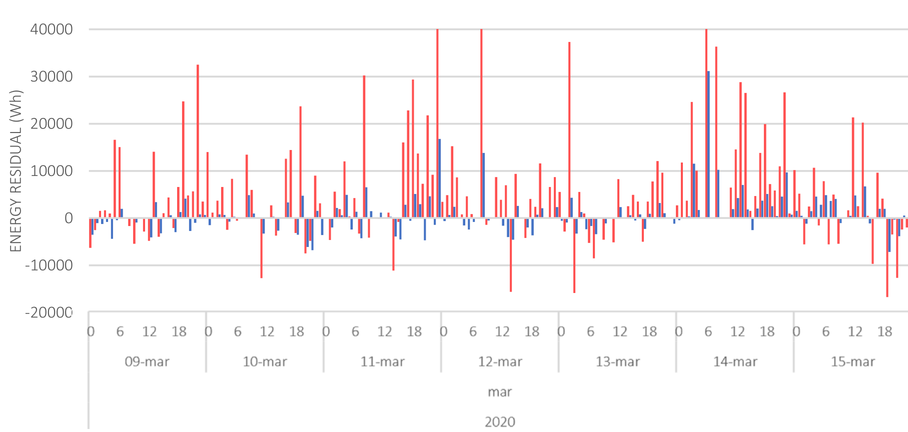

Fig. 15. Week 09–15 of March 2020. Calibrated BEM model evaluation period hourly residual error for heating energy production and electric consumption.

Table 10
Hourly uncertainty index results for electric consumption and thermal energy obtained from the Evaluation period using 2600 h of operation between November 2019 to March 2020.

	International Standard		Baseline Model Results		Calibrated Model Results	
INDEX	ASHRAE	IMPVP	Electric Consumption	Heating Production	Electric Consumption	Heating Production
NMBE	±10%	±5%	53.344%	43.319%	3.118%	−6.573%
Cv(RMSE)	30%	20%	63.121%	56.637%	15.538%	19.040%
R^{2a}	75%	75%	56.540%	55.370%	85.744%	82.570%

[a]Though there is no universal standard for a minimum acceptable R^2 value, 75% is often considered a reasonable indicator of a good causal relationship amongst the energy and independent variables.[9].

Fig. 16. Heating production results for calibrated model performance during the evaluation period from November 2019 to March 2020.

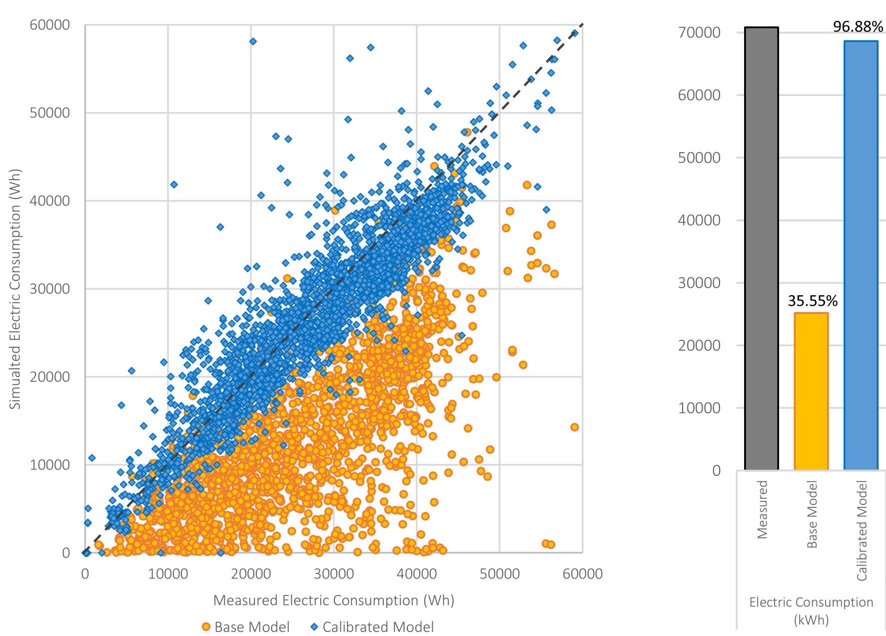

Fig. 17. Electric consumption results for calibrated model performance during the evaluation period from November 2019 to March 2020.

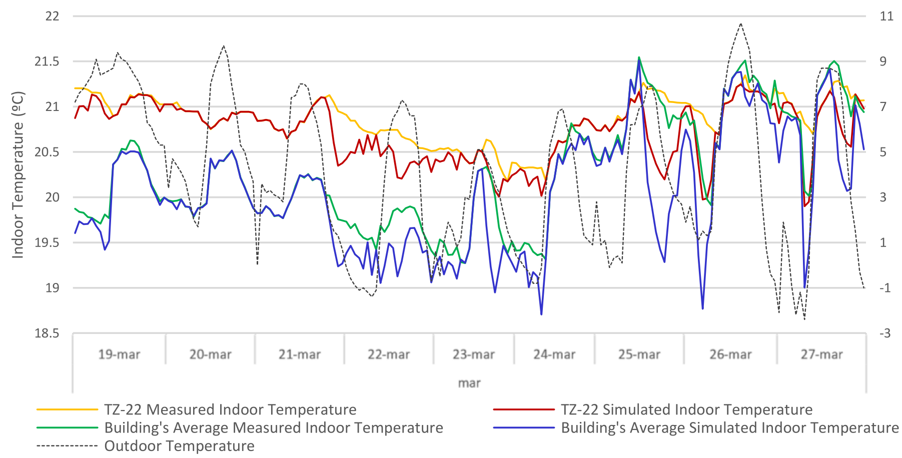

Fig. 18. Week 19–27 of March 2020. Comparison between measured indoor temperature and the calibrated model results.

This becomes clear when analysing the residuals obtained for this week. Fig. 15 displays the hourly error residual for heating production and electric consumption of the week of 09 to 15 of March 2020. In terms of heating energy most residuals are below 50 kW, while in terms of electric consumption most residuals are well under 10 kW, with the vast majority of residuals clustering below 5 kW. The assessment of how well the BEM fits into heating energy and electric consumption is performed through the standardized indices shown below in Table 10.

This fitting of simulated heating energy and electric consumption becomes more evident when displayed in Fig. 16 and Fig. 17, where we can see how the simulated results for the whole evaluation period cluster alongside the center line of ideal behaviour. Moreover, the overall heating energy obtained from the calibrated model is 6.57% above the measured heating energy from the HP group. While in terms of electric consumption the simulation results are 3.12% below the measured consumption.

As expected, Fig. 16 and Fig. 17 show an increase in the dispersion of the calibrated BEM's results when compared to the results obtained from the previous period. Which seems natural because during the evaluation period no parameter optimization nor a calibration process takes place while the BEM model is now stressed under new unseen data. Therefore, the results suggest that the calibrated model performs as expected under the new set of conditions and it is not over-fitted to the training period data.

There are some reasons for a calibrated BEM to have difficulties on complying during its evaluation period. The most common may be related to the probability of occurrence of different boundary conditions, including the equipment's operation range. The calibration or training period must contain enough operational events to describe both: the normal operation of the equipment and specific behaviours like the ones in certain characteristic non recurrent events. That way the training period used may stress the system beyond normal operation and helps finding the parameters values that best describe the equipment's operation. How we capture this data is outside the scope of this study but does pose an interesting question to be further explored. However, it is interesting to note that one of the reasons the calibration performed so well in this study may lie on the amount of points or events that a 10 min time-step calibration process contains in comparison with an hourly calibration approach (A 6 to 1 event ratio). Therefore, the calibration process required only three months of HVAC operational data to train the BEM in contrast with the requirement of a year of data indicated by ASHRAE guideline 14 [7].

When compared to the baseline BEM, it becomes evident that an optimization process of parameter values is required to generate a BEM model that can resemble the behavior of the actual installed system in the building.

The main focus of selecting this 5 months was to test the calibrated system against as many different events as possible, both in terms of weather and equipment operation. In terms of energy consumption, the results of the calibrated model during the evaluation period are shown on Table 10.

Indoor temperature of the different thermal zones in the building was also checked during the evaluation period. Fig. 18 displays an example of the average simulated temperature for the building as well as the one for TZ-22 during a 9 day period of time.

The hourly uncertainty index for simulated indoor temperature in each one of the conditioned spaces in the building during HVAC operation are displayed on Table 11. The building's average MAE is 0.174 °C with an RMSE of 0.294 °C and a R^2 91.897%, meeting the limit suggested on CIBSE [51]. Once again the NMBE and Cv(RMSE) on Table 11 are displayed for comparison purposes and their values are also well within ASHRAE and IMPVP criteria. As explained on Section 4.1, means that the limits set on the uncertainty index on this standards are not applicable for temperature analysis.

The results for TZ-08 and TZ-10 in Table 11 show an improvement during the evaluation period, which would suggest that the effect seen on the calibration period may be caused mainly by occupancy load in the spaces.

Table 11
Hourly uncertainty index results for indoor temperature by thermal zone obtained for the Evaluation period using 2600 h of operation between November 2019 to March 2020.

	Indoor Temperature by TZ										
INDEX	Tz-01	Tz-03	Tz-04	Tz-06	Tz-08	Tz-10	Tz-13	Tz-15	Tz-19	Tz-21	Tz-22
MAE (°C)	0.085	0.042	0.118	0.163	0.415	0.241	0.113	0.063	0.115	0.078	0.072
RMSE (°C)	0.236	0.143	0.302	0.391	0.697	0.489	0.333	0.228	0.357	0.215	0.183
NMBE (%)	0.045	0.061	0.455	0.741	1.945	1.117	0.427	0.158	0.359	0.287	0.327
Cv(RMSE) (%)	1.123	0.669	1.438	1.900	3.298	2.369	1.581	1.099	1.850	1.028	0.865
R^2 (%)	95.338	97.347	93.407	90.860	75.493	86.633	91.481	95.892	91.104	95.996	86.540

5. Conclusions

The multi-step methodology applied to the present case study has shown promising results, by adjusting the parameter values to a degree that calibrates the HVAC system heat production and energy consumption well within international standards using only three month data from 2019 while maintaining indoor temperature of the different thermal zones. Furthermore, it manages to generate a stable simulation through time, as the evaluation analysis performed with data from 2020 in Section 4.2 shows. Additionally, the methodology is flexible enough to allow this multi-step principle to be applied when calibrating other HVAC equipment, subsystem or components from the building itself, either in winter or summer conditions. This multi-step calibration seems to produce favorable results when working with highly detailed white box models.

Regarding the baseline model, which was developed to represent as closely as possible the actual building and its installed system. Taking into account all available technical documentation, cross-reference with surveys, visual inspections, and interviews with the building maintenance and system operator. Results for overall electric energy consumption for the calibration and evaluation period respectively are 37.44% and 64.45% lower than the measured energy consumption. This shows that the results from any baseline model should always be cross checked with control measurement data. Moreover, when compared to the 0.74% and 3.12% obtained from the calibrated BEM, it is evident that this multi-step calibration process has successfully reduced the gap between simulated outputs and metered reality.

The final product of this calibration process is a whole building calibrated BEM that takes into account the building's envelope behavior and incorporates into the simulation the detailed behaviour of its HVAC systems. A BEM that is benchmarked on three distinct levels: indoor climate of the TZ, heating energy production and electric energy consumption; something that to our knowledge has not been performed before. Resulting in a high quality BEM as displayed in Section 4.1 and 4.2. Future studies will focus on further developing this methodology, its application and validation to other HVAC and building systems, testing its flexibility and adaptation with different scenarios and with different HVAC component setups.

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CRediT authorship contribution statement

José Eduardo Pachano: Conceptualization, Methodology, Validation, Investigation, Resources, Writing - review & editing, Supervision. **Carlos Fernández Bandera:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing - original draft, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

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

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Abbreviations

The following abbreviations are used in this manuscript:

AHU	Air Handling Unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	Building Energy Model
BMS	Building Management System
CIBSE	Chartered Institution of Building Services Engineers (RMSE)
Cv	Coefficient of Variation of Mean Square Error
DoE	Department of Energy
DHW	Domestic Hot Water
DR	Demand Response
DX	Direct Expansion
ECMs	Energy Conservation Measures
EU	European Union
FEMP	Federal Energy Management Program
HP	Heat Pump
HPWH	Heat Pump Water Heater
HVAC	Heating Ventilation Air Conditioning
IEA	International Energy Agency
IPMVP	International Performance Measurement and Verification Protocol
M&V	Measuring and Verification
MAE	Mean Absolute Error
MPC	Model Predictive Control
NMBE	Normalized Mean Bias Error
NSGA-II	Non-Dominated Sorting Genetic Algorithm
R^2	Spearman's Rank Correlation Coefficient Square
RMSE	Root Mean Square Error
SABINA	SmArt BI-directional multi eNergy gAteway
Temp.	Temperature
TZ	Thermal Zone
$\Delta\Theta$	Temperature Differential Range
°C	Celsius degrees
kW	Kilowatt
kWh	Kilowatt per hour
mm	Millimeters
m/s	Meters per second
m^3/h	Cubic meters per hour
Pa	Pascals
W	Watts
Wh	Watt per hour
%	Percentage
° or deg	Decimal degrees

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