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1 **Combined use of dynamic building simulation and metamodeling**
2 **to optimize glass facades for thermal comfort**

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21 Combined use of dynamic building simulation and metamodeling

22 to optimize glass facades for thermal comfort

23 Abstract

24 The primary objective of buildings must be to provide a comfortable environment for people.
25 Recently, glass facades have gained popularity due to their aesthetic appearance. However, Low
26 performance facades often allow substantial heat exchange between the indoor and outdoor
27 environment that increases building energy consumption and rapid change in indoor thermal
28 environment near the glass façade. Thus, adequate design of building envelope, namely glass facades,
29 is essential to ensure a trade-off between several aspects, such as aesthetic appearance of the building,
30 occupants' thermal and visual comfort and energy consumption. The main purpose of this study is to
31 quantify the interactions and optimize building design, particularly glass facades, for thermal comfort
32 based on the combined use of numerical simulations, Design of Experiments (DoE) technique and an
33 optimization method. The proposed approach is applied to a real case study, characterized by two glass
34 facades, after subjectively assessing thermal comfort using survey questionnaire. For the analysis, a
35 previously developed and validated dynamic simulation model is used. The combined use of
36 numerical simulations and DoE aims to determine the critical parameters affecting thermal comfort,
37 and to develop meta-modeling relationships between design factors and response variables. The
38 developed meta-models are then used to determine a set of optimal solutions by performing a
39 simultaneous optimization of building design based on the desirability function approach. The results
40 indicate that the optimized design improve thermal comfort conditions as well as energy-savings.
41 Finally, the results show the added value of the proposed methodology towards enhanced thermal
42 comfort conditions.

43 Keywords: PMV, design of experiments, meta-models, sensitivity analysis, numerical
44 simulations, desirability function

45 Nomenclature

46	CI	Clothing Insulation
47	D	Global desirability function
48	IQR	Inter Quartile Range
49	MR	Metabolic Rate
50	MRT	Mean Radiant Temperature
51	PMV	Predicted Mean Vote
52	PPD	Percentage of Persons Dissatisfied
53	Q	Quartile
54	SHGC	Solar Heat Gain Coefficient
55	TS	Thermal Sensation

56	TSV	Thermal Sensation Vote
57	WFR	Window-Floor-Ratio
58	WWR	Window-Wall-Ratio
59	C_i	Regression coefficients
60	d_i	Individual desirability function
61	e_i	Residual
62	r_i	Weighting parameter
63	R^2	Coefficient of determination
64	X_i	Independent coded factor
65	y_i	Actual observation
66	\hat{y}_i	Fitted value
67	Y_i	Predicted response variable
68	ε	Random error term

69 **1. Introduction**

70 Over the last decade, the buildings sector was responsible for 40% of the European
71 Union (EU28) final energy consumption in front of transport (33.2%) and industry (25%) [1].
72 This concern has led the Energy Performance of Buildings Directive (EPBD) to state that the
73 energy efficiency of existing buildings must be improved, and all new buildings must be close
74 to zero energy in 2020 [2]. However, the primary objective of buildings must be to provide a
75 comfortable environment for the people, since they spend 80-90% of the day indoors [3].
76 Additionally, inappropriate indoor thermal comfort leads to lower work efficiency, higher
77 possibility of personnel errors, and indirect effect on the energy consumption of the buildings
78 [4]. Therefore, it is necessary to design low energy buildings in order to fulfil a trade-off
79 between energy-saving and occupants' thermal comfort [5]. Thermal comfort is defined as

80 “that condition of mind which expresses satisfaction with the thermal environment”[6,7].
81 Among all the standard thermal comfort indices [8], Fanger’s [9] Predicted Mean Vote
82 (PMV) and Percentage of Persons Dissatisfied (PPD) are the most applicable indices that can
83 be used to evaluate the thermal comfort within an air conditioned space and to quantify its
84 value [10].

85 In recent years, glass facades and extensive glazing areas are becoming more popular
86 for office, public and educational buildings due to their aesthetic appearance as well as
87 because of users’ requirement of higher light transmittance and better view [11]. However,
88 poorly designed glass facades vastly affect occupants’ thermal comfort, because of the large
89 hot surfaces resulting from dissipated solar radiation [12]. For instance, a high intensity of
90 solar radiation leads to an increase in the interior surface temperature of the glass facade,
91 which leads to an increase in the mean radiant temperature (MRT) and ultimately affecting
92 occupants’ thermal comfort [13].

93 Numerous studies have been conducted to investigate the influence of glass facade
94 design on building energy consumption [14–18], thermal comfort [19–22] and visual comfort
95 [18,22–26]. The vastly investigated parameters are Window-Wall-Ratio (WWR), glazing
96 properties (U-value, solar heat gain coefficient (SHGC) and visible transmittance), and
97 shading device. Thalfeldt *et al.* [14] investigated several facade designs in nearly zero energy
98 building; the study indicated that the performance improved significantly when improving the
99 thermal properties of the window. Poirazis *et al.* [15] carried out building energy simulations
100 for extensive amount of scenarios combining different glazing types and shading solutions for
101 an office building with fully glazed facades, the study concluded that the buildings with fully
102 glazed facades are likely to have higher energy consumption than those with conventional
103 facades. Jin and overend [16] carried out a comparative study on 13 glazing types on the
104 facade of a typical cellular office, the study indicated that high-performance glazing

105 technologies, such as photovoltaic integrated glazing, offer significant improvements over
106 opaque insulated walls and conventional insulated glazing windows, even for extensive
107 glazed envelope, in terms of both energy consumption and indoor environmental quality. Lee
108 *et al.* [17] investigated the effect of window systems on the energy consumption of buildings
109 in five typical Asian climates using regression analysis; the main finding of the investigation
110 is that the WWR must be minimized except for the north facing opaque wall, and the
111 placement of window depends hugely on the climatic conditions. Cheong *et al.* [26]
112 performed comparative simulation study to evaluate the effect of glazing system type on both
113 thermal comfort and daylighting in a highly glazed residential building. The study indicated
114 that improving the glazing type reduces the cooling load and electricity cost. Stavrakakis *et al.*
115 [21] presented a novel computational method to optimize window design for thermal comfort
116 in naturally ventilated buildings. They found that as one of the openings' height increases,
117 thermal sensation is improved. Zomorodian and Tahsildoost [22] assessed the effect of
118 window design on thermal and visual comfort using dynamic simulations in an educational
119 building. The results of the study suggested that solar-control coated glazing with low SHGC
120 and high visual transmission could be an alternative solution to solar shadings. Tzempelikos
121 *et al.* [19] investigated the effect of changing glazing type and shading device on indoor
122 thermal comfort and energy consumption in an office building with extensive glazing area.
123 The study concluded that both thermal resistance and solar transmittance have a huge effect
124 on thermal comfort.

125 The overwhelming majority of the aforementioned studies were performed using
126 building simulation tools, since on one hand, the performed investigations require extensive
127 amount of scenarios to outcome robust results and experimentation could be extensive and
128 time consuming, and on the other hand, building simulation tools have been recognized as a
129 broadly approved method for assessing indoor air quality and energy consumption [27–29].

130 In addition, parametric studies have been used to investigate the proposed scenarios.
131 Although parametric studies provide solid outcomes regarding the influential parameters
132 affecting the studied response, it is of limited accuracy in terms of achieving optimal solutions
133 because it is not continuous and it is hard to identify the interactions between parameters
134 unless a huge number of simulations are performed. In order to overcome this limitation, the
135 numerical results could be used to form a database allocated for meta-modeling process
136 [21,30]. Mathematical meta-models can convert the discretized domain into a continuous one,
137 thus serving as a practical tool, which improves the accuracy of the near-optimal solution
138 without the need of excessive computational power [21]. In recent years, Design of
139 Experiments (DoE) technique has been used with success in the building domain to develop
140 meta-modeling relationships between design factors and response variables [30,31]. Static
141 indoor air temperature was assumed in these studies, even though thermal comfort is more
142 than just an air temperature [32]. To the authors' best knowledge, no previous study deals
143 with the coupling of numerical simulation, DoE and optimization approach to predict thermal
144 comfort as a function of glass facade configuration and other environmental parameters in
145 order to optimize glass facades design for thermal comfort.

146 In this consequence, the objective of this study is to optimize building design,
147 particularly glass facades, for thermal comfort based on the combined use of numerical
148 simulations, DoE technique and desirability function approach. A single room representing a
149 part of an academic low energy building is selected for the investigations. Additionally, a
150 previously developed and validated dynamic simulation model is used for the analysis
151 [13,33]. Afterwards, the DoE is employed for several objectives. At first, it helps analyze the
152 sensitivity of the PMV index to different parameters. In addition, it allows developing meta-
153 modeling relationship between the PMV index and the investigated parameters. Finally, the

154 developed meta-models are validated using several approaches and then utilized to optimize
155 glass facades design for thermal comfort.

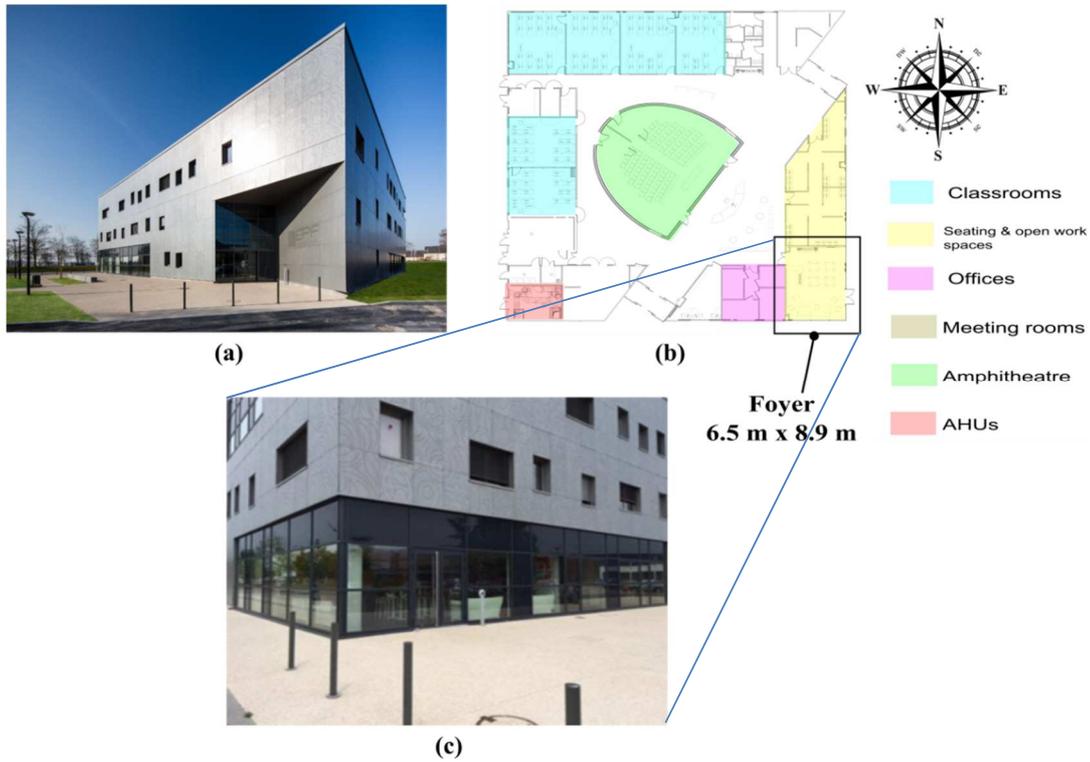
156 **2. Case Study**

157 The considered case study is a highly glazed room, called the foyer, which includes
158 café and seating space. It is a communal place of life in which students meet to eat, rest, and
159 do activities. It is situated in the south-eastern part of the ground floor of a low energy
160 consumption building located in Troyes, France, and designed to meet the French standard
161 requirement RT2012 (Figure 1). The Foyer has a floor area of 58m² and south- and east-
162 oriented glass facades. It is heated by radiators and a dual-flow ventilation system that
163 contains three Air Handler Units integrating heating coils to enable heating and ventilation.
164 Dimensions as well as the physical parameters of the Foyer are summarized in Table 1.

165 Students occupying the Foyer reported a significant difference in temperature from
166 that in other parts of the building and indicated dissatisfaction in the thermal conditions. In
167 order to confirm this allegation, subjective thermal comfort was assessed using survey
168 questionnaire by asking the students to express their thermal sensation, preference and
169 satisfaction. Thermal sensation vote (TSV) was evaluated using the ISO seven-level scale
170 [6,34]. Thermal preference was assessed using a seven-point scale: ‘a lot more cooler’, ‘more
171 cooler’, ‘a bit more cooler’, ‘no change’, ‘a bit more warmer’, ‘more warmer’ and ‘a lot more
172 warmer’. Thermal satisfaction was evaluated using two levels: ‘satisfied’ and ‘dissatisfied’. In
173 addition, students’ activity level was determined using a five-point scale: ‘seated quiet’,
174 ‘standing relaxed’, ‘light activity’, ‘medium activity’ and ‘high activity’. The survey
175 questionnaire, entitled “Current Thermal comfort in the Foyer”, was constructed using the
176 *surveyplant* website [35]. In total, 54 questionnaires were collected and analyzed from
177 students between the ages of 17-22 during December 2016 (From 1st until 12th). It is worth

178 noting that the building was occupied by 281 students and staff members in 2016 [33]. Thus,
 179 the collected questionnaires represent a sample of 90% confidence interval and 10% margin
 180 of error.

181



182

183 Figure 1: Engineering school building overview (a), ground floor map (b) and the Foyer (c).

184 Table 1 : Brief description of the Foyer's characteristics

Location	Troyes, France (latitude 48.2°N, longitude 4.07°E)
Net area	58.0m ²
Dimensions	6.525m x 8.9m
Ceiling height	2.54m
Orientation	South and east facing glass facades
Roof	U-value = 0.4W.m ² .K ⁻¹
Internal wall	U-value = 4.1W.m ² .K ⁻¹
Glass facade	Window Floor ratio = 0.6; double glazing with U=2.8W.m ² .K ⁻¹ and SHGC=0.6; equipped with internal shading.
Internal gains	Light=3.6W.m ² , occupancy=0.2person.m ² , appliance=2W.m ²
Operating hours	All days: 8am–8pm
HVAC	
(a)Ventilation	Supply air temperature 20°C, heat recovery system efficiency 66% Air volume flow rate 208m ³ .h ⁻¹
(b)Radiators	Supply water temperature function of outdoor temperature Maximum water volume flow rate 0.1m ³ .h ⁻¹

185 **3. Methodology**

186 **3.1. Design of Experiments**

187 An Experiment is defined as test in which purposeful changes are made to the input
188 parameters of a system/process so that the experimenter may observe and identify the reasons
189 for changes in the response variable [36]. Poorly designed experiments can often lead to
190 ineffective use of valuable resources and inconclusive results. Hence, experiments should be
191 well-designed. One-factor-at-a-time is a popular approach, in which the influence of the tested
192 parameters is measured by changing the level of one parameter while maintaining other
193 parameters at their levels [37]. The major disadvantage of this method is that it fails to
194 consider any possible interaction between the parameters [37]. Contrarily, in the DoE
195 approach, the influence of each parameter on the studied process is measured simultaneously
196 on several levels of all other parameters, thus taking into consideration all the occurring
197 interactions between parameters [36].

198 The DoE technique is a statistical method used to approximate the mathematical
199 relationship between different factors affecting several response variables, and most often one
200 response variable. It can be used to simplify parametric studies by significantly reducing by
201 the required number of experiments or simulations [30]. The obtained mathematical models,
202 also known as meta-models, can be used instead of numerical simulation tools to simplify and
203 accelerate the parametric studies to find optimal solutions. It is also utilized to analyze the
204 effect of each factor on the response variable and the interaction between factors. To
205 implement DoE technique, the following steps should be followed [36,38]:

- 206 1. Recognition and statement of the problem.
- 207 2. Selection of the response variable
- 208 3. Choice of factors, levels, and ranges

- 209 4. Choice of experimental design
 210 5. Performing the experiment
 211 6. Statistical analysis of the data
 212 7. Conclusions and recommendations

213 The Analysis of Variance (ANOVA) in combination with Fisher’s statistical test (p-
 214 value < 0.05) can be used to test the significance of the model along with model terms. The
 215 significance of a factor or its effect is determined based on its P-value. If the P-value of a
 216 factor is less than 0.05, it is considered as significant [39]. Additionally, graphical
 217 illustrations, such as the Pareto charts and the normal plots of standardized effects, can be
 218 utilized to identify the significant terms.

219 3.2. Meta-modeling and regression coefficients

220 One of the main objectives of the DoE technique is to pursue a suitable mathematical
 221 model, called “meta-model”, which approximates the response variable as a function of
 222 predefined factors. The most common meta-models are the first-order linear model, the linear
 223 model with interaction terms, the pure quadratic model, and the complete quadratic model,
 224 successively expressed as follows [36]:

$$Y_i = C_0 + \sum_{i=1}^n C_i X_i + \varepsilon \quad (1)$$

$$Y_i = C_0 + \sum_{i=1}^n C_i X_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^n C_{ij} X_i X_j + \varepsilon \quad (2)$$

$$Y_i = C_0 + \sum_{i=1}^n C_{ii} X_i^2 + \varepsilon \quad (3)$$

$$Y_i = C_0 + \sum_{i=1}^n C_i X_i + \sum_{i=1}^{n-1} \sum_{j=i+1}^n C_{ij} X_i X_j + \sum_{i=1}^n C_{ii} X_i^2 + \varepsilon \quad (4)$$

227

228 where Y_i is the predicted response variable, X_i , X_j and X_iX_j are the independent coded factors
229 and the two-factors interaction, C_0 , C_i , C_{ii} , and C_{ij} represent the regression coefficients for
230 intercept, linear, quadratic and interaction terms, respectively, and ε is a random error term
231 that accounts for the experimental error. Indeed, the transition from dimensional to coded
232 factors must be made by applying the following formulation:

$$X_i = \frac{x_i - (x_{i,high} + x_{i,low})/2}{(x_{i,high} - x_{i,low})/2} \quad (5)$$

233 where X_i is the coded value of the variable x_i ranging between -1 and +1, and $x_{i,low}$ and
234 $x_{i,high}$ are the values of the variable at low and high levels, respectively. Simple matrix
235 multiplication is then used to determine the coefficients of the meta-model using the least
236 square method [30].

237 **3.3. Meta-models validation**

238 The adequacy of the model, and as a result the performed analysis, can be done by
239 graphical analysis of residuals [36]. The residual (e_i) is defined as the difference between the
240 actual observation (y_i) and the corresponding fitted value (\hat{y}_i):

$$e_i = y_i - \hat{y}_i \quad (6)$$

241 If the model is accurate, the residuals should be “structure-less”; in particular, they
242 should be unrelated to any other variable including the predicted response [36]. A simple
243 check is to plot the residuals versus the fitted values. This plot should not reveal any obvious
244 pattern [36].

245 In addition, a very useful method is “The Normality Assumption”, which is to
246 construct a normal probability plot of the residuals. If the underlying error distribution is
247 normal, this plot resembles a straight line, and thus confirming the validity of the model [36].

248 Moreover, computer programs for supporting DoE display some other useful
249 information. The coefficient of determination (R^2) is loosely interpreted as the proportion of
250 the variability in the data “explained” by the ANOVA model. The “adjusted- R^2 ” is a variation
251 of the ordinary R^2 that reflects the number of factors in the model. It can be a useful statistic
252 for more complex experiments with several design factors when evaluating the impact of
253 increasing or decreasing the number of model terms is desired.

254 The obtained meta-model is used to find desirable results, such as maximizing or
255 minimizing the response variable. However, in many cases the term “desirable” is a function
256 of more than one response. Therefore, a simultaneous optimization procedure is needed to
257 find a compromise solution [40].

258 **3.4. Optimization method**

259 Simultaneous consideration of multiple-responses involves first building an
260 appropriate mathematical model for each response and then trying to find a set of operating
261 conditions, design factors, which in some sense optimizes all responses or at least keeps them
262 in desired ranges.

263 In this consequence, the simultaneous optimization technique, known as the
264 desirability function approach, represents a useful approach to optimization of multiple
265 responses. The desirability function approach proposed by Harrington [41] and then modified
266 and popularized by Derringer and Suich [42] aims to simultaneously optimize multiple
267 equations. Its basic idea is to convert a multiple response problem into a single one by
268 converting each response y_i into an individual desirability function d_i that ranges from zero,
269 if the response is outside the limits, to one if the response is at its target. The individual
270 desirability functions have different formulations depending on the desired objective. If the

271 objective is a maximum, a minimum or a target value, the desirability functions are described,
 272 respectively, by the following equations:

$$d_i^{max} = \begin{cases} 0 & \text{if } y_i < L \\ \left(\frac{y_i - L}{T - L}\right)^r & \text{if } L \leq y_i \leq T \\ 1 & \text{if } y_i > T \end{cases} \quad (7)$$

$$d_i^{min} = \begin{cases} 0 & \text{if } y_i > U \\ \left(\frac{U - y_i}{U - T}\right)^r & \text{if } T \leq y_i \leq U \\ 1 & \text{if } y_i < T \end{cases} \quad (8)$$

$$d_i^{target} = \begin{cases} 0 & \text{if } y_i < L \\ \left(\frac{y_i - L}{T - L}\right)^{r_1} & \text{if } L \leq y_i \leq T \\ \left(\frac{U - y_i}{U - T}\right)^{r_2} & \text{if } T \leq y_i \leq U \\ 1 & \text{if } y_i > U \end{cases} \quad (9)$$

273 where L, T and U are successively the lower, the target and the upper limits, and r_i is a
 274 weighting parameter used to assess the importance for the response to be close to the desired
 275 objective. The individual desirability functions are then combined in the so-called global
 276 desirability function (D) as expressed in Equation (10):

$$D = (d_1 \times d_2 \times \dots \times d_n)^{1/n} = \left(\prod_{i=1}^n d_i \right)^{1/n} . \quad (10)$$

277 Lastly, the algorithm searches for the set of input factors to maximize the overall desirability
 278 function D [43] using the Nelder-Mead simplex method [44].

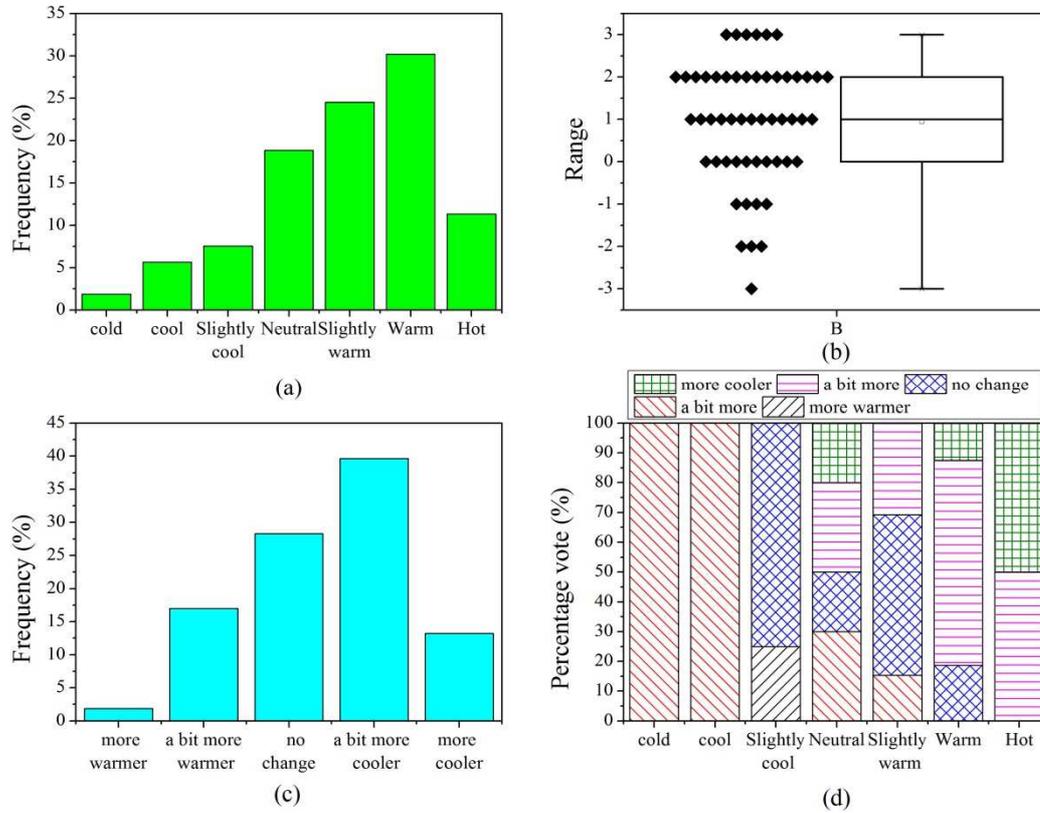
279 **4. Results and discussion**

280 **4.1. Subjective assessment of thermal comfort**

281 *4.1.1. TSV and thermal preference*

282 Using the comfort survey questionnaire, TSV and thermal preference of the students
283 were assessed using the questions “How do you feel inside the foyer?” and “How would you
284 prefer the indoor condition of the foyer to be?” respectively. The distribution of collected
285 subjects’ responses is shown in Figure 2. The results show that the distribution of students’
286 thermal sensations was skewed toward the warm side. The most frequently selected vote was
287 “Warm”. More accurately, about 30 % of the students selected this option. In addition, 24.5%
288 of the votes were for the “slightly warm” option. Further, the frequency for "cold" TSV is
289 very small. To test the statistical significance of this response and the possibility to be
290 considered an outlier, numerous types of possible statistical methods can be used [45,46]. In
291 this study, two different methodologies, known as Tukey’s method and Grubbs' test, were
292 employed to detect outliers in the data. Tukey’s method is based on box plots that identify the
293 first (Q1) and third (Q3) quartiles of the data [45]. The difference between these values is
294 known as the interquartile range (IQR). The range for outlier detection is then established by
295 identifying the inner and upper fences, located at a distance 1.5 IQR below Q1 and above Q3.
296 If the value is less than the lower fence or higher than the upper fence, these values are
297 considered as outliers. The Grubbs' test is a method that uses the approximate normal
298 distribution to detect a single outlier in the dataset [46]. It detects outliers in the dataset
299 through an established hypothesis with two statements – no outlier found or an outlier found
300 in dataset. In our case, the box plot of the TSV (Figure 2b) shows that the “cold” vote lays on
301 the upper fence of the box plot, and the performed Grubbs’ test indicated that the “cold” vote

302 is far from the rest, but is not a significant outlier. Based on these results, the response is not
 303 considered as an outlier.



304

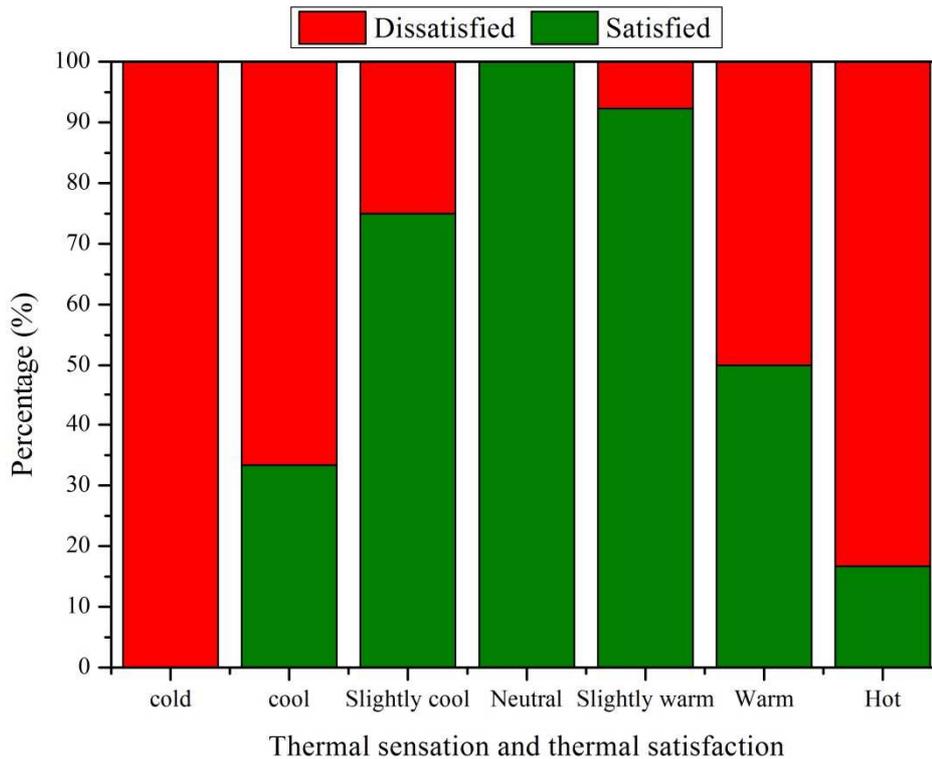
305 Figure 2: Statistical summary of survey questions: (a) TSV, (b) box plot of TSV, (c) thermal
 306 preference and (d) relationship between thermal sensation and thermal preference.

307 The distribution of thermal preference was broadly distributed, but was mainly
 308 concentrated on the “a bit cooler” option. More specifically, about 39% of the students
 309 selected the option “a bit cooler” and about 28% selected the “no change” option. Figure 2d
 310 shows the detailed relationship between thermal preference and thermal sensation. The first
 311 important inference is that the neutral thermal sensation was not preferred by the majority of
 312 students. About 80 % of the students who voted for ‘Neutral’ thermal sensation expressed an
 313 expectation to change the thermal conditions in the Foyer, by voting ‘a bit warmer’, ‘a bit
 314 cooler’, and ‘more cooler’. The second important inference is that students tended to be more
 315 receptive to ‘slightly warm’ conditions. With about 50% of the students who voted ‘slightly

316 warm' did not vote to change the thermal conditions, and 56.25 % of the students who felt
317 'warm' preferred a bit cooler thermal conditions.

318 *4.1.2. TSV and Satisfaction*

319 Thermal satisfaction of the students was evaluated using the question "Are you
320 satisfied with the indoor conditions of the foyer?" it was noted that 37% of the students'
321 responses were dissatisfied. This value is above standards recommendations for the three
322 different levels of acceptable classes of thermal comfort [6,47]. This means that the thermal
323 comfort in the studied room is below expectations. Figure 3 illustrates the thermal satisfaction
324 of the students as a function of TSV. One can observe that a neutral thermal sensation
325 corresponds to the most satisfaction assessment, although 80% of students voted to change the
326 thermal conditions (Figure 2d). These results show that, occupants may ask for cooler or
327 warmer conditions even though they are satisfied with the indoor environment. In addition,
328 when thermal sensation moves from neutral, more votes for dissatisfaction appear in the
329 results. Another important inference is that the students expressed the least dissatisfaction
330 when they felt slightly warm, while more dissatisfaction was expressed when they felt slightly
331 cool. This may have occurred because the students became acclimatized to neutral or slightly
332 warm thermal conditions in winter owing to the wide use of heating systems.



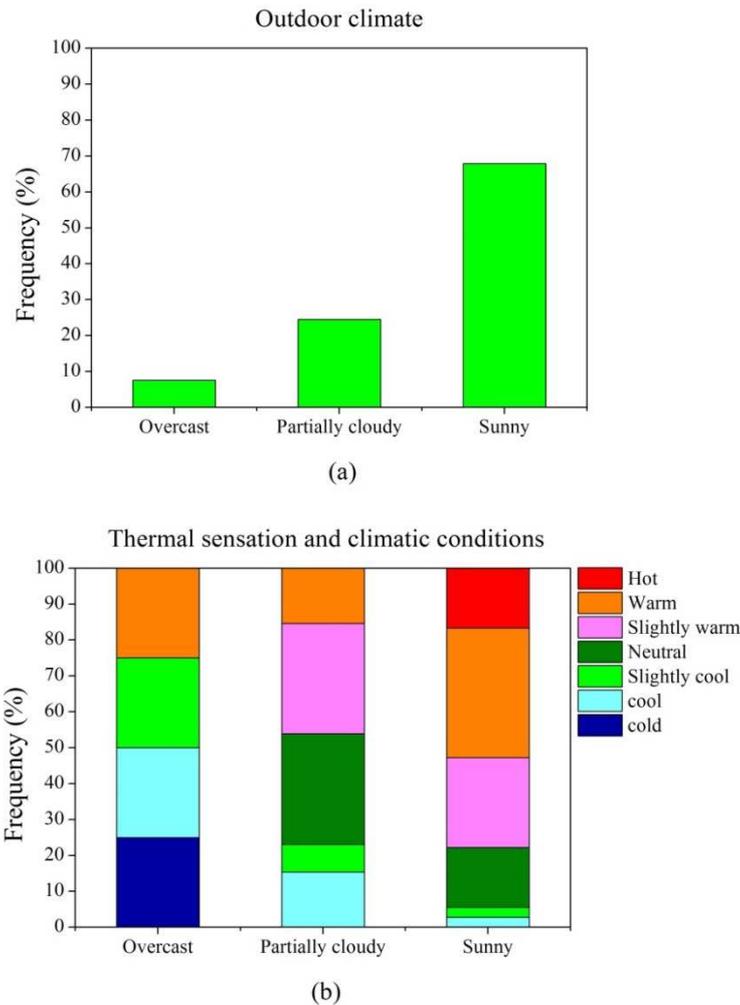
333

334 Figure 3: Relationship between thermal sensation and thermal satisfaction.

335 *4.1.3. TSV and climate*

336 In order to examine the relationship between thermal sensation and outdoor climatic
 337 conditions, the students were asked to answer the question “How would you describe the
 338 weather outside today?” and the three options were: “overcast”, “partially cloudy”, and
 339 “Sunny”. These three options were based on weather data collected by a weather station in
 340 Barberey located 11.5km from the considered case study and are displayed online [48]. Figure
 341 4 shows the distribution of collected responses and the detailed relationship between TSV and
 342 outdoor climate. The results show that the majority of the students, nearly 70%, answered the
 343 survey questionnaire during a winter day with sunny sky. In addition, slightly warm, warm
 344 and hot were voted by the overwhelming majority of the respondent, nearly 80%, who
 345 answered sunny. On the other hand, the results show that during a partially cloud day, about
 346 70% of the respondent voted between “slightly cool” and “slightly warm”. Moreover, the

347 “cold” and “hot” votes appeared only during “overcast” and “sunny” days, respectively.
 348 These results show a wide variation in thermal sensation during different climatic conditions.
 349 These results could be correlated to the presence of fully glazed facades because frequent
 350 changes in the outdoor climate affect the MRT, and eventually students’ thermal comfort.



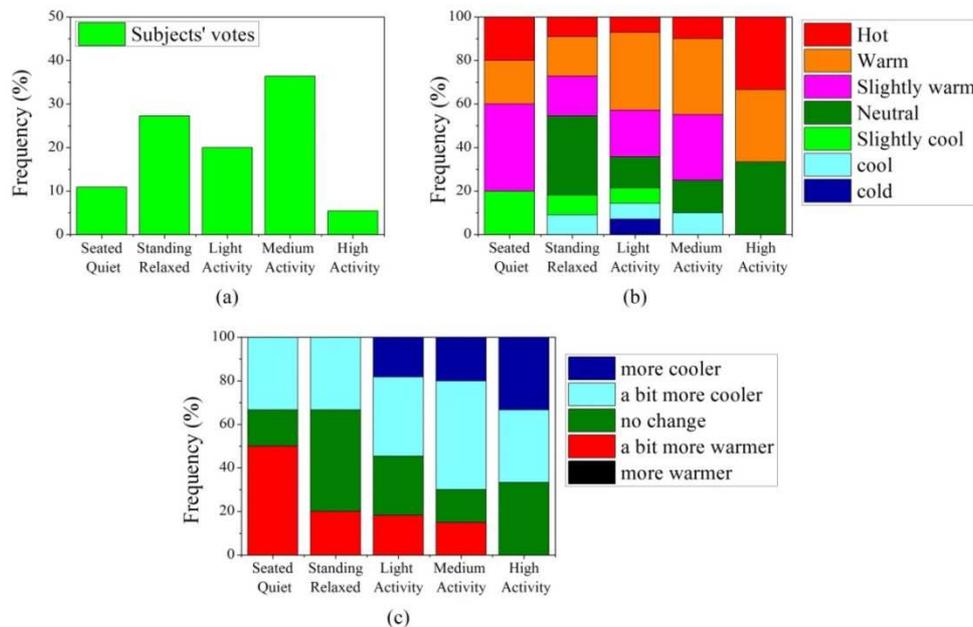
351
 352 Figure 4: Statistical summary of survey questions: (a) outdoor climatic conditions during the
 353 questionnaire time and (b) relationship between thermal sensation and climatic conditions.

354 *4.1.4. Effect of activity level on thermal sensation and preference*

355 Activity level of the students attending the Foyer was evaluated using the question
 356 “How would you describe your activity level in the foyer?” Figure 5 shows the distribution of

357 collected responses, the relationship between activity level and TSV, and the detailed
 358 relationship between activity level and thermal preference. The statistical results show that
 359 students' activity level was broadly distributed, but was centered around the three options
 360 'standing relaxed', 'light activity' and 'medium activity'. The results show that about 60% of
 361 the students' respond with an activity level higher than 'standing relaxed', the assumed
 362 activity level during the design phase. This justifies why the 'warm' option appeared the most
 363 in the TSV.

364 Another important inference driven from the results is that neutral sensation appeared
 365 mainly with the standing relaxed votes and continued in descending order as we move away.
 366 Moreover, 46.6% of the respondents voted 'standing relaxed' preferred no change in the
 367 thermal conditions. Furthermore, the majority of thermal preference for cooler thermal
 368 environment is distributed among the activity levels above the design value, while warmer
 369 thermal preference is concentrated mainly on the seated quiet option.

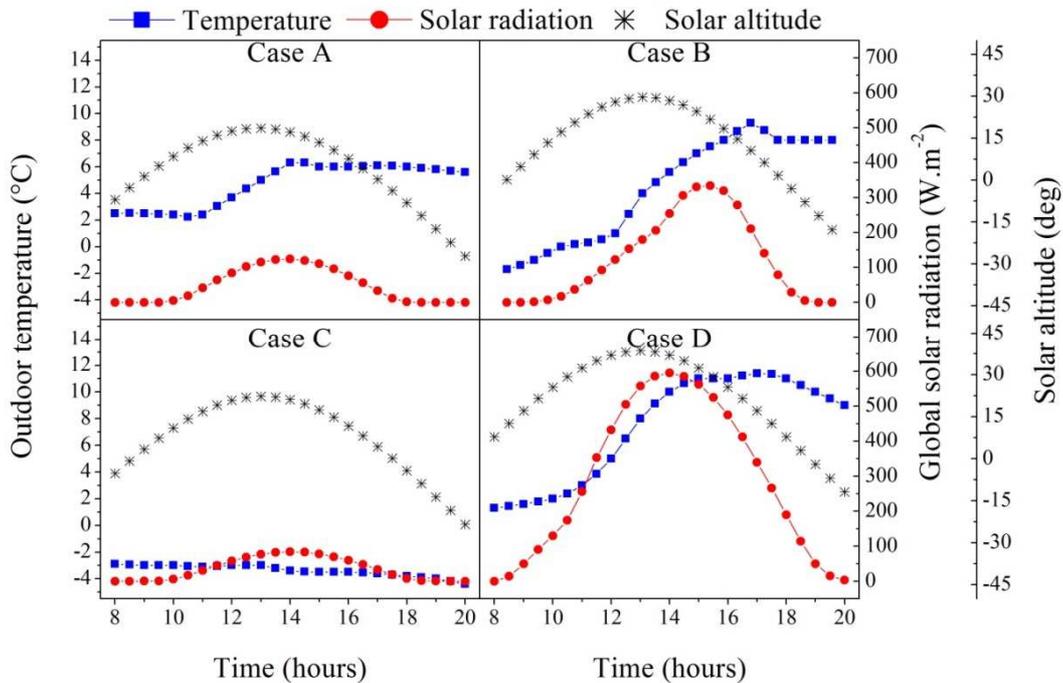


370

371 Figure 5: Statistical summary of survey questions: (a) students' activity level, (b) relationship
 372 between thermal sensation and activity level and (c) relationship between thermal preference
 373 and activity level.

374 **4.2. Thermal comfort assessment using numerical simulations**

375 In order to evaluate and analyze the thermal comfort features of the foyer, a previously
 376 developed and validated numerical simulation model, for the considered case study, was used
 377 [13,33]. The model was developed using Dymola® (Dynamic Modeling Laboratory), a
 378 simulation environment used to translate a Modelica model into an executable program. The
 379 thermal performance simulations highlighted the evolution of the PMV index and the MRT on
 380 four winter days corresponding to bright overcast, partly cloudy, dark overcast and sunny
 381 skies, noted as cases A, B, C and D, respectively. Outdoor temperatures, global solar
 382 radiations and solar altitude angles are illustrated in Figure 6. Case A represents a typical
 383 winter day with no direct solar radiation due to overcast sky. Case B signifies a winter day
 384 with relatively high outdoor temperature and solar radiation. Case C designates a winter day
 385 with low outdoor temperature and weak solar radiation. Case D denotes a winter day with
 386 relatively high outdoor temperature and intense solar radiation.

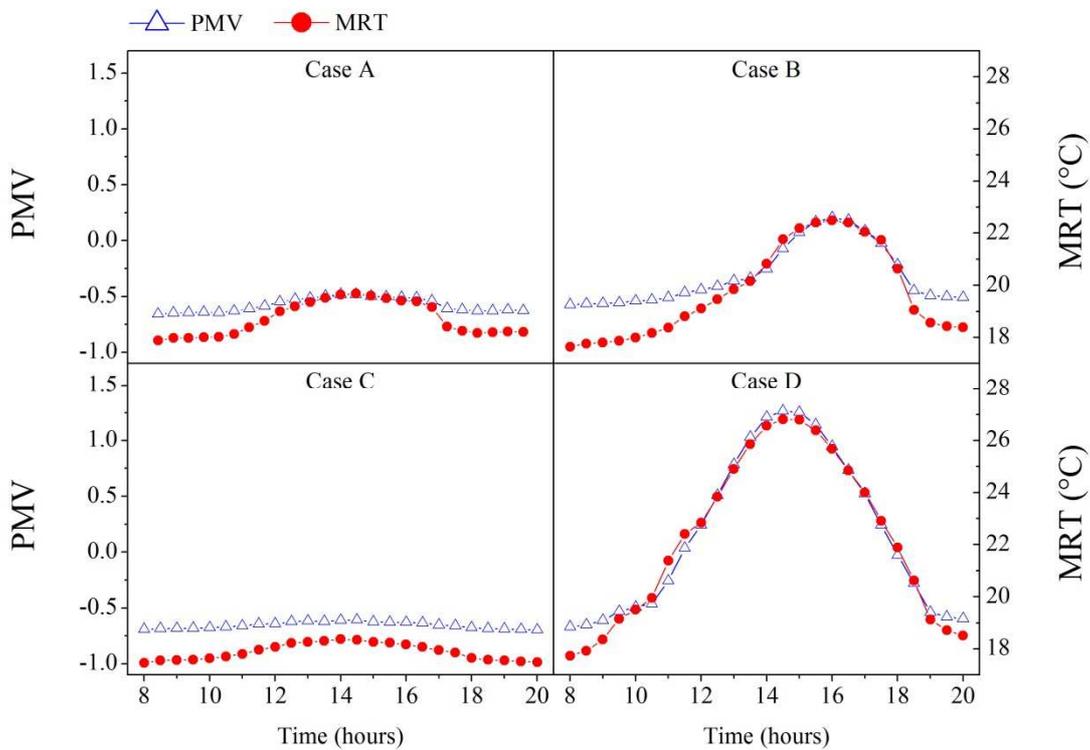


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Figure 6: Outdoor climatic conditions of the four studied days.

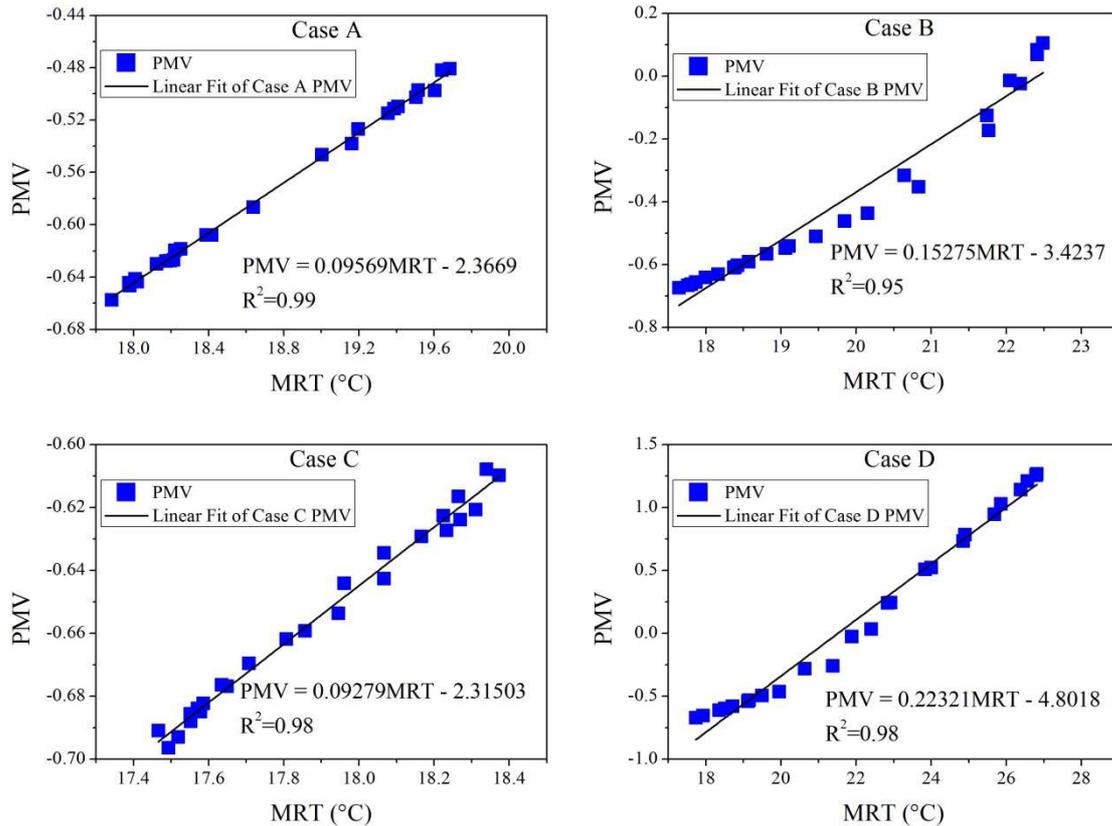
389 PMV index and the MRT of the four studied days are illustrated in Figure 7. For cases
 390 A and B, the PMV index was stable until 10:00; it then started to increase to reach its
 391 maximum when the outdoor temperature and solar radiation reached their maximum at 14:30.
 392 The PMV index then decreased and maintained a stable value. For case C, the PMV index
 393 was below the acceptable comfort range throughout the entire occupied time. However, for
 394 case D, the PMV index exceeded the acceptable upper limit of PMV +0.5.



395

396 Figure 7 : PMV and MRT of the four studied days

397 Figure 7 shows that PMV followed the same trend as the MRT, which also followed
 398 the same trend as the solar radiations. The obtained values of PMV were then correlated with
 399 MRT values to quantify the correlation between both parameters, as shown in Figure 8. A
 400 good correlation is observed showing R^2 values greater than or equal to 0.95, meaning that
 401 more than 95% of variance is explained by the variation of MRT. This indicates that PMV
 402 variations are correlated to the MRT variations due to the presence of extensive glass areas.



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Figure 8 : Correlation between PMV and MRT.

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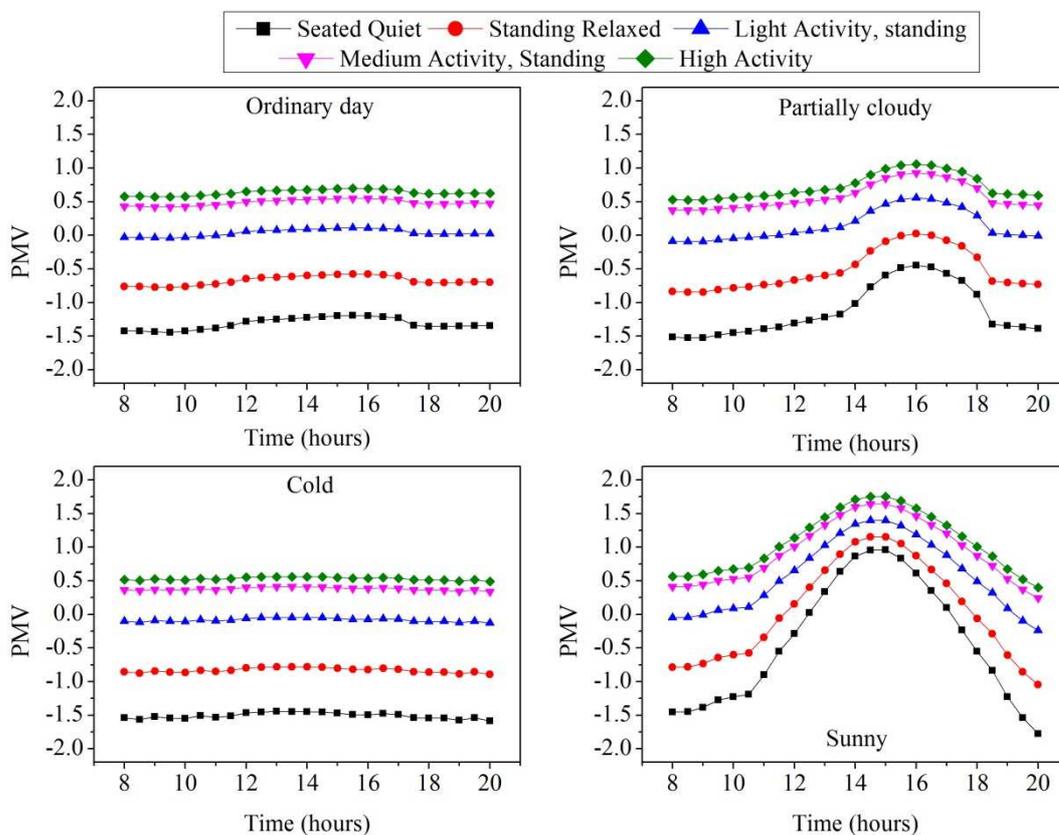
415

416

Moreover, simulation results are in a good agreement with the survey results, and the obtained results justify why 75% of the votes in an overcast day were between “slightly cool” and “cold”. In addition, PMV index results of a day with relatively high outdoor temperature and strong solar radiation confirm the 80% appearance of the three votes, “slightly warm”, “warm” and “hot”.

Furthermore, students’ votes show a different activity level while spending time at the Foyer. In this regards, an investigation using the validated model was carried out to evaluate the effect of activity level on the PMV index during the four studied days. Figure 9 shows the PMV index for the different activity levels. The results show that, for an ordinary or cold winter day, the PMV index falls below the acceptable comfort limits for a student with seated quiet or standing relaxed activity level. However, the PMV index was maintained within the acceptable comfort range for a Light or Medium activity levels, and around the upper comfort

417 limit for high activity level. Additionally, on the day with intense solar radiation, PMV
 418 exceeded the upper comfort limit for all activity levels during the presence of the solar
 419 radiation. These results explain the appearance of different votes and confirm the high
 420 variability of students' thermal sensation during the same period. For example, a student with
 421 low activity level present in the Foyer during the lack of solar radiation may experience a
 422 thermal sensation between "slightly cool" and "cold". However, a student with the same
 423 activity level present in the Foyer during the occurrence of intense solar radiation may
 424 experience a "slightly warm", "warm" or "hot" thermal sensation depending on other factors.



425

426 Figure 9: Effect of activity level on the PMV index in the four studied days

427 To sum up, the subjective assessment of students' thermal comfort in the Foyer show
 428 that less than 65% of the students were satisfied with the thermal environment. The results
 429 show that the variations in thermal sensation are related to several factors, e.g. students'
 430 activity level and climatic conditions, as well as acclimatization to specific thermal

431 conditions. On the other hand, PMV index is directly and indirectly influenced by other
432 factors, e.g. clothing insulation. In this consequence, the proposed approach is applied to the
433 Foyer in order to determine the most critical parameters affecting the PMV value, then to
434 optimize the glass facades configuration for thermal comfort.

435 4.3. Sensitivity study

436 4.3.1. Response variables and choice of factors and levels

437 The response variables are the average daily, maximum, and minimum PMV values.
438 The reason behind the average daily value is that it makes no sense to have a weekly, monthly
439 or yearly PMV value because it can frequently change during the day; in addition the average
440 can be considered as a representative value to replace the hourly values. However, the average
441 value alone, in the case of occupants' feeling, is not meaningful if not complemented by the
442 maximum and minimum values. This helps in determining if the PMV value exceeded the
443 upper or lower acceptable comfort limit.

444 PMV is influenced by room temperature, MRT, relative humidity, air velocity,
445 metabolic rate, and clothing insulation. Relative humidity and air velocity were excluded from
446 the sensitivity study, since PMV was found to be less sensitive for both parameters compared
447 to the four other parameters [49,50]. Besides, since MRT is highly influenced by the outdoor
448 climatic condition, as previously discussed, it was replaced by the sol-air temperature. This
449 last is a parameter defined as “the outside air temperature which, in the absence of solar
450 radiation, would give the same temperature distribution and rate of heat transfer through a
451 wall/roof as exists due to the combined effects of the actual outdoor temperature distribution
452 plus the incident solar radiation” [51]. The sol-air temperature was found to be a good
453 illustration of the weather conditions [52]; its mathematical formulation is presented in
454 [51,53]. Lastly, the effect of the external glass facades on the PMV index was considered

455 using both Window-to-Floor-Ratio (WFR) and glazing type as two independent factors
 456 influencing the response variable.

457 Each considered parameter has a lower (-1) and higher (+1) level. The high level of
 458 the WFR (60%) and glazing type (double glazing with $u\text{-value} = 2.8 \text{ W.m}^{-2}\text{.K}^{-1}$ and $\text{SHGC} =$
 459 0.77) represents the base case study, and the low level, 16% WFR and triple low-emissivity
 460 glazing ($u\text{-value} = 0.7 \text{ W.m}^{-2}\text{.K}^{-1}$ and $\text{SHGC} = 0.3$), has been selected with respect to the
 461 values that are recommended by the French and the European standards [54,55]. The daily
 462 average sol-air temperature was calculated and the minimum and maximum values were
 463 chosen to represent the lower and higher levels. While, the levels of the remaining factors
 464 were selected based on the questionnaire results and the recommended values by the standards
 465 [54,55]. Table 2 reports the considered parameters and their corresponding codes and levels.

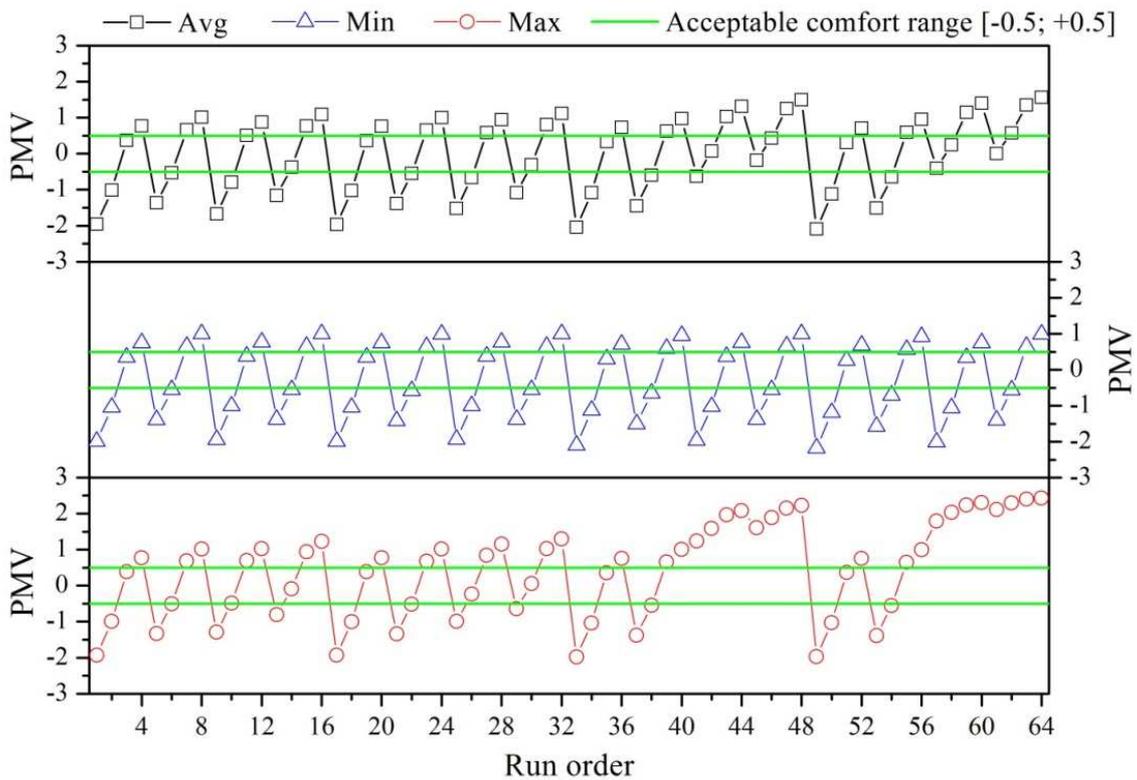
466 Table 2: Investigated factors and their corresponding codes and levels.

Factor	Code	Unit	Level	
			-1	+1
<i>Clothing insulation</i>	<i>A</i>	clo	0.8	1.2
<i>Metabolic rate</i>	<i>B</i>	W.m^{-2}	58	125
<i>Room temperature</i>	<i>C</i>	$^{\circ}\text{C}$	19	21
<i>Sol-air temperature</i>	<i>D</i>	$^{\circ}\text{C}$	-2.2	17.2
<i>glazing type (u-value)</i>	<i>E</i>	$\text{W.m}^{-2}\text{.K}^{-1}$	0.7	2.8
<i>(g-value)</i>			0.3	0.77
<i>WFR</i>	<i>F</i>	%	16	60

467 4.3.2. Choice of experimental design and performing the experiments

468 DoE was performed using a two-level full factorial design. This design considers all
 469 possible factors combination. The full factorial design aims to identify the significant
 470 variables that influence the response variable. In addition, it helps to analyze the interaction
 471 between these factors, and also it offers more precise results compared to fractional factorial
 472 design and avoids specious conclusions [36]. The number of experiments is 2^k , where k is the
 473 number of factors. This design results in 64 experiments to investigate the main effect of

474 factors and their interactions. Additionally, center points were added to the design to examine
 475 the adequacy of the model for capturing the curvature expressed in the response. Figure 10
 476 shows the design matrix (64 runs) and the response variables resulting from the simulation
 477 results (numerical results are reported in Table A of the supplementary information).
 478 Minitab[®] software, a statistical computer package, was used to analyze the data of Figure 10.



479

480 Figure 10: DoE simulation results (each run represents a unique combination of factors levels)

481 *4.3.3. Statistical analysis of the data*

482 ANOVA was carried out in order to identify the significant factors. The results of
 483 ANOVA reported in Table 3, (complete ANOVA tables are reported in Tables B, D and F in
 484 the supplementary information), indicate that the linear and 2-way interactions between
 485 factors are significant, while the remaining interactions and the curvature are not. As a result,

486 the relationship between the investigated parameters and the response variable is deemed to
 487 follow a linear equation.

488 Table 3: ANOVA results for average, minimum and maximum PMV values.

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value
Average PMV						
Model	63	68,4953	68,4953	1,0872	6166,54	0,01
Linear	6	63,4854	63,4854	10,5809	60012,77	0,003
2-Way Interactions	15	4,67	4,67	0,3113	1765,81	0,019
3-Way Interactions	20	0,3354	0,3354	0,0168	95,13	0,081
4-Way Interactions	14	0,0045	0,0045	0,0003	1,8	0,531
5-Way Interactions	6	0	0	0	0,03	0,999
6-Way Interactions	1	0	0	0	0	0,977
Curvature	1	0	0	0	3,29	0,321
Error	1	0,0002	0,0002	0,0002		
Total	64	68,4955	68,4955			
Minimum PMV						
Model	63	74,2413	74,2413	1,1784	4337,36	0,012
Linear	6	72,6844	72,6844	12,1141	44587,27	0,004
2-Way Interactions	15	1,5306	1,5306	0,102	375,56	0,04
3-Way Interactions	20	0,0255	0,0255	0,0013	4,69	0,351
4-Way Interactions	14	0,0008	0,0008	0,0001	0,2	0,957
5-Way Interactions	6	0	0	0	0,02	0,999
6-Way Interactions	1	0	0	0	0	0,982
Curvature	1	0	0	0	0,13	0,777
Error	1	0,0003	0,0003	0,0003		
Total	64	74,2416	74,2416			
Maximum PMV						
Model	63	104,256	104,256	1,6549	1394,38	0,021
Linear	6	82,704	82,704	13,784	11614,36	0,007
2-Way Interactions	15	19,791	19,791	1,3194	1111,74	0,024
3-Way Interactions	20	1,738	1,738	0,0869	73,2	0,092
4-Way Interactions	14	0,023	0,023	0,0016	1,37	0,593
5-Way Interactions	6	0	0	0	0,03	0,999
6-Way Interactions	1	0	0	0	0	0,978
Curvature	1	0	0	0	0,02	0,908
Error	1	0,001	0,001	0,0012		
Total	64	104,257	104,257			

489 The Pareto charts for standardized effects for the average daily, minimum and
 490 maximum PMV values are shown in Figure 11. The bars display the variables and their

491 interactions, where all the bars that exceed the vertical dashed line are considered significant.

492 The results reported in Figure 11 show that the metabolic rate (B) has the highest effect on all

493 the response variables. In addition, the daily average and maximum values were significantly

494 influenced by the daily average sol-air temperature (D), clothing insulation (A), interaction

495 between sol-air temperature and WFR (DF), set-point temperature (C) and WFR (F).

496 However, the minimum PMV value was significantly influenced by clothing insulation (A),

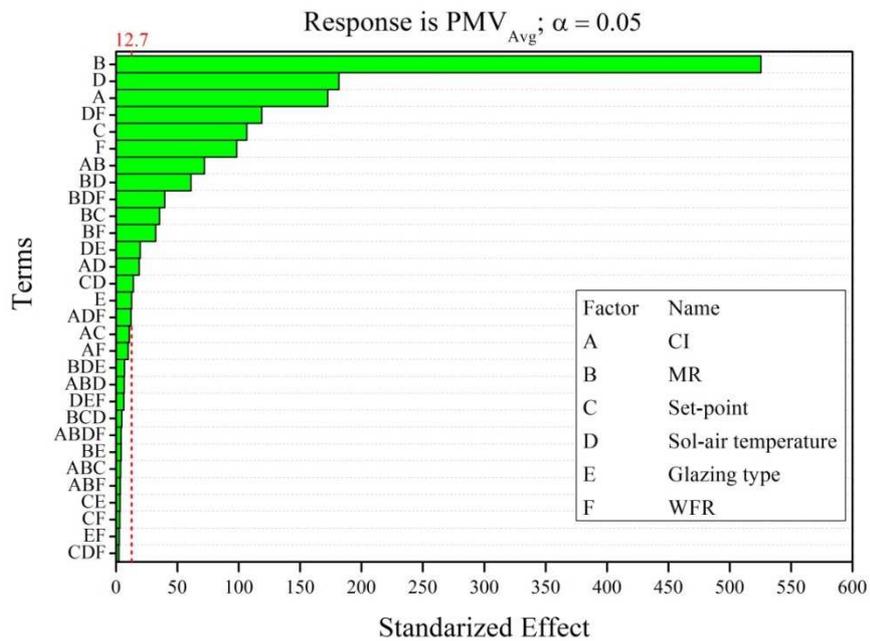
497 set-point temperature (C), interaction between clothing insulation and metabolic rate (AB)

498 and WFR (F), respectively. Effects of other factors and their interactions are in descending

499 order as shown in Figure 11. These results are in a good agreement with the previously

500 discussed results regarding the effect of activity level and outdoor climates on the thermal

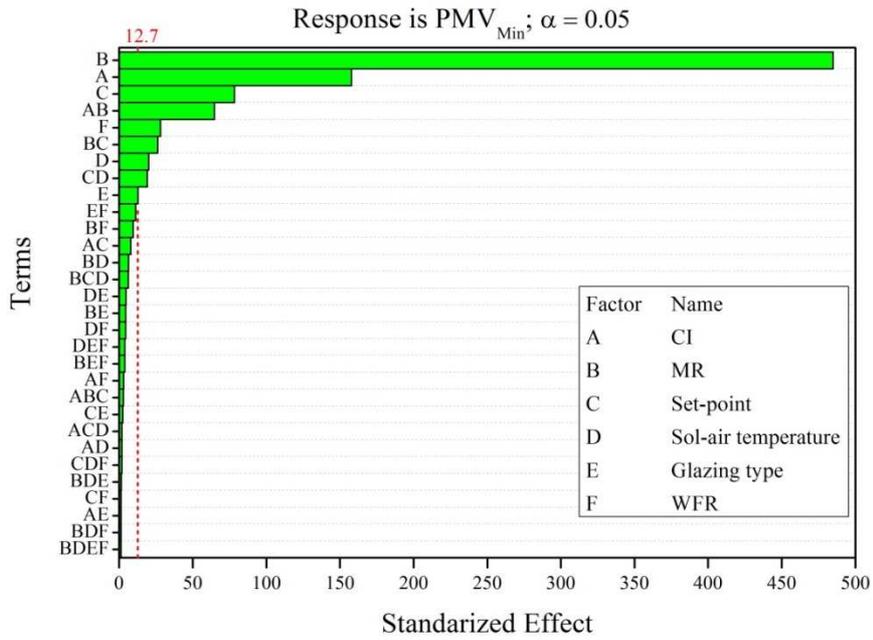
501 sensation of the students.



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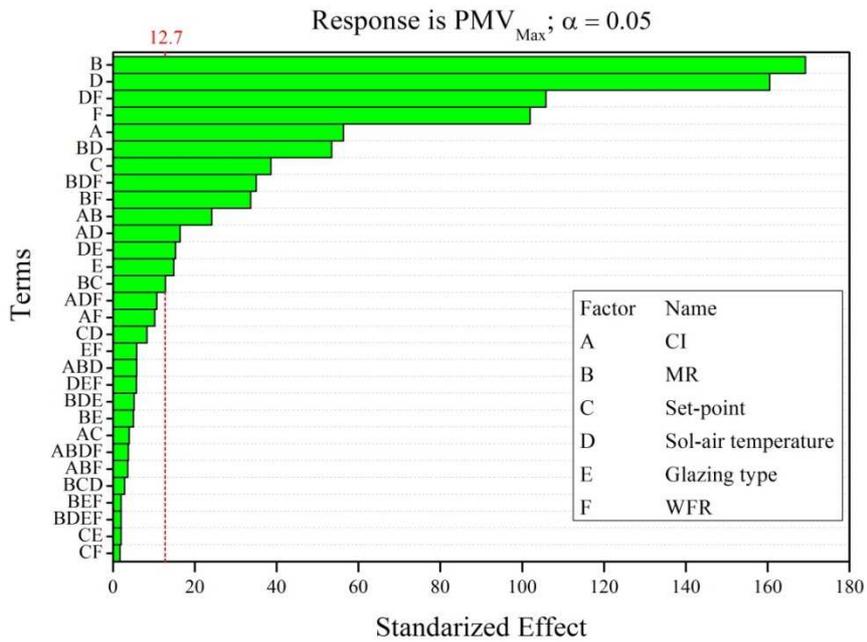
(a)



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(b)



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507

(c)

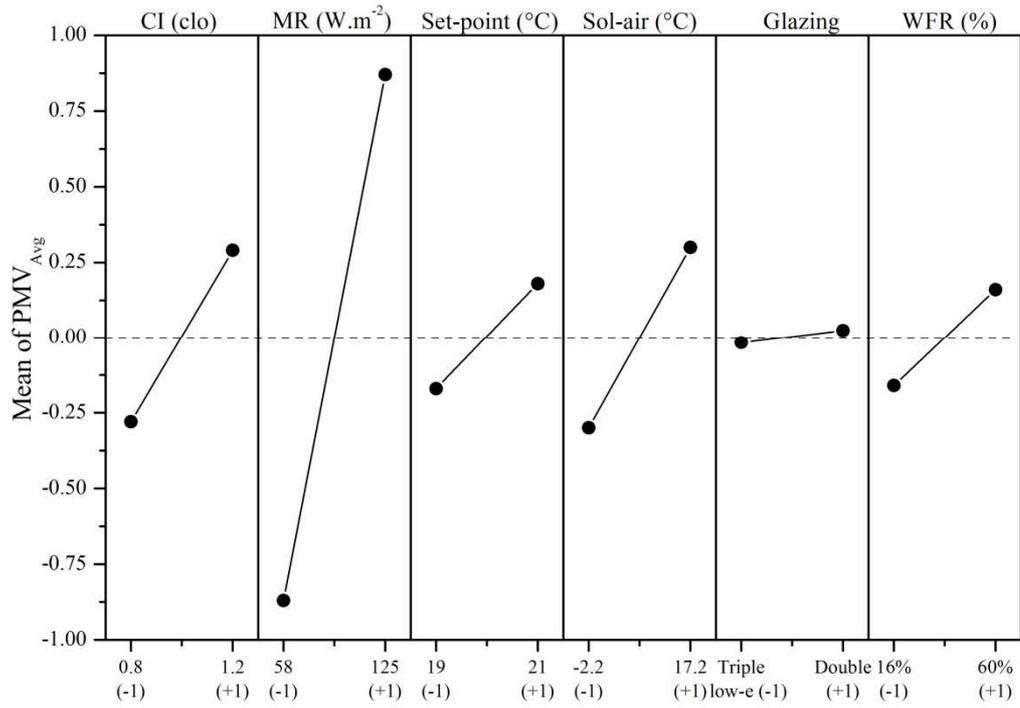
508 Figure 11 : Pareto plots of standardized effects at $p = 0.05$ for: (a) daily average PMV, (b)

509

minimum PMV and (c) maximum PMV.

510 Figure 12 illustrates the main effect plot of each of the studied factors. The effect of a
511 factor is defined as the change in the response due to the change in the level of the factor. It
512 can be clearly seen that the metabolic rate was the most significant parameter affecting the
513 PMV values, while glazing type was the least significant. These results confirm that in the
514 investigated Foyer, students' thermal comfort is highly affected by their activity and clothing
515 levels. Furthermore, maximum PMV values are sensitive to climatic conditions and glazing
516 area more than the set-point temperature, which confirms the effect of glass facades on the
517 variations of PMV.

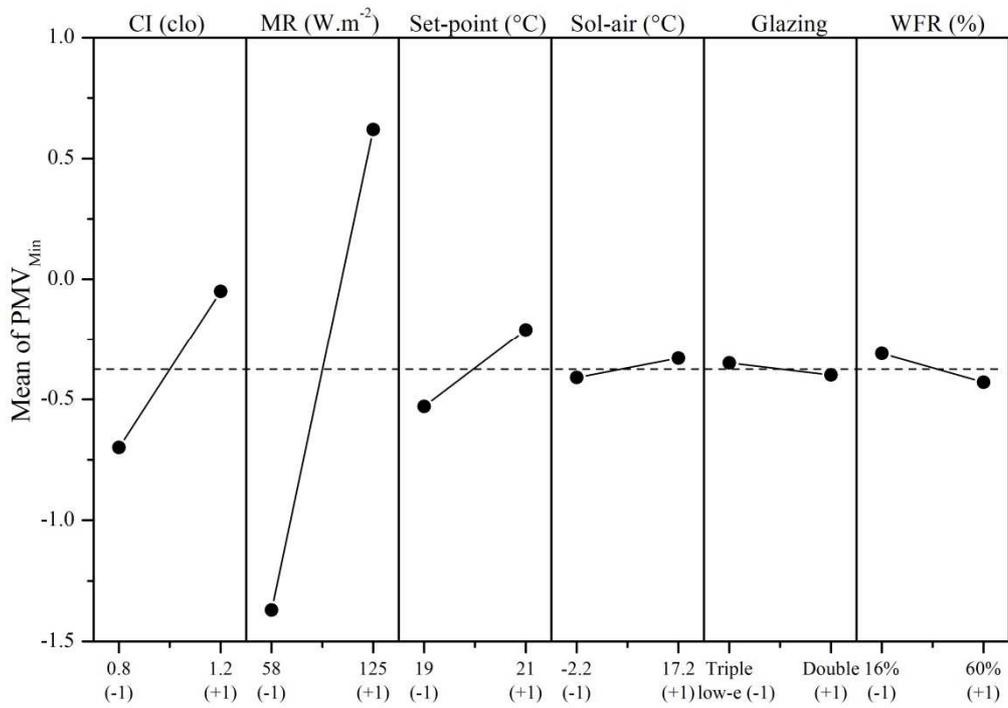
518 After identifying the main effects, it is important to study the interactions between
519 them, since this was found to be significant using the Pareto charts, as described in Figure 11.
520 Interactions occur when the effect of a factor is dependent on the level of another one. Figure
521 13 shows the interaction plot for the daily average, maximum and minimum PMV values. The
522 interaction plot allows to easily identifying interactions between two factors. It plots the mean
523 response of two factors for all occurring combinations. Non-parallel intersecting lines indicate
524 that an interaction between factors occurs, while parallel lines signify no interaction between
525 them. The results reported in Figure 13 show that several lines are not parallel but the
526 interaction between the sol-air temperature and the WFR has the most significant impact on
527 the daily average and maximum PMV values. This interaction effect indicates that the
528 relationship between PMV value and the outdoor climatic conditions depends on the external
529 glazed surface. As the external glazed surface area decreases, the effect of outdoor climatic
530 conditions become less important. Hence, decreasing glazing area results in more consistent
531 thermal comfort conditions. The results also show that the interaction between metabolic rate
532 and clothing insulation has the most significant impact on the minimum PMV value.



533

534

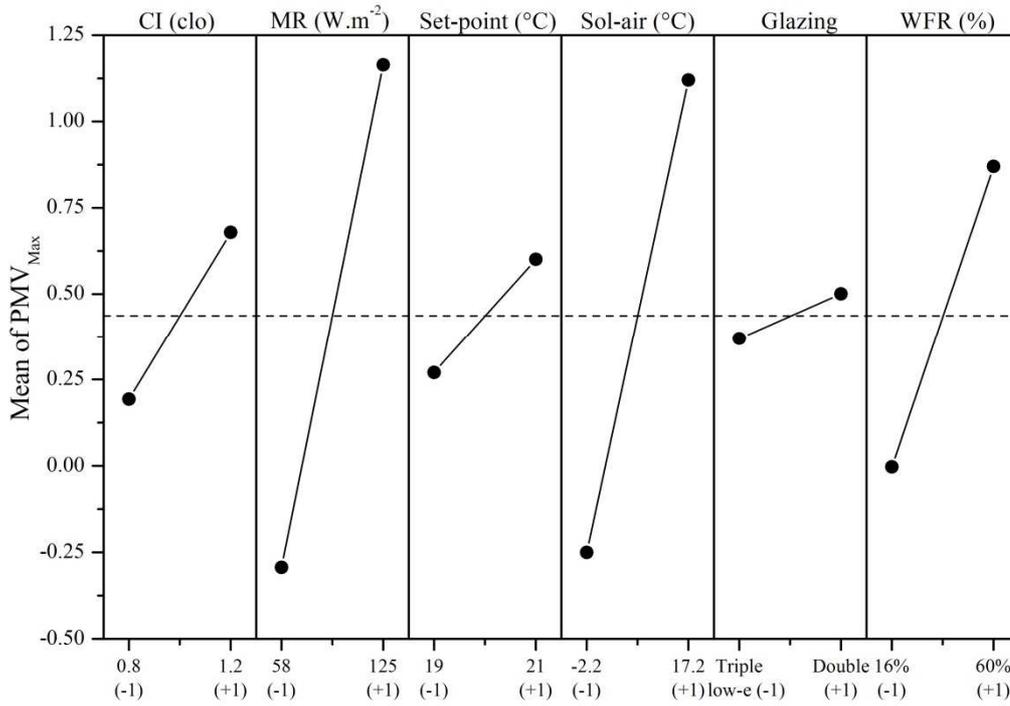
(a)



535

536

(b)

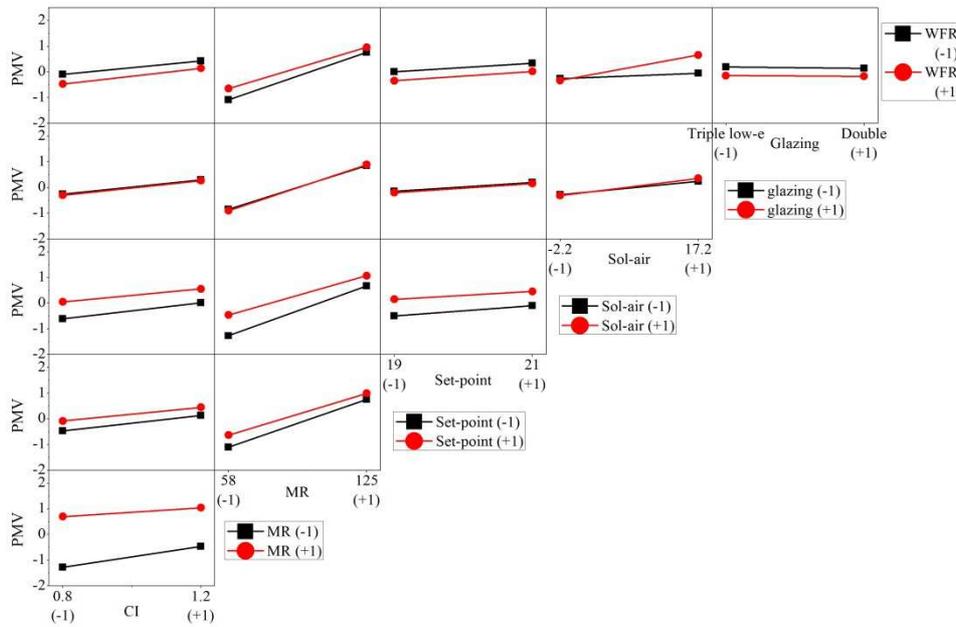


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(c)

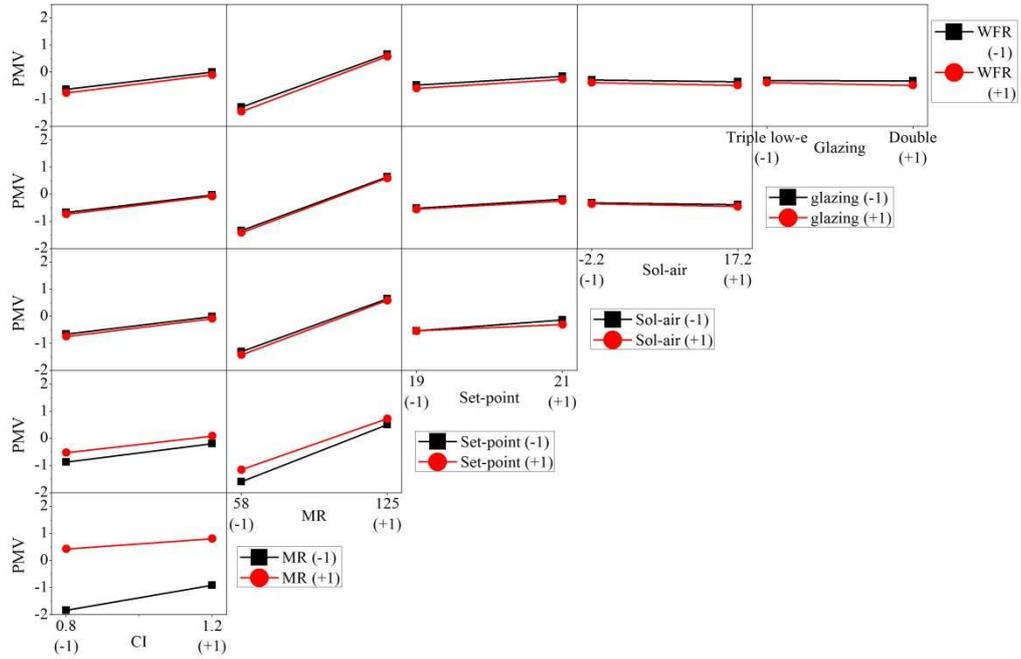
539 Figure 12: Main effect plot for: (a) daily average PMV, (b) minimum PMV and (c) maximum
 540 PMV.



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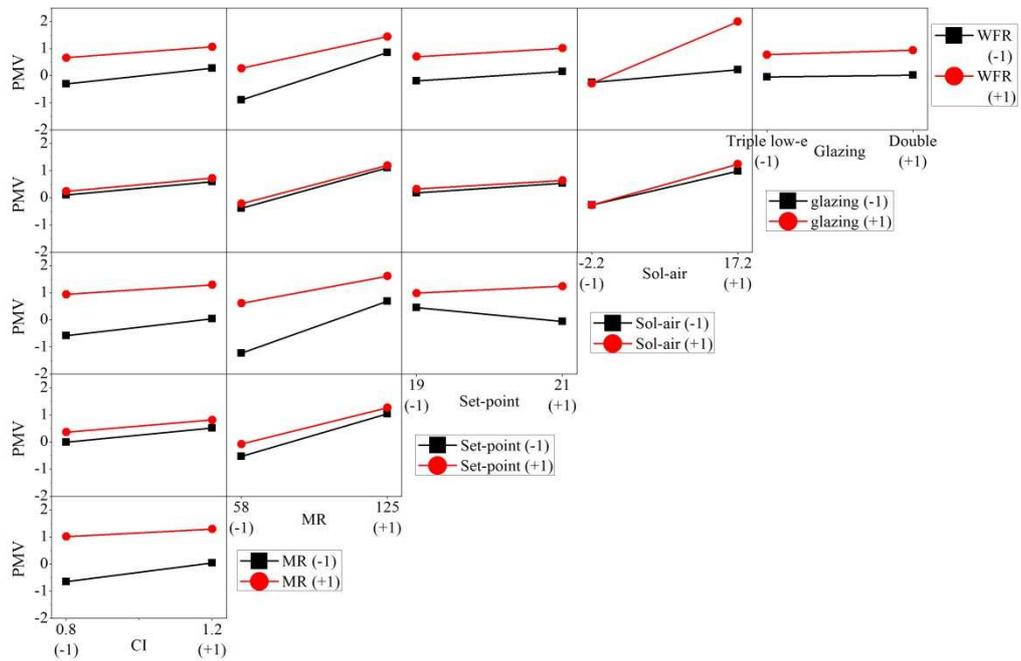
(a)



543

544

(b)



545

546

(c)

547 Figure 13: interaction plots for: (a) daily average PMV, (b) minimum PMV and (c) maximum

548

PMV

549 4.3.4 Development of meta-models for the prediction of the PMV values

550 Tables C, E and G of the supplementary information report the coefficients (column 3)
 551 of fitting polynomials to the simulation results by linear regression analysis. The ANOVA test
 552 shows that the meta-models for PMV values predictions are statistically significant at a 95%
 553 confidence level ($p < 0.05$). The obtained meta-models can be simplified by eliminating the
 554 non-significant factors ($p > 0.05$). The best fit meta-model equations that describe the
 555 average, the minimum and the maximum PMV values are given by Equations (11), (12) and
 556 (13), respectively.

$$\begin{aligned}
 PMV_{avg} = & 0.00372 + 0.28635 \times A + 0.87226 \times B + 0.17675 \times C \\
 & + 0.30146 \times D + 0.02108 \times E + 0.16296 \times F \\
 & - 0.11939 \times AB - 0.03119 \times AD - 0.05882 \times BC \\
 & - 0.10105 \times BD - 0.05360 \times BF - 0.02331 \times CD \\
 & + 0.03271 \times DE + 0.19716 \times DF
 \end{aligned} \tag{11}$$

$$\begin{aligned}
 PMV_{Min} = & -0.37557 + 0.32530 \times A + 0.99898 \times B + 0.16164 \\
 & \times C - 0.04150 \times D - 0.02642 \times E - 0.05801 \times F \\
 & - 0.13309 \times AB - 0.05402 \times BC - 0.03939 \times CD
 \end{aligned} \tag{12}$$

$$\begin{aligned}
 PMV_{Max} = & 0.43566 + 0.24247 \times A + 0.72880 \times B + 0.16611 \times C \\
 & + 0.69132 \times D + 0.06404 \times E + 0.43896 \times F \\
 & - 0.10397 \times AB - 0.07044 \times AD - 0.05513 \times BC \\
 & - 0.22996 \times BD - 0.14480 \times BF + 0.06577 \times DE \\
 & + 0.45554 \times DF
 \end{aligned} \tag{13}$$

557 The ANOVA results of the models indicate good performance with $R^2 (> 0.98)$ and
 558 adjusted- R^2 (0.97). The value of adjusted- R^2 indicates that more than 97% of the total factors
 559 associated with the PMV are attributed to the selected parameters of the model. The Predicted
 560 R^2 is in reasonable agreement with the Adjusted- R^2 ; i.e. the difference is less than 0.2.

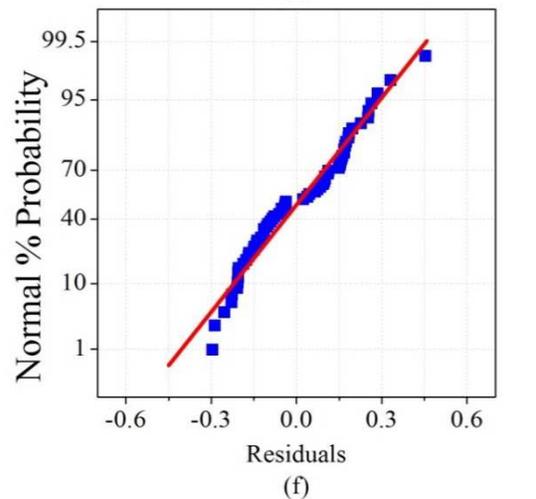
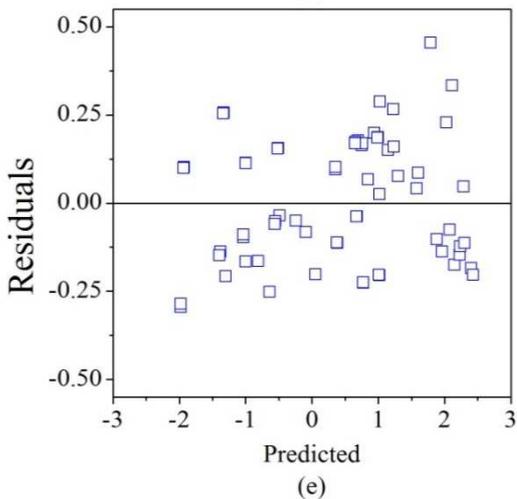
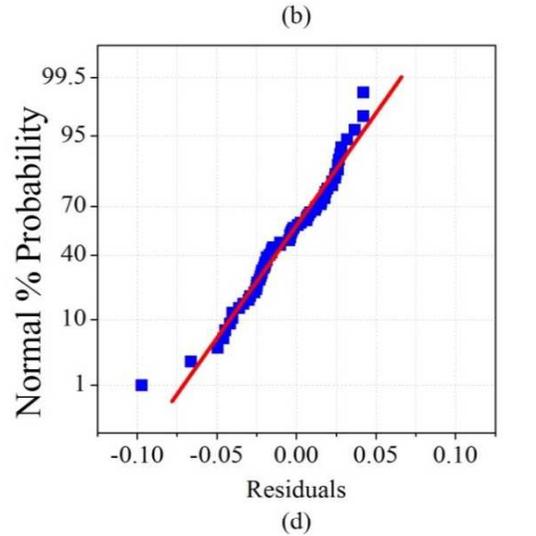
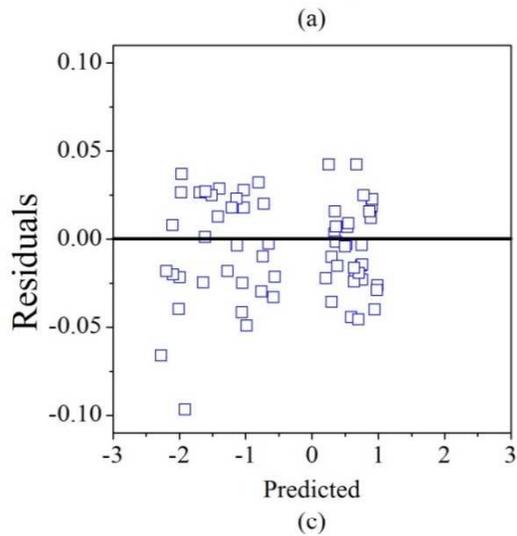
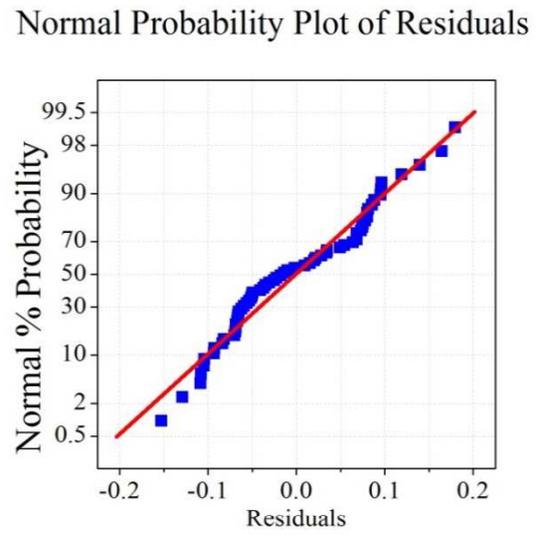
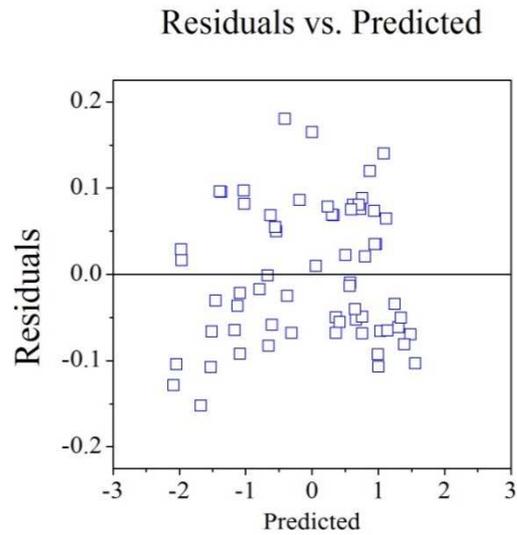
561 Moreover, residuals versus predicted values plot and normal probability plot of
 562 residuals are two graphical approaches that are used to check the validity of a regression
 563 model [39]. The residual versus predicted response plots illustrated in Figure 14 show that
 564 less patterned structures are observed for the three deemed responses indicating that the

565 proposed models are adequate. In addition, the normal probability plots shown in Figure 14
566 designate that the residuals followed a straight line, thus confirming the validity of the
567 models.

568 Furthermore, 50 additional simulations were performed with different factors' levels
569 using the numerical model and the results were compared to the meta-model predictions. The
570 obtained results are shown in Figure 15. A good correlation is observed showing a R^2 value
571 of 0.99, meaning that 99% of variance is explained by the obtained meta-model. Therefore,
572 the meta-models are considered to be valid and adequate. These meta-models can be used
573 instead of the numerical model as a fast and simple way to predict the thermal comfort
574 condition within an indoor environment. However, the reliability of these meta-models is
575 limited to a similar case study and the considered range of variation of the investigated
576 factors.

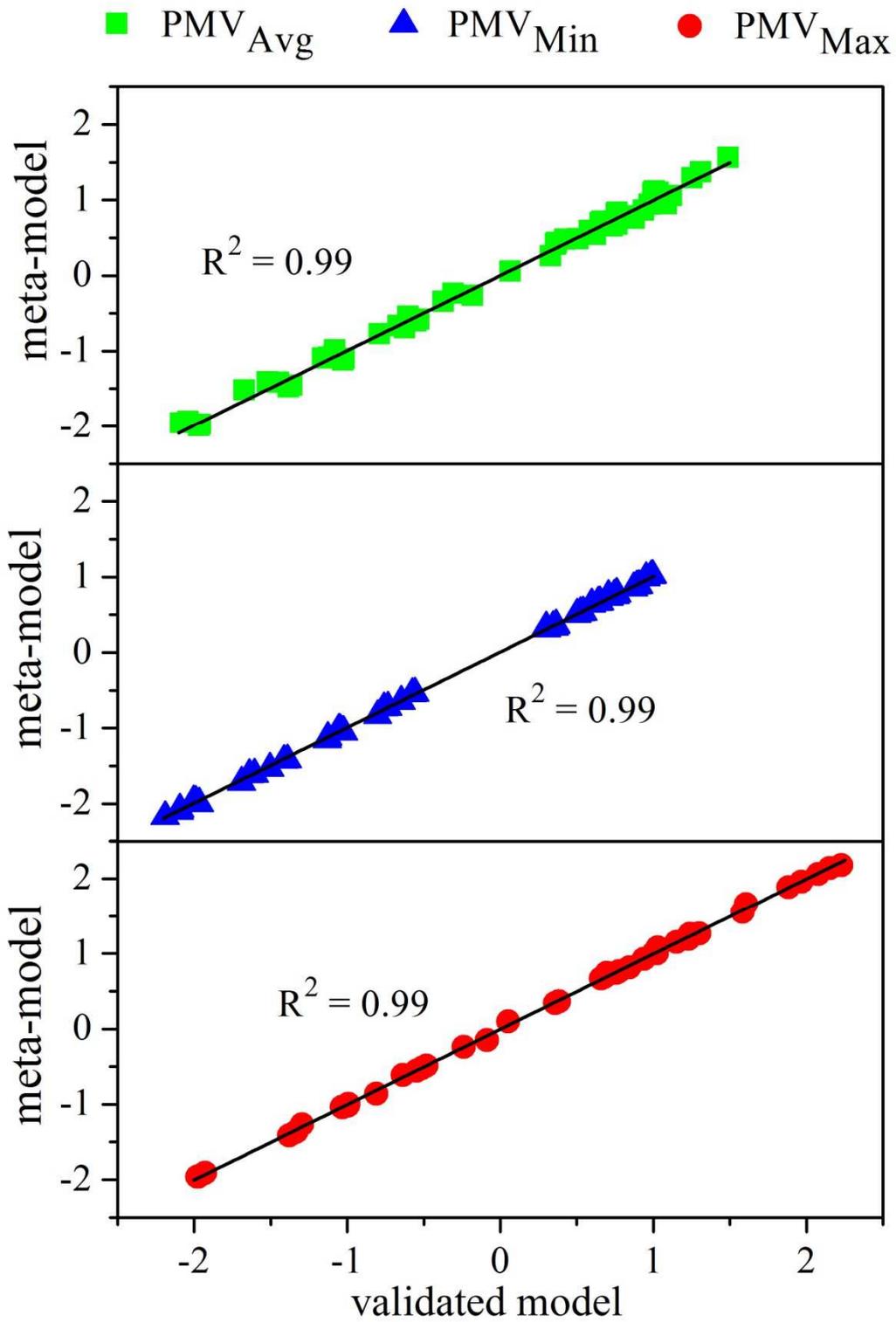
577 *4.3.5. Determination and analysis of optimal solutions*

578 Finally, an optimization is carried out using the obtained meta-models. The response
579 variables are the average, minimum and maximum PMV values. The objective is to maintain
580 these values within the recommended acceptable thermal comfort range of [-0.5;+0.5] [6].
581 The range of variation of the set-point temperature, glazing type and WFR is kept as indicated
582 in Table 2, while the metabolic rate and clothing insulation were assumed to vary in the
583 ranges of [66.5;73.5] and [0.95;1.05], respectively, representing sedentary activity and typical
584 winter clothing with 5% variation [56].The sol-air temperature parameter was excluded from
585 the optimization because it is an uncontrollable parameter. The objectives and constraints of
586 the optimization are summarized in Table 4.



587

588 Figure 14: Residuals versus fitted values, (a), (c) and (e), and Normal probability of residuals,
 589 (b), (d) and (f), for average, minimum and maximum PMV values, respectively.



590

591 Figure 15: Coefficient of determination between simulation results and the meta-model

592

predictions.

Table 4: objectives and constraints of the optimization

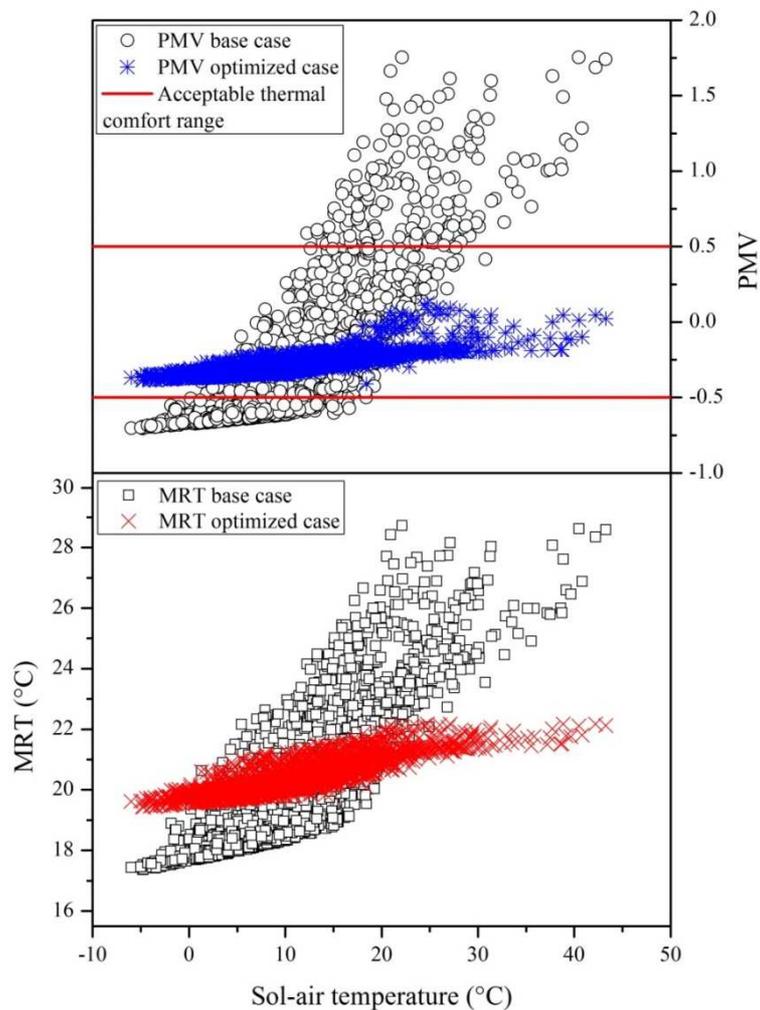
Name	Objective	Lower limit	Upper limit
PMV Minimum PMV Maximum PMV	Is maintained in a range	-0.5	+0.5
Constraints			
CI	Is maintained in a	0.95	1.05
MR	range	66.5	73.5
Set-point		19	21
Glazing type		Triple low-e	double
WFR		0.16	0.6

594 The numerical optimizations show that the maximum D value, $D=1$, is provided when
595 the set-point temperature, the glazing type and the WFR are 21°C , double glazing, and 16%,
596 respectively. The optimization results suggest that using this combination of parameters yields
597 average, minimum and maximum PMV values of -0.381, -0.5 and 0.107, respectively. This
598 same combination of parameters is then simulated using the Dymola model; the obtained
599 average, minimum and maximum PMV are -0.284, -0.41 and 0.124, respectively. These
600 results are in a good agreement with the outcomes predicted by optimizing the meta-models,
601 thus confirming the validity and adequacy of the obtained results.

602 In addition, the optimized case is compared to the base case and the obtained hourly
603 numerical values of PMV and MRT are presented in Figure 16. The results show that the
604 optimized design yields better thermal comfort condition within the studied room. More
605 specifically, it leads to alleviate the high MRT values during high sol-air temperatures, thus
606 preventing the PMV values from exceeding the upper acceptable limit. On the other hand, it
607 reduces the heat loss through building envelope thus leading to increasing MRT during cold
608 times, which means improved PMV values during low sol-air temperature values.

609 Furthermore, although the optimized case allows an increase in the set-point
610 temperature to maintain acceptable thermal comfort condition, it results in reducing the
611 heating energy consumption. An energy audit for the whole building comprising the Foyer is

612 performed in [33]. One can refer to this study for a detailed description about the total number
613 of days requiring heating and the outdoor climatic conditions. The total heating energy
614 consumption of the base case, set-point 20°C, was 3034 kWh per year, while that of the
615 optimized case was 2566 kWh per year. These results are correlated to the optimized glazing
616 area that results in improved thermal resistance of the external walls, allowing the reduced
617 transmission heat loss under low sol-air temperature, thus improving the heating energy
618 consumption.



619

620 Figure 16: Numerical hourly values of (a) PMV index and (b) MRT of the base-case and the
621 optimized-case designs.

622 **5. Conclusion**

623 Adequate design of building envelope is essential to ensure a trade-off between
624 several aspects, such as aesthetic appearance of the building, occupants' thermal and visual
625 comfort and energy consumption. The aim of this study was to optimize building design for
626 thermal comfort. The proposed method is based on the combined use of numerical
627 simulations, DoE technique and the desirability function approach.

628 Firstly, a real case study characterized by two glass facades was selected for the
629 investigations. Subjective thermal comfort was assessed using questionnaire survey. The
630 collected responses indicated that 37% of the respondents were dissatisfied with the thermal
631 environmental conditions. Next, a previously developed and validated model was used to run
632 simulations, and the obtained results were in agreement with the collected responses.

633 Then, a sensitivity analysis based on the combined use of numerical simulation and
634 DoE technique was performed. From this analysis, the most significant parameters and
635 interactions affecting the response variables (average, minimum and maximum PMV value)
636 were determined, as well as mathematical relationships, referred as meta-models, which
637 approximate the response variables as a function of predefined factors were developed. The
638 meta-models were validated using graphical analysis of residuals and the coefficient of
639 determination R^2 . The residual versus predicted response plots demonstrated less patterned
640 structures; the normal probability plots indicated that the residuals followed a straight line and
641 the coefficient of determination was greater than 0.98, thus confirming the validity of the
642 meta-models.

643 Lastly, an optimization procedure using the desirability function approach was carried
644 out. The objective of the optimization was to maintain the PMV values within the acceptable
645 comfort range of [-0.5; 0.5]. The results indicated that the optimized design yields better
646 thermal comfort conditions, PMV values ranged from -0.381 to 0.107. In addition, it reduces

647 heating energy consumption, even though it requires increased heating set-point. This
648 indicates that an optimized design of building envelope is vital to achieve energy-saving and
649 thermal comfort, rather than just reducing the set-point temperature.

650 This study demonstrated that optimizing building design for thermal comfort can be
651 achieved by adequate treatment of building envelope design, i.e. glass facades configuration
652 in our case. Although the proposed approach outcomes robust and credible results, its
653 limitation is that few parameters and response variables were considered in the analysis. In
654 addition, both u-value and SHGC of the glazing were considered simultaneously. Future work
655 will focus on increasing the number of parameters and response variables by simultaneously
656 considering several issues, as well as applying the proposed approach to other buildings
657 typologies.

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