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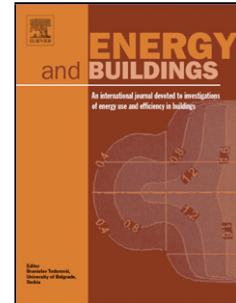
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1 A calibration methodology for building dynamic models  
2 based on data collected through survey and billings

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9 **Abstract**

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11 THIS REASON THE FOLLOWING MANUSCRIPT MAY DIFFER IN STYLE FROM THE SUB-  
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13  
14 A correct dynamic building modeling requires a proper definition of all  
15 the parameters that can affect the model outputs. While a preliminary  
16 survey will lead to a precise design of the building envelope, other param-  
17 eters, such as the temperature set-point and the air leakage, are difficult  
18 to accurately evaluate, thus introducing errors in the model. Further-  
19 more electrical and thermal consumption invoices are based on monthly  
20 records while simulations tools use hours or even more detailed time  
21 steps. For all these reasons, the present work is aimed at the definition  
22 of a a calibration process based on survey, billings and dynamic modeling  
23 that takes into account the operator-dependent parameters. The inno-  
24 vative idea behind this calibration process consists of the comparison  
25 of the real and simulated energy signatures. 176 + 40 simulations were  
26 run in order to find the set of parameters that most accurately overlap  
27 the simulated and real energy signatures leading to the calibration of  
28 the model. The case study is a retail superstore of 3544 m<sup>2</sup> floor area  
29 built in central northern Italy. Results demonstrate the validity of the  
30 approach proposed showing a calibrated signature with about 1% dis-  
31 crepancies from the real case one. The approach can be extended to  
32 different simulation software since the main advantage of the energy sig-

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33 nature is to simplify consumption outputs interpretation even in case of  
34 complex buildings. A further innovative consequence of the methodology  
35 proposed is its capability to promptly identify inefficiencies in the build-  
36 ing subsystems, i.e. the HVAC control, thus leading to a fast correction  
37 of the root cause without the implementation of complex and expensive  
38 monitoring devices.

39 *Keywords:* Retail building models, parametric analysis, Energy efficiency solutions, Dynamic  
40 Modeling, Model calibration

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## 41 1. Introduction

42 The software for dynamic building simulation represents a powerful  
43 tool for the design of new energy efficient buildings as well as the analy-  
44 sis of existing buildings in order to reduce their energy consumption [1].  
45 In fact, most of the simulation software available on the market allows to  
46 predict the power and energy consumption outputs resulting in combina-  
47 tion with the temperatures and other environmental parameters. In such  
48 a way, it is possible to guarantee a consumption reduction without com-  
49 promising the comfort and, in some cases, even increasing it [2, 3]. The  
50 way this software is able to produce such detailed outputs is through so-  
51 phisticate simulation engines that run on a meticulous description of the  
52 building such as EnergyPlus or TRNSYS[4]. For the analysis of existing  
53 facilities, the major risk is the wrong definition of some parameters that  
54 will inevitably lead to wrong outputs. A further complication is the lack  
55 of verifiability that the designer has on some of these parameters. In fact,  
56 while the transmittance of walls or windows can be easily assessed by

57 the right tools, other user-dependent parameters cannot be measured so  
58 easily, e.g. the air change due to ventilation/leakage or the actual point  
59 imposed by the thermostats [5, 6, 7] . All this, together with contingent  
60 variations between the design data and the actual operative conditions of  
61 the building, suggests to validate the simulation tool by a calibration of  
62 the model [8]. .The most commonly used way to proceed is to compare  
63 the real natural gas and electric bills with the simulated consumption  
64 [9]. This approach, however, can be considered effective only for gen-  
65 eral comparison and validation. In fact, in case of an overall annual (or  
66 seasonal) value comparison, all the valuable dynamic data produced by  
67 the simulation are cut off. An opposite case is the ASHRAE guidelines,  
68 which suggest a comparison done on monthly or hourly basis [10]. This  
69 comparison requires processing a large amount of data just to outline  
70 the values that are out of the maximum error (5 or 10% as suggested  
71 by [1]), but no further information is given on how to proceed in order  
72 to obtain a better calibration of the model. More complex analyses of  
73 model validity can be found in literature, i.e. the work from Manfren et  
74 al. is based on a meta-model approach used to outline advantages and  
75 the drawbacks of various calibration strategies [11].

76 The aim of this work is the definition of a calibration approach that  
77 takes the dynamic behavior of the building-HVAC systems interaction  
78 into account but does not require more data than usually available from

79 billing reports or similar summary information. The proposed method  
80 is based on the comparison between the energy signature of the real  
81 building with the energy signature of the simulated one. The energy  
82 signature is an effective tool able to describe the dynamic behavior of a  
83 building thanks to the correlation between the energy consumption and  
84 the outside temperature [12]: these data are collected monthly or some-  
85 times weekly, so the signature keeps track of the dynamic phenomena  
86 that characterizes the building. In such a way it is possible to calibrate  
87 the model and also to outline the reason behind the differences of an in-  
88 correct calibration at the same time. Further to the simple calibration,  
89 the proposed approach allowed to learn about the building through an  
90 indirect process. In fact, values that were difficult to collect in an on-  
91 field survey are here identified through the calibration process. [12, 13].  
92 After this it is possible to promptly outline malfunctioning as well as  
93 wrong uses of the HVAC systems in terms of ventilation, infiltration and  
94 temperature control, even in those cases where there is no time for long  
95 on-site measurements and monitoring or there is a lack of information  
96 from the survey.

97 The way to proceed chosen for this work, outlined in Figure 1, is as  
98 follows: first a case study building was chosen for the work. It is a retail  
99 store building dating back to the 1970s that consists of more than 3544  
100 m<sup>2</sup> of floor surface. Then a field survey was performed to identify all

Figure 1: Generic parameter definition and calibration process flow chart

101 the parameters required to model the building by Design Builder soft-  
102 ware, together with the draft of its real energy signature [5]. The next  
103 step generically consisted in the identification of the uncertain parame-  
104 ters and their respective ranges. After that, a parametric approach for  
105 multiple simulations was adopted, focusing on temperature set-point and  
106 ventilation air change. By means of the jEPlus, tool [14], the building  
107 was simulated under 176 different possible combinations of the uncertain  
108 parameters [14]. Every simulation resulted in an energy signature that  
109 was then compared with the actual one obtained from the case study.  
110 The minimization of the differences between the simulated and real sig-  
111 natures enables the definition of the parameter set that validates the  
112 model.

113 Further results were obtained through a more specific parametric anal-  
114 ysis within the neighborhood of the optimum point found in the previ-  
115 ous analysis, reported in Section 2.1. A more detailed description of the  
116 adopted methodology is reported in the following sections.

### 117 1.1. Energy signature

118 The monitoring and calibration of the model is based on the 'en-  
119 ergy signature'. It consists in a graphical method to assess the energy  
120 behavior of a building according to EN 15603 standard, Annex B [15].  
121 The signature is based on the correlation between energy consumption

122 and outside temperature, or even degree-days. [16, 12]. In the heating  
123 season analysis, the straight line that best fits the point cloud is the  
124 energy signature. The energy signature of the superstore investigated in  
125 this work is reported in Figure 2. . The average external temperature is  
126 recorded at regular intervals. These intervals can be as small as one hour  
127 while the most common time steps are the week or the month [15, 17].  
The analysis proposed for the investigated signature focuses on the win-

Figure 2: Real energy signature of the case study

128  
129 ter period but the signature can also be extended to the summer period  
130 in order to evaluate the behavior of the air cooling systems as reported  
131 by Yu and Chan [18]. The effectiveness of the energy signature analy-  
132 sis on commercial buildings was extensively proven by Rabl and Rialhe  
133 in 1992 when they screened more than 50 commercial buildings using  
134 this technique [19]. In this work the data collected enables to define the  
135 energy signature on a monthly basis.

136 1.2. Use of energy signature and other calibration methods

137 A model calibration leads to many benefits, for example identifying  
138 and evaluating savings or finding input parameter errors [20]. Liu et al.  
139 show a methodology for the rapid calibration of energy consumption sim-  
140 ulations for commercial buildings based on the use of "calibration signa-  
141 tures", which characterize the difference between measured and simulated  
142 performance [21]. Thanks to simulation programs the characteristic cal-



143 ibration signatures can be calculated. First of all the initial run is done  
144 using the values collected during the survey as input; then the paramet-  
145 ric program changes some of these parameters within a given range and  
146 runs the simulation again as reported in Section 2.3. The results of these  
147 two simulations are plotted versus the outdoor air temperature and then  
148 an evaluation is done to establish whether a simulation is sufficiently  
149 calibrated or not. As Liu et al. show, there are several methods to eval-  
150 uate the reliability of the calibrations as the Root Mean Square Error  
151 (RMSE) or the Mean Bias Error (MBE). Liu and Liu studied a quick  
152 method for calibrating simplified building energy simulation models of  
153 commonly used HVAC systems, using an office building as a case-study  
154 [22]. Their model is calibrated using two weeks of measured heating and  
155 cooling data. In this way, the root mean squared error RMSE (used  
156 as parameter to evaluate the reliability of the model) is significantly  
157 reduced. Reddy et al. [23] studied a method for calibrating building  
158 energy models to monthly measured data. After completing an audit of  
159 the building, a "base-case" model of the building is created and then,  
160 by means of a parametric optimization analysis, a number of calibrated  
161 models for the building is determined. Raftery et al. [20] focus their  
162 study on the necessity to bring the principle of evidence-based decision-  
163 making to the calibration method. They argue that, in order to improve  
164 the effectiveness of calibration, it is extremely important to change the

165 input parameters only according to available evidence under defined pri-  
166 ority. Other studies focus on the importance of the building audit in  
167 order to determine appropriate values for the observable parameters of a  
168 building simulation model. Surveys, field measurements and interviews  
169 with building managers are the first part of an accurate calibration since  
170 the real building operation is often different from the specifications as-  
171 sumed and documented during the design and construction phases. Heo  
172 et al. [24] improved a calibration method based on a statistical formula  
173 which takes into account three levels of uncertainties: parameter uncer-  
174 tainty in the energy simulation model, discrepancy between the model  
175 and the true behavior of the building, and observation errors. Their case  
176 study demonstrates that this methodology can correctly evaluate energy  
177 retrofit options.

## 178 2. Calculation

179 In the following paragraph the case study and the definition of the  
180 model are described. The energy signature together with specific indexes,  
181 based on the differences between the real and simulated data, are effective  
182 tools to verify the congruence of the modeling process.

### 183 2.1. Model construction and calibration

184 The construction of the building model is realized through the *Design-*  
185 *Builder* dynamic modeling software, a Graphical User Interface (GUI)  
186 of *EnergyPlus* [5]. In order to validate the model, a comparison between

187 the real and simulated consumption data is performed. Particular atten-  
188 tion is paid to the thermal energy consumed by the building. Natural  
189 gas consumption is easily evaluated going through the bills. Then, the  
190 energy used can be evaluated considering the efficiency of the natural  
191 gas boiler, here considered 0.84 as reported by the manufacturer. The  
192 bills are provided on a monthly basis, forcing the calibration process to  
193 use the same time step. This work focuses on the calibration process  
194 acting on those operative parameters that elude the design specs: ven-  
195 tilation/leakage and actual temperature set-point. Even if these values  
196 are specified during the design of the building, they are strongly user-  
197 dependent and not completely predictable. The calibration method used  
198 is a parametric analysis of the uncertain or non-homogeneous values of  
199 the case study obtained through *jEPlus*, a powerful tool that runs several  
200 "batch of jobs" in parallel [14]. The entire and generic procedure behind  
201 this work calculation is outlined in the list below:

- 202 1. *In situ* survey and data collection;
- 203 2. Design of the base-case model with DesignBuilder;
- 204 3. Draft of the real-case energy signature of the case study;
- 205 4. Production of the energy signature of the simulated-case from model  
206 outputs and real weather data;
- 207 5. Comparison between energy signatures and evaluation of the error  
208 indexes defined in Section 2.3;

- 209 6. Choice of uncertain parameters  $X_i$  ( $i=1,\dots,n$ ), if the base-case model  
210 is not representative of the real consumption;
- 211 7. Definition of the variation ranges and the incremental step width for  
212 each of the  $X_i$  parameters;
- 213 8. Parametric analysis, using *jEPlus*, of the simulations which charac-  
214 terize each possible combination of the above parameters;
- 215 9. Identification of the simulation characterized by the lowest differ-  
216 ences with the real building. This solution calibrates the model.

## 217 2.2. Case study

218 The case study is a retail store built in the 1970s, located in Bologna  
219 (Italy). The 3D building render is depicted in Figure 3. In accordance  
220 with Italian regulations as summarized in UNI/TS 11300-1, which di-  
221 vides Italy into six climate zones based on the degree-day value (e.g.  
222 Bologna is in the E climate zone [25]) and attribute to each of them a  
223 conventional heating period (from October 15<sup>th</sup> to April 15<sup>th</sup> in the case  
224 study). The total area occupied by the building is 3544  $m^2$  and most of  
225 it consists of the sales floor area. The building is composed by several  
226 areas, listed below:

- 227 • Sales area = 3227  $m^2$ ;
- 228 • Bar area = 163  $m^2$ ;
- 229 • Bakery area = 39  $m^2$ ;

Figure 3: Case study

Figure 4: Superstore heating consumption in 2013

- 230 • Fish shop area =  $19 \text{ m}^2$ ;
- 231 • Entrance area =  $34 \text{ m}^2$ ;
- 232 • Low and normal temperature refrigerators and remaining areas =  $62$   
233  $\text{m}^2$

234 The subdivision into areas concern the electrical consumption only,  
235 while all the activities take place within the same open space. For this  
236 reason the building can be modeled as a single thermal zone.

237 The building envelope is made of a structure in reinforced concrete,  
238 weakly isolated with 0.02 m of extruded polystyrene foam (XPS). The  
239 covering is a hollow-core concrete roof isolated with 0.1 m of expanded  
240 polystyrene (EPS). In the histograms in Fig. 4 and Fig. 5 the thermal  
241 and electric consumption of the superstore measured in 2013 are repre-  
242 sented.

243 In order to create both the real and the simulated energy signatures,  
244 weather data is required. It is obtained considering the hourly varia-  
245 tions of the outside temperature over the entire period of simulation;  
246 the hourly external temperature was obtained from the database of the  
247 IdroMeteoClima Arpa Service, Dexter System [26].

Figure 5: Superstore electric consumption in 2013

248 *2.3. DesignBuilder modeling and jEPlus simulations*

249 The realization of the base-case simulation is made by the Design-  
250 Builder software, defining firstly the geometric model. Afterwards the  
251 model is completed by filling in all the modules of the software with the  
252 input data obtained from energy audits, design specs and a technical  
253 survey. For this model, the HVAC systems were simulated using the  
254 "compact mode" feature [27]. In this work, the parameters considered  
255 for the calibration process are those that lack of actual definition in the  
256 model due to their intrinsic dependency on the operator/user. In the  
257 case study the survey reports a target set-point temperature of 20 °C.  
258 However this value, as a result of interviews conducted during the survey,  
259 is not respected by users, since they can act independently and arbitrar-  
260 ily, manually modifying this parameter. The user feedback is also highly  
261 variable, showing a high indeterminacy that makes it impossible to es-  
262 timate the correct value. For this reason the set-point temperature has  
263 been selected as a parameter for calibration.

264 Another parameter, which could not be estimated with adequate preci-  
265 sion, is the ventilation/leakage air change (in volumes per hour). It can  
266 be affected by errors due to windows being opened manually by users,  
267 or to a wrong timing of the automatic doors of the supermarket or even  
268 differences between the air leakage estimated in the design and the sur-

269 vey and the real ones. Therefore also this parameter has been chosen for  
270 the calibration.

271 The calibration focused on the heating energy consumption and not on  
272 the electrical one; in fact the real and simulated electrical energy signa-  
273 tures showed a good matching since the first simulation, as reported in  
274 Figure 6.

275

276 In Italy UNI 10339:1995 provides the minimum air flow rate, which  
277 is  $9 \cdot 10^{-3}$  m<sup>3</sup>/s of fresh air per person. Such Italian technical rule is  
278 currently being re-written according to the EN 13779:2007 (UNI EN  
279 13779:2008), which uses an approach based on indoor air quality. How-  
280 ever it requires minimum air flow volumes higher than the two lowest  
281 levels (IDA 3 and IDA 4) considered by the EN 13779. These levels  
282 correspond to moderate or low air quality, and may be the preferential  
283 choice if energy efficiency is a main target. As a consequence of this,  
284 the result presented here are to be considered precautionary in these  
285 terms. The air flow rate of UNI 10339 is closed to IDA 2 level of EN  
286 13779. Generally speaking, EN 13779 and recent works are supporting  
287 a flexible approach based on CO<sub>2</sub> measurement [28, 29, 30]. In order to  
288 properly set-up a simplified parametric analysis, the different sources of  
289 air circulation were arranged into the modeling of the AHU parameters.

290 First of all the nameplate characteristics of the AHU were considered:

Figure 6: Pumps, thermoventilation and lighting real and simulated energy signature

- 291 • Air flow rate,  $Q_{out}$ :  $35000 \frac{m^3}{h}$
- 292 • Return flow,  $Q_r$ :  $28000 \frac{m^3}{h}$

293 Then the recirculation rate was lowered to its 85% as consequence of  
 294 the preliminary investigation done on this case-study [31]; therefore the  
 295 return flow is reduced to  $23800 \text{ m}^3/\text{h}$ . It follows that the total flow for  
 296 each AHU is:

$$Q_{tot} = Q_{out} - 85\% \cdot Q_r = 35000 - 23800 = 11200 \left[ \frac{m^3}{h} \right] \quad (1)$$

297 The mechanical ventilation system consists in 3 AHU,

$$Q_{tot_{AHU}} = Q_{tot} \cdot 3 = 11200 \cdot 3 = 33600 \left[ \frac{m^3}{h} \right] \quad (2)$$

298 Dividing this flow by the volume within the building envelope, it is  
 299 possible to obtain the first iterate value of leakage/ventilation ( $lv$ ) in  
 300 [vol/h]

$$lv = \frac{Q_{tot_{AHU}}}{V} = \frac{33600}{20501} = 1.6 \left[ \frac{Vol}{h} \right] \quad (3)$$

301 This value is in line with other studies in the literature, i.e. Zaatari et  
 302 al. investigated the influence of air exchange rates from 0.5 to 2 on the  
 303 concentration of some specific pollutants in the indoor air [32].



304 The specific parameters are varied until the model is calibrated, and  
305 a significant range and a proper step of variation had to be defined for  
306 each of them. 176 simulations were run with the support of *jEPlus*.  
307 The following ranges of variation were considered:

- 308 • *Heating set-point temperature*: from 18 °C to 23 °C, with a step of  
309 0.5 °C;
- 310 • *Ventilation/leakage*: from 1.4 to 2.9  $\frac{Vol}{h}$ , with a step of 0.1  $\frac{Vol}{h}$ .

311 After those 176 simulations, a thickening is done around the values of  
312 temperature and ventilation/leakage presenting square errors (defined  
313 below) in the neighborhood of 0.1. The thickening consists in 40 further  
314 simulations and it is aimed to verify that the temperature set-point and  
315 ventilation values that provide the absolute minima of root mean squared  
316 and safety aimed error indexes, which estimate the convergence between  
317 the real and the simulated case, were exactly the ones found during the  
318 first 176 simulation analysis:

- 319 • *Heating set-point temperature*: from 20 °C to 20.9 °C, with a step  
320 of 0.1 °C;
- 321 • *Ventilation/leakage*: from 1.5 to 1.8  $\frac{Vol}{h}$ , with a step of 0.1  $\frac{Vol}{h}$ .

322 The thickening is carried out for only the heating set-point temperature,  
323 while for the ventilation/leakage there is no need to fit the values because  
324 the step chosen before was already small enough.

325

326 Once the simulations are carried out, the results are analyzed and dis-  
 327 cussed, comparing the real energy signatures with those obtained with  
 328 the simulations. The results are analyzed with the help of two error in-  
 329 dexes which estimate the correspondence between the real and simulated  
 330 case.

331

- Root mean squared error (RMSE);

332

- Safety aimed error (SAE): between  $m$  and  $q$  relative errors.

333

334 The slope  $m$  is that of the energy signature that corresponds to the  
 dispersion through the building envelope for transmission and ventilation  
 335 [12]. A good slope matching indicates a similar monthly consumption  
 336 trend between the simulated and the real building. The intercept  $q$   
 337 indicates the expected consumption for an external temperature of  $0^\circ\text{C}$   
 338 and usually is a good indicator of the consumption behavior in winter  
 339 months.

340

In order to estimate the actual matching between real and simulated  $m$   
 341 and  $q$ , the relative error of each one is considered.

$$E_{rel,m} = \frac{|m_{real} - m_{simulated}|}{|m_{real}|} \quad (4)$$

342 where:

343

- $E_{rel,m}$  = slope ( $m$ ) relative error;

344

- $m_{real}$  = real energy signature slope;

- 345 •  $m_{simulated}$  = simulated energy signature slope.

$$E_{rel,q} = \frac{|q_{real} - q_{simulated}|}{|q_{real}|} \quad (5)$$

346 where:

- 347 •  $E_{rel,q}$  = intercept ( $q$ ) relative error;
- 348 •  $q_{real}$  = real energy signature intercept;
- 349 •  $q_{simulated}$  = simulated energy signature intercept.

350 The simulations with the closest resemblance to the real consumption  
351 produces a relative error lower than 10%.

352 The SAE error index is defined as follows:

$$SAE = \sqrt{E_{rel,m}^2 + E_{rel,q}^2} \quad (6)$$

353 This error index is used to favor estimated energy signatures charac-  
354 terized by both slope and intercept values close to the real ones. An  
355 estimated energy signature with the same slope of the real signature but  
356 with a completely different intercept is not representative. In the same  
357 way, an estimated energy signature with an intercept matching the real  
358 one, but with a completely different slope is not representative.

359 The RMSE is defined as follows:

$$RMSE = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^n (C_{real,i}^2 - C_{simulated,i}^2)^2} \quad (7)$$

360 where

- 361 •  $C_{real,i}$  = real consumption of the i-th month;
- 362 •  $C_{simulated,i}$  = simulated consumption of the i-th month.

363 The results obtained show that, minimizing the presented error indexes,  
 364 it is possible to achieve convergence with the best solution which mini-  
 365 mizes the safety aimed error.

366

367

### 368 3. Results and discussion

#### 369 3.1. Preliminary considerations

370 The documentation provided by the staff does not contain all the re-  
 371 quired information related to the stratigraphy of the main walls of the  
 372 building. Based on the final use of the case study building, its year of  
 373 construction, information collected during the survey and using the aba-  
 374 cus wall structures developed by CTI (Comitato Termotecnico Italiano  
 375 [33]), the wall and roof stratigraphy is identified and reported in Table  
 376 1.

Main walls	Roof
Ceramic/clay tiles (0.02 m)	Cast Concrete (0.1 m)
Cast Concrete (0.07 m)	XPS Extruded Polystyrene (0.02 m)
XPS Extruded Polystyrene(0.02 m)	Cast Concrete (0.1 m)
Cast concrete (0.07 m)	Plaster (0.002 m)
Plaster (0.002 m)	

Table 1: Main walls and roof stratigraphy

Figure 7: Base case results

377 Prior to carrying out the parametric analysis, some preliminary oper-  
378 ations were conducted:

- 379 • Exporting the .idf file, that is the EnergyPlus input script file, from  
380 DesignBuilder (EnergyPlus 8.1 version);
- 381 • Using IDFVersionUpdater, an EnergyPlus tool, it was possible to  
382 convert the .idf file into an EnergyPlus 8.2 version file (last release  
383 when the operations were done).

384 Then jEPlus requires three input files:

- 385 • Weather data file (.epw format): the same used in DesignBuilder;
- 386 • The .idf file;
- 387 • The .rvi file: this file defines the required output variables. It can  
388 be generated by the EnergyPlus tool ReadvarsESO.

389 *3.2. Results of the model without calibration (base case)*

390 In this paragraph a comparison between the real thermal consumption  
391 and the base case simulated one is carried out as reported in Figure 7.

392 After the construction of real and simulated energy signatures, the  
393 quality of the model is evaluated through the proposed error indexes  
394 reported in Table 2.

395 From a graphical point of view, Figure 8 shows the comparison be-  
396 tween the real (solid line) and simulated energy (dashed line) signatures

Error index	Value
<b>RMSE</b>	$1.251 \cdot 10^4$
<b>SAE</b>	0.064

Table 2: Error indexes of base case model

397 for the uncalibrated model.

398

Figure 8: Real (solid line) and base case (dashed line) energy signature

399 It is possible to observe that, on average, the real consumption is  
 400 higher than the simulated one, although both are characterized by similar  
 401 trends.

### 402 3.3. First batch of simulations results

403 After the first parametric analysis, 176 simulations were performed, in  
 404 which the set-point temperature and the ventilation/leakage were varied.  
 405 In order to facilitate the comprehension of the influence of the chosen  
 406 parameters on the calibration errors, Figure 9 was drafted plotting in a  
 407 three dimensional graph all the results of the first batch of simulations.  
 408 The graph shows the influence of both set-point and leakage on the SAE.

409

Figure 9: First batch of simulations results - SAE, rotation 1

Figure 10: First batch of simulations results - SAE, rotation 2

410 In Figure 9 it is possible to observe that the mutual variation of the  
 411 two parameters correspond to an homogeneous trend of the error value.

412 The semi-transparent horizontal plan sections the surface dividing it into  
413 two areas. The area under the plane contains all the most representative  
414 simulations with a SAE less than 10%.

415 Figure 10 was obtained as a rotation of Figure 9 and it shows that there  
416 is only one absolute minimum for the SAE function.

417 The presence of a singular point of absolute minimum is welcome because  
418 it could represent the parameters set that most accurately calibrate the  
419 model. For the first step of calibration this set was found to be: temper-  
420 ature set-point of  $20.5^{\circ}C$  and a ventilation/leakage of 1.6 Vol/h. From  
421 an opposite point of view, each other combination of the two parame-  
422 ters present in the plot represents a "possible superstore" where different  
423 temperature and leakage were set.

424 Similarly to what was discussed about Figure 9 and 10, Figure 11 shows  
425 the 3D graph in which the two varied parameters are related to the  
426 RMSE.

427

Figure 11: First batch of simulations results - RMSE

428 This graph as well as the previous one shows an absolute minimum  
429 for the error, that, again, corresponds to a temperature of  $20.5^{\circ}C$  and a  
430 ventilation/leakage of 1.6 Vol/h. In this way it is possible to identify the  
431 singular parameter combination which leads to a minimization of both  
432 error indexes simultaneously. Table 3 shows the comparison between the

Figure 12: Absolute minimum solution results

433 real case and the calibrated model in terms of thermal energy consump-  
 434 tion. In Figure 12 the two minimized error indexes calculated for the  
 435 calibrated simulation are reported.

Error index	Value
<b>RMSE</b>	$1.213 \cdot 10^4$
<b>SAE</b>	0.013

Table 3: Absolute minimum solution errors

436 In Figure 13 a comparison between real (solid line) and simulated  
 437 (dashed line) energy signatures is shown.

438

Figure 13: Best solution of 176 simulations energy signature

439 It is possible to observe that the energy signature of this calibrated  
 440 model is closer to the real energy signature than the base-case signature  
 441 was. Furthermore the value of 1.6 Vol/h outlines that the building can  
 442 easily benefit from a better control of ventilation and leakage air flows.  
 443 The flow rate calculated through the calibration is high enough to satisfy  
 444 the requirements described in the UNI 10339 that suggests 0.25 Vol/h for  
 445 this superstore and high enough to meet the requirements for air quality  
 446 level specified by EN 13779. Therefore simple solutions like the use of  
 447 power-inverter-driven AHU motors controlled by the CO<sub>2</sub> levels in the  
 448 return air can generate remarkable savings for this building.



## 449 3.4. Second batch of jobs simulations

450 After the previous 176 simulations, a thickening has been performed  
451 in the neighborhood of the values of temperature that most accurately  
452 calibrated the model in the first batch of jobs. Forty simulations were  
453 held, as depicted in section 2.2 varying the set-point temperature in the  
454 range of 20-21 °C. Figure 14 shows the graph which relates the two varied  
parameters to the SAE.

455 Figure 14: Second batch of simulations results - SAE

456 Even after the thickening, Figure 14 shows how the mutual variation  
457 of the two parameters correspond to an homogeneous trend of the er-  
458 ror value. As well as in the previous graphs, the semi-transparent plan  
459 which sections the multicolor surface delimitates an area in which the  
460 simulated consumption are representative of those of the building. This  
461 plan correspond to a value of SAE of 10%. Also for this batch of job sim-  
462 ulations, it is possible to highlight in Figure 14 that there is an absolute  
463 minimum for the SAE function. The combinations of parameters which  
464 have a  $SAE < 10\%$  are around the absolute minimum, which corresponds  
465 to a temperature of 20.6 ° C and a ventilation/leakage of 1.6 Vol/h. In  
466 this case also, each of the other combinations of the two parameters  
467 represents a possible intervention for the building model.

468 Figure 15 reports the graph in which the two varied parameters are  
469 related to the other error index, the RMSE. There is an absolute mini-

Figure 15: Second batch of simulations results - RMSE

Figure 16: Absolute minimum solution results (Second batch of jobs)

470 mum for the RMSE, it corresponds to a temperature of 20.6 ° C and a  
 471 ventilation/leakage of 1.6 Vol/h. Also in this case it is possible to iden-  
 472 tify the singular parameter combination which leads to a minimization  
 473 of both error indexes simultaneously. In Figure 16 a comparison between  
 474 the real and this simulated consumption is shown.

475 In Table 4 the two minimized error indexes calculated for this sim-  
 476 ulation are reported. In particular the SAE index is reduced the most  
 477 during the calibration process (from 0.064 to 0.011). The RMSE was also  
 478 reduced during the calibration but the reduction was less pronounced. In  
 479 Figure 17, the final comparison between real (solid line) and simulated  
 (dashed line) energy signatures is shown.

Figure 17: Best solutions of 40 simulations energy signature

480

481 3.5. Best solution and possible uses of the model

482 From the results of the analysis it is possible to identify an absolute  
 483 minimum for the SAE and an absolute minimum for the RMSE; these  
 484 values lead to the convergence of the solution that minimizes both er-

Error index	Value
<b>RMSE</b>	1.206·10 <sup>4</sup>
<b>SAE</b>	0.011

Table 4: Absolute minimum solution errors (Second batch of jobs)

485 rors simultaneously, which correspond to the combination of a set-point  
486 temperature of 20.6 °C and a Ventilation/leakage of 1.6 vol/h. This  
487 combination is the best solution that enables significant reduction of the  
488 error indexes and it can be considered the combination of parameters  
489 that leads to the calibration of the model. The calibrated model has  
490 an energy signature almost coincident with that of the real case, with  
491 an error less than 1%. This value is significantly lower than the value  
492 calculated for the first batch of jobs simulations.

493 Once the model is calibrated it can be used for two main purposes:

- 494 • The standard use of a calibrated model consists in testing possible  
495 improvements on it before moving forward with their real implemen-  
496 tation
  
- 497 • A different consequence of the proposed methodology is the indirect  
498 evaluation of some values that were impossible to define during the  
499 survey. In the case study investigated in this work, the calibration  
500 allowed to define the real air change and temperature set-point val-  
501 ues. A comparison between these values and the design or optimal  
502 ones helps to immediate define primary actions to control energy  
503 consumption reductions based on ventilation, infiltration and tem-  
504 perature control.

#### 505 4. Conclusions

506 The calibration method proposed in this work produced effective and  
507 reliable outputs as a result of the synergy between the energy signature  
508 tool, for evaluation of the modeling results, and the parametric multiple  
509 simulations approach carried out by means of jEPlus. The model was  
510 based on data collected through the survey. The final result is a building  
511 dynamic model which represents the dynamic behavior of the real case  
512 well, with an error around 1%. The evaluation and consequent calibra-  
513 tion were based on two different errors: the SAE and the RMSE. The  
514 concomitant minimization of both errors guarantees the reliability of the  
515 optimal calibration set of parameters found. This study also outlined the  
516 importance of a correct tuning of the user-dependent parameters like air  
517 leakage and temperature set-point that are difficult to evaluate during  
518 the survey and that can considerably change the energy consumption of  
519 the building. The method proposed here can be extended to others dy-  
520 namic simulation software because it is not customized on Design Builder  
521 or jEPlus platforms.

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- Parametric analysis is used together with the energy signature for calibration of the model
- Statistic indexes are used to determine the best calibrating solution
- The calibrated solution allows to define better use of the HVAC system

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