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Citation for the published version (APA 6th)

Goia, F., Haase, M., & Perino, M. (2013). Optimizing the configuration of a façade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective. *Applied Energy*, 108, 515-527. doi:<https://doi.org/10.1016/j.apenergy.2013.02.06>

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Highlights

- Integrated thermal-daylighting simulations on a low energy building are performed.
- Optimal WWR of the façade that minimize the total energy demand is searched.
- Optimal WWR were found in the range 35-45%, regardless the orientation.
- If state-of-the-art technologies are used, WWR doesn't play a crucial role (maximum influence: 11%).
- The optimal configurations are tested against different building geometries and HVAC efficiencies.

1 **Optimizing the configuration of a façade module for office buildings by**
2 **means of integrated thermal and lighting simulations in a total energy**
3 **perspective.**

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9

10 **Abstract**

11 The building enclosure plays a relevant role in the management of the energy flows in buildings and in the
12 exploitation of the solar energy at building scale and an optimized configuration of the façade can contribute to
13 reduce the total energy demand of the building. Traditionally, the search for the optimal façade configuration is
14 obtained by analyzing the heating demand and/or the cooling demand only, while the implication of the façade
15 configuration on the energy demand for artificial lighting is often not addressed.

16 A comprehensive approach (i.e. including heating, cooling and artificial lighting energy demand) is instead
17 necessary to reduce the total energy need of the building, and the optimization of a façade configuration
18 becomes no longer straightforward, because non-linear relationships are often disclosed.

19 The paper presents a methodology and the results of the search for the optimal transparent percentage of a
20 façade module for low energy office buildings. The investigation is carried out in a temperate-oceanic climate,
21 for the four main orientations, on three versions of the office building, and with different HVAC system's
22 efficiency. The results show that, regardless of the orientations and the façade area of the building, the optimal
23 configuration is achieved when the transparent percentage is between 35% and 45% of the total façade module.
24 The north-exposed façade presents the highest difference between the optimal configuration and the worst one,
25 while the south-exposed façade is the one that suffers the least in case of the “worst” configuration.

26 1. Introduction

27 It is a well-established belief that the façade can play a crucial role in the management of the energy flows and
28 thus contribute to achieve energy efficiency in building. The conventional approach focuses mainly on the
29 “negative” aspects related to the role of the façade (i.e. on the heat loss during the heating season), and in this
30 framework the transparent elements of the façade are the weakest spot. However, it is now becoming more and
31 more common to consider the “positive” feature of the transparent part of the façade, i.e. the ability to exploit
32 the solar gain to reduce the heating demand (passive solar heating), and the possibility offered by the façade to
33 provide daylighting for the indoor environment.

34 One of the main ways through which the façade configuration affects the total energy efficiency of the building
35 is the balance between the opaque and the transparent elements, and the relevance of this parameter on the
36 behavior of the façade has been again demonstrated in a recent sensitivity analysis on an office building
37 equipped with automated shading [1]. The analysis of the balance between the transparent and the opaque part
38 of a façade can thus provide useful information for the design of the future buildings that present low energy
39 demand, as required by the recent EU directive (EPBD recast) [2].

40 The configuration of the façade can affect three terms of the annual energy need of a building, as defined in EN
41 15603 [3]: the energy need for heating (E_H), the energy need for cooling and dehumidification (E_C), the energy
42 need for lighting (E_L). The other three terms of the total energy need of the building – i.e. energy need for
43 ventilation and humidification, hot water and other services – are not directly affected by the configuration of
44 the façade.

45 The aim of this paper is to demonstrate that the optimization¹ of a façade requires the contemporary evaluation
46 of E_H , E_C , and E_L , and that integrated thermal-daylighting simulations are necessary. The paper investigates a
47 hypothetical, single skin façade module, realized with market-available, state-of-the-art technologies. A
48 methodology to assess the optimal configuration of the façade module (optimal Window-to-Wall Ratio², WWR)
49 is then presented. The research activity is aimed at giving practical information to façade manufacturers and

¹ In this paper, the term “*optimal configuration*” means the Window-to-Wall Ratio (WWR) that minimizes the annual primary energy demand of the building. In other words, the optimization concerns exclusively the WWR, while all the other variables (e.g. the materials of the façade modules, the properties and the performance of the subcomponents) are kept constant. The term “*annual primary energy demand*” means the sum of the energy demand for heating, cooling and lighting.

² The Window-to-Wall Ratio (WWR) is defined as the ratio between the net glazing area and the gross exterior wall area.

50 practitioners about the “average” configuration of a façade for an office building which incorporates best
51 available technologies, in the framework of low energy buildings.

52 Since the climate plays a role in the configuration of the façade, a central Europe climate, representative of a
53 wide area of Atlantic and Central Europe, was chosen. Of course, the actual optimal configuration depends on
54 the exact features of the building, but this study can provide a method, as well as a rule-of-thumb, that can be
55 used during the preliminary design stage. Furthermore, it highlights some aspects that must be taken into
56 account during the detailed design phase and points out the relevance of an integrated analysis.

57 **2. State of the art**

58 The impact of the fenestrations on the energy performance of the building is a hot-topic, which has been
59 investigated for a long time. Since the first analyses dated in the '70-'80 [4-5], the implication of the façade on
60 the lighting energy demand was pointed out. It is important to mention that even though most of the analyses
61 that have been carried until now focused on either the thermal or the lighting aspect, a global energy approach
62 was already adopted in some of the first investigations [6]. The most relevant finding of these research activities
63 was the relevant role of the WWR: optimum WWR resulted in significant energy saving (more than 50%) for
64 heating, cooling and lighting.

65 In the following years, the influence of the materials [7-9], the dimension of the fenestration [8,9], and the
66 integration of active elements as PV panels [10] have been investigated. A particular focus has been placed on
67 office buildings [11] and on the implications of the façade configuration in different climates [12], including
68 heating-dominated [10] and cooling-dominated [13] climates. Results are difficult to be summarized because of
69 their extent, but it is possible to notice a general trend towards a lower influence of the WWR on the energy
70 performance of the façade as it improves – i.e. when more efficient technologies (e.g. more insulated buildings,
71 more efficient HVAC systems, more efficient lamps) are employed.

72 With the increase of the research on low energy buildings, the impact of the fenestration on this kind of
73 construction has been evaluated too [14-16], both for heating dominated climates [14] and for cooling-
74 dominated climates [16]. However, the focus was often placed almost only on the thermal aspects, neglecting
75 the implications on the visual environment and on the energy demand for lighting. In particular, light energy
76 consumption was not evaluated in the majority of the last cases, making difficult to obtain results in a total

77 energy perspective. On the contrary, research activities focusing only on the potential savings due to a better use
78 of daylighting can be also found [17].

79 Recently, the trade-off between energy-related issues and visual comfort has been investigated for glazing
80 systems without solar shading devices [18]. It was pointed out that windows optimized exclusively for visual
81 comfort leads to large energy consumption. On the other side, the optimization of the window size for low
82 energy consumption only does not meet visual acceptance criteria. A tradeoff is therefore necessary.

83 The relevance of the incorporation of shading systems for both solar and visual control in office buildings is
84 highlighted by a research on the incorporation of fix or dynamic solar shading systems [19]. In particular, the
85 influence both of the size of the window and of the shading device's typology was investigated. The façades
86 with dynamic solar shading showed the best performance with respect to total energy demand, and façades with
87 fixed solar shading the worst. Furthermore, it was found that, in a Danish climate, the difference in total energy
88 demand between the worst and best-performing façade, for a given orientation, does not exceed 16%.

89 The integration of shading devices into fenestrations increases the degree of complexity of the system. In fact,
90 the use of shading devices provides considerable advantages [19-23] with respect to a static fenestration, but
91 different typologies and control strategies can be adopted – and different performance achieved. On this topic,
92 integrated thermal and daylighting analyses for perimeter office spaces in Montreal were carried out [20],
93 evaluating the impact of WWR on visual and thermal performance and artificial lighting. The results showed
94 that, for south-facing facades, a WWR = 30% can ensure natural daylight illuminance values higher than 500
95 lux for 76% of the working time in a year. Larger windows do not result in significant increase in useful
96 daylight. Comparing with the reference case without shading, an appropriate shading control (exterior roller
97 shade) can halve the cooling energy demand. Although the artificial lighting demand is increased in case of
98 solar shading, an optimal solution can be found and a reduction of 12% in the total energy demand achieved.

99 The impact of interior roller shades in combination with different window sizes was analyzed in two different
100 climates (Chicago and Los Angeles), in small private offices [22]. The complex interactions of the several
101 parameters were analyzed and discussed in details, demonstrating that automated shades may lead to reduction
102 (or increase) of the total energy demand, depending on the combination of the other parameters. Among the
103 results, it should be highlighted that façades with a transparent percentage in the range 30-50% can determine
104 the lowest total energy demand in particular cases.

105 The adoption of overhanging and/or blinds and of WWR in an office building located in Santiago de Chile was
106 recently investigated by means of integrated thermal lighting simulations [23]. It was shown that the WWR
107 influences to a great extent the energy demand, especially when no sun shading systems/overhanging are
108 exploited. A fully glazed façade may determine a energy demand for cooling and heating more than six time
109 higher than that of a façade with WWR = 20%, external solar protection and selective glazing. This latter
110 configuration is capable of providing useful daylight during around 80% of the working time.

111 Another additional complexity that arises with integrated solar shading system is the choice of the control
112 criteria [24]. Usually, the shading device is controlled as a function of the glare risk, or as a function of the
113 incident (or transmitted) solar irradiance, or activated in case of cooling load, or its displacement is based on the
114 prediction of the indoor illuminance level. The selection of the appropriate control strategy plays a crucial role
115 in the interior conditions and in the energy saving potentials. For office rooms, it is preferable not to let direct
116 sunlight entering, and in the case of the adoption of venetian blinds, they should be rotated to block sunrays.

117 As far as the numerical tools are concerned, the literature review reveals that, when such dynamic shading
118 systems are modeled, it is difficult to perform integrated thermal-lighting simulations with a high degree of
119 accuracy, especially for non-expert users and practitioners. Most of the research activities reported in literature
120 were carried out with specifically developed codes. Numerical tools that accurately simulate either the thermal
121 or the lighting aspects are well-available, but integrated software tools very often make use of simplified
122 methods and assumptions that may reduce the degree of accuracy.

123 **3. Method**

124 The implications of the façade configuration on the energy consumption of an office building are investigated
125 by means of a façade made of prefabricated modules. The choice of modeling a façade in terms of façade
126 modules is due to the fact that a façade module is a particularly relevant case study as far as the WWR is
127 concerned. Furthermore, façade modules are gaining popularity, especially in present-day commercial and office
128 buildings, and are seen as potential, market-available technology, to increase energy efficiency in buildings –
129 both in new constructions and in renovations.

130 **3.1 Façade module technology**

131 The façade module is a single skin façade technology, 3.7 m width and 3.4 m height, and it is realized with
132 market-available technologies. The façade module is composed by two surfaces: a transparent part and an

133 opaque part. The transparent surface is made of a triple glazing with low-E coatings made with clear glass panes
134 and integrated external solar shading devices – i.e. a highly-reflective external venetian blind system (blind slate
135 reflectivity: 80%). When displaced, the venetian blinds cover the entire net glazing area; the angle of the
136 venetian blinds is adjusted continuously in order to block the direct solar rays. The U-value of the glazing is 0.7
137 $\text{W m}^{-2} \text{K}^{-1}$, the SHGC is 0.46, and the visible transmittance is 0.53.

138 The opaque part is realized with a sandwich panel, made with 0.025 m thick Vacuum Insulation Panels, a 0.12
139 m thick rockwool insulation layer and some plasterboard layers (total thickness of the plasterboard layers is 5
140 cm). The outer surface of the opaque surface is made of a metal panel. The U-value of the opaque sandwich is
141 $0.15 \text{ W m}^{-2} \text{K}^{-1}$. The façade module presents also a thermal break aluminum frame with U-value of $1 \text{ W m}^{-2} \text{K}^{-1}$.

142 Five different WWR are used during the search for the optimal configuration: from WWR = 20% (equivalent to
143 ca. 2.5 m^2 transparent area each module) to up to WWR = 80% (equivalent to ca. 10.0 m^2). The surface of the
144 façade module that is not transparent is made of both the aluminum frame (around 10% of the total façade
145 module area) and the opaque sandwich panel. Thermal bridges due to module-to-module connections are
146 neglected. Details on the different geometries and aspects are illustrated in Fig. 1.

147 **3.2 Office building specifications and data processing**

148 The optimal configuration of the façade module is investigated for an office building characterized by a typical
149 layout, located in of Frankfurt (Germany), which belongs to a temperate-oceanic climate, Cfb according to
150 Köppen climate classification [25].

151 The plan concept of the building is derived by a “typical” office building developed in the frame of the IEA
152 Annex 27 activity [26]. The office building plan presents a central corridor with cell offices on both the sides of
153 the corridor; building services, staircase and lifts are at the two ends of the corridors (Fig. 2a). The cell office
154 dimensions are: 3.6m (w) x 5.4m (l) x 2.7m (h); the interior surface visible reflectance coefficients of the walls,
155 ceiling and floor are 70%, 70% and 40% respectively. Each cell office has one façade that borders with the
156 outdoor environment, and it is made of a façade module. The office building has a concrete structure with
157 concrete slabs and lightweight interior partitions, an atrium area at ground level (heated) and an underground
158 level (not heated). Specifications of the building services and settings are given in Table 1; the internal loads and
159 lighting-related data are illustrated in Table 2 and derived from [27]; mechanical ventilation specifications are
160 taken from [28]. The occupation time is set 8am-5pm, Monday through Friday.

161 After the simulations are performed, the building is virtually “divided”, along the axis of the central corridor, in
 162 two volumes (half of the total volume each), and each of the two volumes is associated to a façade orientation
 163 (cf. Fig 2b-2c). Since the building is considerably smaller in width than in length, the building presents two
 164 main façades – i.e. north façade and south façade, if the main corridor is aligned along the axis east-west, or east
 165 façade and west façade if the corridor is aligned along the axis north-south. Therefore, during the data post-
 166 process phase, each building only presents two façades: south and north façades (cf. Fig 2b), or east and west
 167 façades (cf. Fig. 2c). As a consequence, the energy demand associated to a single orientation takes also into
 168 account the energy demand associated to areas that do not necessarily present this orientation³. The reason for
 169 modeling an entire building instead of a single cell office, as some other research activities do (e.g. [17-20]), is
 170 to correctly take into account the energy demand of the entire building – which is not made only by cell offices.
 171 This way, the energy performance obtained for a façade orientation is more representative than a simulation
 172 concerning the cell office alone, because closer to the real situation.

173 3.3 Optimization procedure and simulations

174 The aim of the search is to find the WWR of the façade module that minimizes the total energy demand of the
 175 building E_{tot} (Eq. 1), where E_H is the heating primary energy demand, E_C is the cooling primary energy demand,
 176 and E_L is the lighting primary energy demand, on a yearly base. The conversion factor for electrical energy to
 177 primary energy was 2.5 [kWh_{pe}/ kWh_{ce}].

$$178 \quad E_{tot} = E_H + E_C + E_L \text{ [kWh}_{pe} \text{ m}^2 \text{ y}^{-1}] \text{ (Eq. 1)}$$

179 If it is considered as a problem of allocation of resources (the optimal allocation of glazing surface and opaque
 180 surface in a given façade module surface), the objective function is (Eq. 2):

$$181 \quad f : \min \{E_{tot}(WWR)\} \text{ (Eq. 2)}$$

182 However, since the transparent part incorporates a solar shading system and this introduces more dynamicity to
 183 the façade module, a preliminary analysis on the influence of this system of the final result is needed. In
 184 particular, it is necessary to identify the best strategy for the activation of the solar shading device since it has
 185 huge implications on the final result. After some preliminary investigations, that are not reported here for the

³ E.g. In a building where the corridor is aligned along the axis east-west, the south orientation also takes into account volumes that have a west and east orientations (where the building services, lifts and staircases are). The north orientation follows the same rule.

186 sake of brevity, the following strategy is adopted: the solar shading devices are activated if the zone cooling rate
187 in the previous time-step were non-zero and if the solar radiation incident on the window exceed a certain set-
188 point value. The adopted strategy is a compromise between a strategy that focuses only on the thermal aspects
189 and a strategy that is based on the daylight exploitation. In fact, the choice to activate the venetian blinds in case
190 of a simultaneous cooling load and solar irradiance exceeding a target value, avoids the activation of the shading
191 systems in case of cooling loads caused by internal gains. This strategy should therefore provide adequate
192 daylight still avoiding the excess of cooling load.

193 However, the determination of the optimal set-point value for the activation of the solar shading (i.e. the set-
194 point value that determines the lowest total energy demand) is not straightforward: too low set-point values may
195 reduce the cooling energy demand, but increase the lighting energy demand and the heating energy demand; too
196 high set-point values can produce the opposite effect. Thus, the search for the best set-point value becomes an
197 optimization procedure itself. This procedure must be repeated for each orientation and for each WWR, since
198 different orientations and WWR may have different optimal set-point values.

199 In order to perform this task, it is thus necessary to analyze one by one the orientations, and to test different
200 WWR for the same orientation. Therefore, during this first round, the façade module (with a certain WWR) is
201 adopted only on the orientation under investigation, while the opposite orientation is made of a fully opaque
202 wall. For each WWR (20%, 35%, 50%, 65% and 80%), different set-point values for the activation of the solar
203 shading system are tested: 100 Wm^{-2} , 200 Wm^{-2} , 300 Wm^{-2} , and 400 Wm^{-2} . A total of 20 combinations are
204 therefore evaluated.

205 Once the optimal activation flux for each WWR and orientation is found, a second round of simulations is then
206 performed: 25 possible combinations are investigated for each building and couple of orientation, by combining
207 the 5 different WWR on the two opposite façades. During this round, the different WWRs adopt the optimized
208 set-point values for the solar shading activation previously determined. A scheme of the workflow is illustrated
209 in Figure 3.

210 **3. 4 Integrated thermal-lighting simulations and limitations**

211 The integrated thermal and daylight simulations are carried out using the *EnergyPlus* software [29], performing
212 calculations on hourly basis for the entire year. A daylighting calculation is performed each heat-balance time-
213 step when the sun is up. The electric lighting control system (continuous dimming control) is simulated to

214 determine the lighting energy needed to make up the difference between the daylighting illuminance level and
215 the design illuminance set-point. Finally, the zone lighting electric reduction factor is passed to the thermal
216 calculation, which uses this factor to reduce the heat gain from lights [30]. One reference point for the daylight
217 calculation is chosen in each cell office, placed on the centre line of the office, at 3.6 m from the façade, at a
218 height of 0.80 m from the floor.

219 Ramos and Ghisi [31] analyzed the reliability of the *EnergyPlus* software in daylight simulation, for different
220 room geometries, WWR and locations. It was pointed out that *EnergyPlus* presents some problems in the
221 calculation of both the Daylight Factors and the external illuminance values, when compared to a more
222 advanced software tool for daylight simulations – i.e. *Radiance*. In particular, *EnergyPlus* presents some
223 inaccuracies in the calculation of the internal reflection – the greater the importance of the portion of light
224 reflected in the indoor environment, the greater the difference found between *EnergyPlus* and *Radiance*.
225 Furthermore, the comparison between the calculated and measured external horizontal illuminances shows great
226 differences both for the diffuse and direct illuminances – the *EnergyPlus* programme overestimates these values.

227 However, it must be stated that a great similarity was found between the internal illuminance obtained by
228 *EnergyPlus* and by *Radiance* – maximum difference of 20%. This means that, even if *EnergyPlus* shows some
229 limitations in daylight calculation, it is still possible to perform integrated simulations with this code, and to
230 evaluate the impact of the configuration of the façade on the energy demand for lighting.

231 3. 5 Daylight analysis

232 Daylighting analyses are carried out by making use of two performance indexes: the Daylight Autonomy (*DA*)
233 [32] and the Useful Daylight Illuminance (*UDI*) [33]. The *DA* measures the percentage of the working year
234 during which the illuminance threshold on the working plane (i.e. 500 lux) is maintained by the natural light
235 alone. The *UDI* measures how often the daylight on the working plane is within a specific illuminance range.
236 Therefore, three different *UDI* are used, following the range limits proposed by Nabil and Mardaljevic [33]:

237 - *UDI₁₀₀₋₅₀₀*, which shows the percentage of the working year when the daylight illuminances, although not
238 enough to meet the threshold, are considered effective either as the only source of light or combined with
239 artificial lighting;

240 - *UDI₅₀₀₋₂₀₀₀*, which shows the percentage of the working year when the daylight illuminances are perceived
241 either as desirable, or at least tolerable, and no artificial lighting is used;

242 - $UDI_{>2000}$, which shows the percentage of the working year when the daylight illuminances may produce visual,
243 and can therefore give an indirect, quantitative yet simplified information about the glare discomfort risk.

244 Although limits or suggested values for UDI have not yet been standardized and fully accepted, it is
245 straightforward that high $UDI_{500-2000}$ values (e.g. >50%) result in suitable (or at least acceptable) exploitation of
246 daylighting; even higher values are sign of a proficient design of the natural light exploitation. A less direct
247 relationship can be instead drawn as far as the $UDI_{>2000}$ is concerned, which is correlated to glare discomfort
248 risk. If it is probably true that low values of may result in less glare discomfort risk, it is not clear what can be a
249 (upper) limit value for this metric. Considering that very low $UDI_{>2000}$ values cannot be reached even in well-
250 **designed indoor environments**, a reasonable threshold value that may work as a rule-of-thumb can be found in
251 the range 10-20% (the lowest, the best).

252 **3.6 Reliability analyses**

253 In order to assess the reliability of the achieved results (i.e. the optimal WWR), two further investigations are
254 performed: the stability of the results is tested, within the same building typology, against different building
255 geometries; moreover, the stability is also tested against different HVAC systems that present higher or lower
256 efficiencies.

257 In order to test the stability with respect to the building geometry, three configurations (different geometries,
258 same layout) of the same office building are later simulated. **The three building (codes: B1, B2 and B3) share**
259 **the same plan concept, technologies and services and the details on the geometry of three buildings are given in**
260 **Table 3. A change in the depth of the building was not considered since this would probably result in a different**
261 **plan concept (e.g. a double corridor configuration) and thus in a different building typology. The Surface-area-**
262 **over-volume ratio, SA:V, for each building is also given as a synthetic parameter of the building geometry: it is**
263 **defined as the ratio between the total surface area of the building that surrounds the heated/cooled volume and is**
264 **exposed to outdoor conditions (including the surface area that touches the ground), and the heated/cooled**
265 **volume of the building.**

266 The stability of the optimal façade configuration with respect to different efficiencies of the HVAC system is
267 investigated too. The efficiency of the SCOP is increased by 25% or decreased by 25%. In Table 4, the HVAC
268 efficiencies are reported. Four possible configurations are evaluated and resumed in Tables 5:

269 1) a reference SCOP heating and an more efficient SCOP cooling;

- 270 2) a reference SCOP heating and a less efficient SCOP cooling;
- 271 3) a more efficient SCOP heating and a reference SCOP cooling;
- 272 4) a less efficient SCOP heating and a reference SCOP cooling.

273 The reference building (B2, SA:V = 0.25 m⁻¹) is used during this phase, and the combination of different
274 efficiencies and different building geometries is not investigated.

275 4. Results

276 4.1 Optimal set-point value for the activation of the solar shading device

277 In Table 6, the optimal set-point values for the activation of the solar shading system, for each orientation and
278 transparent percentage, are presented. In Figure 4 and 5, the extra energy demands caused by non optimal set-
279 point values are plotted – when the extra energy demand is 0, the optimal set-point value is reached.

280 The optimal activation set-point decreases as the transparent percentage increases, for a south-exposed façade
281 (Fig. 4a). In the case of a WWR = 20%, the solar heat flux that minimizes the total energy demand is 400 Wm⁻².
282 On the contrary, in the case of WWR = 80%, the best set-point value is 100 Wm⁻². Intermediated WWR require
283 intermediated activation fluxes. The highest deviation between the optimal set-point value and the worse set-
284 point value is achieved in the case of WWR = 80% and a set-point of 400 W m⁻² – 6% more energy than in the
285 case of the optimal activation heat flux.

286 Solar shading devices should not be placed on a north-exposed façade (cf. Fig. 4b), since the lowest total energy
287 demand is always achieved with activation flux equal or greater than 400 W m⁻² – which never occurs on a
288 north-exposed façade. A low set-point value (e.g. 100 Wm⁻²) reduces the ability to exploit daylight and increases
289 the total energy demand of about 5-7%.

290 In the case of a west-exposed façade (Fig. 5a), the optimal set-point value is usually in the range 200-300 Wm⁻².
291 The only façade module configuration that requires a different set-point value (400 Wm⁻²) is WWR = 20%, and
292 a “wrong” set-point value may cause an increase in the total energy demand of about 3-4 %. East-exposed
293 façade (Fig. 5b) shows a similar behaviour to west-exposed façade. The lowest set-point value (100 Wm⁻²) is
294 always the less efficient, regardless the WWR. A non-optimal set-point value can increase E_{tot} of about 4-6%.

295 4.2 Optimal configuration of the façade module

296 After the optimal activation set-point values are determined, two B2 buildings (having SA:V = 0.25 m⁻¹) are
297 simulated: one with south and north façades (cf. Fig 2b); one with west and east façades (cf. Fig. 2c). Therefore,
298 two façades are analyzed by means of the same set of simulations. 25 simulations for each building are then
299 necessary, given by the combination of 5 different WWR for the front façade, and the same 5 different
300 transparent surface percentages for the back façade. This also determines that, for each WWR analyzed on the
301 front façade, five different E_{tot} are obtained, depending on the configuration of the back façade.

302 For each orientation analyzed, five E_{tot} parametric curves are thus obtained, where the parameter is the WWR of
303 the opposite façade (Figures 6-7). It must be stated that, regardless the transparent percentage of the opposite
304 façade, the difference in the E_{tot} for each transparent percentage is always lower than 3% (south-exposed
305 façade); furthermore, the parametric curves show the same pattern; moreover, the minimum value of E_{tot} is
306 always reached around the same value of transparent percentage. It is thus possible to affirm that the influence
307 of the opposite façade is not significant for the scope of the research, even if it has an influence on the final E_{tot} .

308 In the case of a south-exposed façade module (Fig. 6a), the optimal configuration has a WWR between 35% and
309 45%. The difference in performance between the “optimal” and the “worst” configurations is about 6%. The
310 performance of the north-exposed façade (Fig. 6b) is also affected by the configuration of the opposite façade.
311 In particular, when the WWR of the south-exposed façade is 20%, the performance of the north façade worsens
312 considerably. A less relevant change in the performance of the façade is registered when the south façade has
313 WWR > 35%. The optimal configuration of the north-exposed façade module, regardless the WWR of the
314 opposite (south) façade, is achieved when WWR is in the range 35-50%. The difference in the performance
315 between the optimal and the worse WWR is just more than 11% – being WWR = 30% the worst configuration.

316 The performance of the west-exposed façade module (Fig. 7a) shows a lower dependence on the configuration
317 of the opposite (east) façade. The dependence increases when the opposite façade has WWR > 50%. The
318 difference between the optimal and the worst configuration is about 7%. The optimal configuration is achieved
319 when WWR is in the range of 35-45%. The pattern of the east-exposed façade module (Fig. 7b) is similar to that
320 of the west-exposed façade, and the best configuration is again achieved when WWR is in the range 35-45%.
321 The difference in E_{tot} between the best and the worst configuration is about 8-9%.

322 4.3 Daylighting and visual environment

323 In Figure 8 the DA, and the $UDI_{100-500}$, $UDI_{500-2000}$ and $UDI_{>2000}$ are shown, for all the four main orientation, as
324 functions of the WWR. The values given in Figure 8 are the average values over the entire work plane (0.80 m
325 from the floor) of the office room, and include dynamic use of solar shading devices.

326 Regardless the orientation, $DA > 50\%$ is obtained for façade configurations with $WWR > 30\%$, and the
327 maximum value of DA (about 70%) occurs when $WWR = 80\%$ (Fig. 8a). The similarities in the reached values,
328 that seem to be independent from the façade orientation, can be explained considering that the activation of the
329 venetian blinds differs for each WWR and orientation.

330 Even if a systematic investigation of the impact of façade configuration on glare is out of the scope of this work,
331 the analysis of $UDI_{>2000}$ may give advice of the risk of glare discomfort in the room. In Figure 8b it is possible
332 to observe that the worse condition ($UDI_{>2000} \approx 25\%$) is reached in case of a south oriented façade, with $WWR =$
333 65% , or in case of an east oriented façade, with $WWR = 80\%$. In the range where the optimal façade
334 configurations lie (i.e. $35\% < WWR < 50\%$), the $UDI_{>2000}$ is about 20% for a south exposed façade, and about
335 12% in east/west exposed façades.

336 In Figures 8c and 8d the $UDI_{100-500}$ and $UDI_{500-2000}$ are shown, respectively. In particular, it can be notice that for
337 about 45-55% of the time, the average illuminance values fall in the range 500-2000 lux, regardless the façade
338 orientation, provided that $WWR > 30\%$. Within the optimal façade configuration range, south, west and east
339 exposed façades present a $UDI_{500-2000} \approx 50\%$, and the north exposed façade a $UDI_{500-2000}$ in the range 55-60%.

340 A more detailed analysis of the visual environment inside a south-exposed office is carried out. The useful
341 daylight illuminance distribution on the work plane is plotted in Figure 9 as a function of the distance from the
342 façade. Risk of glare discomfort is relatively high, regardless the WWR, in the area closest to the façade, while
343 far away from the façade $UDI_{>2000} < 30\%$ (Fig. 9b). A good light distribution and uniformity is revealed by the
344 analysis of $UDI_{500-2000}$ (Fig. 9a). For $WWR > 35\%$, the central area of the office room (0.9-4.5 m from the
345 façade) shows $UDI_{500-2000}$ in the range 40-50%, meaning that for about half of the time the most important part
346 of the office room presents satisfactory (and tolerable) daylight conditions, preventing the use of artificial light.

347 **4.4 Reliability of the optimal configurations**

348 *4.4.1 Reliability with respect to the geometry of the building*

349 During this phase, the average value of E_{tot} is used for each WWR of the façade module. As previously
350 described, for each WWR analysed on the front façade, five different E_{tot} are obtained, depending on the
351 configuration of the back façade. The E_{tot} plotted in Figures 10-11 are the average of the five different E_{tot} ,
352 obtained from the simulations with different WWR in the back façade. This can be done because the influence
353 of the opposite façade is found not to be relevant when the optimal configuration is searched.

354 The analysis points out that the building geometry affects the total energy performance of the building – the
355 lower the SA:V, the best the total energy performance. However, it also shows that the optimal WWR is
356 independent from the building geometry (Figures 10-11): the patterns for the three buildings B1, B2 and B3 are
357 very similar and the minimum value is always reached in the same interval.

358 A more detailed analysis reveals that different geometries have a relevant influence on the energy demand for
359 heating E_H . In Fig. 12a and Fig 12b, E_H as a function of the WWR is presented, for a south-oriented and a north-
360 oriented façade module, respectively. It is possible to notice that the three patterns are similar but with a
361 difference in magnitude – this difference is of course caused by the different geometry of the three buildings. It
362 is also possible to notice that E_H is not really affected by the WWR in a south oriented façade (Fig 12a). This is
363 probably due to the relatively high density of the internal loads, which contributes to reduce the energy demand
364 for heating. Passive use of solar energy (solar heating), which may occur in case of large transparent surfaces,
365 seems to have little or no influence on the energy demand. In fact, even if the activation of the shading also
366 blocks possible passive solar gains, their influence on the final energy demand is not significant: if solar shading
367 systems were not activated, a reduction of maximum 7% on the E_H would be achieved. On the other case, the
368 total energy demand of the building would increase considerably (up to 40% more) because of the increased E_C .
369 Contrary to what observed in the south-exposed façade, in the case of a north-oriented façade module (Fig. 12b)
370 a higher WWR in the façade module determines a higher energy demand for heating E_H .

371 The energy demand for cooling E_C and lighting E_L (Fig. 12c and 12d, respectively) is almost independent from
372 the building geometry. In Fig 12c, the three plots related to the three different buildings are very similar in shape
373 and in values. This means that this parameter has little or no influence on the cooling energy demand. For the
374 reference case (B2, SA:V = 0.25 m⁻¹), the cooling energy demand may increase by more than 70% from the
375 optimal WWR to the worst WWR, with a non-linear trend as the WWR increases.

376 The energy for lighting E_L as a function of WWR is plotted in Fig. 12d, for a south exposed façade. The energy
377 for lighting shows also a low dependence on the building geometry, mainly due to the fact that, in the simulated
378 buildings, **the higher SA:V (correspondent to B3)**, the higher the ratio between the office rooms (that can exploit
379 daylight) and other spaces (where no daylight exploitation occurs). The lowest energy consumption for lighting
380 is achieved with high WWR, even if each WWR adopts a different shading activation set-point. E_L can be
381 increased by more than 40%, if the worse configuration is chosen. It is worth mentioning that in Fig. 12 only the
382 data concerning south- and north-exposed façade modules are reported; however, similar conclusions and trends
383 can be seen for the other two orientations.

384 4.4.2 Reliability with respect to the HVAC system efficiency

385 In Figure 13, the E_{tot} as a function of the WWR is plotted, in case of HVAC systems with different efficiencies.
386 The curves are, of course, translated because of the higher/lower efficiency of the HVAC system, but a change
387 in the SCOP heating determines very little consequences on the shape of the E_{tot} curves. The only orientation
388 that is slightly affected by a better/worse SCOP heating is the north (Fig. 13b). However, since the shape of the
389 curves does not change (or change very little), the optimal WWR is always reached in the same interval. It is
390 thus possible to state that the optimal configurations are independent from the efficiency of the heating systems
391 – assuming that the SCOP heating stands in the range $2.6 \pm 25\%$.

392 An improvement/worsening of the performance of the cooling system has a wider impact on the shapes of the
393 E_{tot} (WWR) function instead. Higher efficiency flattens the E_{tot} curve, allowing the optimal configuration to be
394 more transparent. For a south-exposed façade module (cf. Fig. 13a), the optimal configuration changes: from a
395 WWR in the range 35-45% to WWR in the range of 45-55%. This behaviour can be observed for all the other
396 orientations as well (Fig. 13c and 13d), with very similar trend. A less efficient cooling system affects the shape
397 of the E_{tot} curve too, but with a lower impact on the position of the minimum value of the E_{tot} : the optimal
398 configuration is almost always a little less transparent (about 5%) than the one calculated with the reference
399 HVAC system. The south-exposed façade module (cf. Fig. 13a) is the one that is most affected by the worsening
400 of the cooling equipment's performance.

401 5. Discussion

402 Apparently, the search for the optimal WWR of a façade module in a low-energy office building reveals that the
403 façade configuration has little influence on the final total energy demand (E_{tot}) of the building. This result is in

404 trend with the findings from the literature review, revealing that the less the energy consumption, the less the
405 impact of the façade on it: from a reduction up to 50% in the late Seventies [4] (when conductance of an opaque
406 wall was more than $5 \text{ W m}^{-2} \text{ K}^{-1}$, single glazing was a standard solution and luminous efficacy was about 20 lm
407 W^{-1}), down to about 16% [19] for a low energy building, and further down to about 10% in this paper.

408 The optimal WWR can be found, almost regardless the orientation, in the range $35\% < \text{WWR} < 45\%$. The north
409 orientation is that where a “wrong” WWR has the deepest impact. In this case, an increase of just more than
410 11% in the E_{tot} can occur, if a low transparent percentage is chosen ($\text{WWR} = 20\%$) instead of an optimal WWR.
411 For the other orientations, the increase in the E_{tot} with respect to the optimal solution is between 6% and 9%. It
412 is important to state that there seems not to be an orientation where the optimal WWR is completely different.
413 This is a positive aspect that may allow a simplification to be done, during the first stage of the design of a
414 building, as well as an advantage in terms of prefabrication of the façade modules.

415 However, it is important to underline that the technologies that are adopted by the façade are robust and efficient
416 in term of prevention of heat losses and heat gains; furthermore, a preliminary optimization of the set-up value
417 for the activation of the solar shading systems was carried out. Thus, the chosen technology and the adopted
418 control strategies are already optimized.

419 Moreover, the high density of internal loads may also play a role in the reduction of the influence of the façade
420 on the energy demand of the building. In order to highlight this aspect, some simulations with different internal
421 loads and presence of solar shading system are carried out and the impacts of these changes evaluated. In Figure
422 14 the reference configurations (full internal loads) and the configurations without internal loads (from electric
423 equipment and people) are shown, for a south- and a north-exposed façade (Figs. 14a and 14b, respectively). It
424 is possible to notice that, without internal loads, the increase in energy demand due to the worst WWR
425 configuration is more than 20% (south façade); furthermore, the optimal WWR also changes. As far as a north-
426 exposed façade is concerned, E_{tot} increases by about 13%, and the optimal WWR changes too

427 As far as the impact of the use of solar shading system is concerned (Fig. 15), the only south-exposed façade has
428 been analysed. A non-optimal WWR in case of absence of solar shading may determine an increase in the in the
429 E_{tot} of more than 50% (Fig. 15a). In case of contemporary absence of internal loads and solar shading systems
430 (Fig. 15b), due to the balance between the increased solar gain and the reduced internal loads, the difference on
431 the energy demand between the best and worst WWR is only about 19%, and the optimal WWR under these
432 circumstance is very similar to that of the reference configuration (full internal loads, venetian blinds).

433 It is therefore possible to state that the façade configuration (WWR) presents a low impact on the final energy
434 demand, in office buildings, only if the façade is made with up-to-date technology and managed in a proper
435 way. The relatively low influence of the WWR on the E_{tot} is confirmed by the reliability analysis: the optimal
436 WWR, within the same building type (single corridor office building with cell offices), seem to be almost
437 independent from the exact geometry of the building, as well as from a different efficiency of the HVAC
438 system. Only a noticeable increase in the efficiency of the cooling equipment may determine a slightly change
439 in the optimal configurations – allowing more transparent façade modules to be realized and a decrease of the
440 total energy demand achieved.

441 This finding may allow building with rather different appearances to be designed, since the WWR may not
442 determine a huge increase in the energy demand of the building. On the other side, it can be highlighted that it is
443 possible to reach an optimal configuration, which may reduce to the minimum extent – as far as allowed by the
444 technology – the total primary energy demand of the building.

445 Finally, as far as the impact of different WWR on the visual environment, it can be seen that the different
446 activation flux for each WWR (and orientation) reduces the influence of the different WWR on the visual
447 environment. The daylighting conditions are very similar for all the WWR, except for the lowest values ($20\% <$
448 $WWR < 30\%$): under these circumstances, the DA is lower than 50% for some orientations and $UDI_{500-2000}$ is
449 lower than 45% for all the orientation. No substantial differences are revealed by the analysis of the orientations:
450 only a north-oriented façade (where venetian blinds are never displaced) the $UDI_{500-2000}$ reaches higher value
451 compared to the other façade, especially for high WWR ($UDI_{500-2000} = 70\%$ in case of $WWR = 65\%$). The south,
452 west and east exposed façades also show a very similar trend of the $UDI_{>2000}$. It is mandatory to remember that,
453 some dedicated research activities [27] has shown the tendency of *Energy Plus* to overestimate the illuminance
454 level, though this inaccuracy is still acceptable. As result of this fact, simulations of the visual environment may
455 present a lower degree of accuracy, compared to the thermal simulations.

456 **6. Conclusion e future works**

457 The results of the research activity show that the configuration (WWR) of an advanced façade module (with
458 state-of-the-art technologies) has a low influence on the total energy need of the building. The north-exposed
459 façade is the one that may suffer most from a “wrong” configuration, while the south-exposed façade is the one
460 where the influence of the façade configuration is the lowest. The minimum total energy demand is always

461 achieved when WWR is in the range 35-45%. In this range, daylighting conditions are also satisfactory and this
462 transparent percentage can therefore be considered a good starting point in preliminary design phase The
463 analyses show a little dependence of $E_{tot}(WWR)$ on the building geometry and the HVAC's efficiency, but a far
464 higher dependency is revealed if the internal loads are changed, or if the solar shading systems are not (properly)
465 activated. This behavior can be explained considering that the influence of the façade in the case of a low-
466 energy building is much lower than it used to be in conventional building – of course, provided that state-of-the-
467 art technologies are adopted, and that solar shading systems (and their activation) are optimally exploited.

468 The method has been applied in this paper to an office building located in a temperate oceanic climate, that
469 represents a large area of Atlantic and Central Europe, and results are therefore significant for this climate only.
470 In the future, the method will be applied to different locations in order to highlight the influence of each climate
471 on the optimal WWR and to give advices for façade design of low-energy office buildings in different climates.

472

473 **Acknowledgements**

474 The authors would like to thank prof. Anne Grete Hestnes of NTNU and Dr. Berit Time of SINTEF for
475 reviewing the paper and their advices. The Research Centre on Zero Emission Building of the Faculty of
476 Architecture and Fine Art, Norwegian University of Science and Technology (Norway) and the SINTEF
477 Building and Infrastructure (Norway) are gratefully acknowledge for support and host during the “*Bando Alta*
478 *Formazione*” internship, a programme of Politecnico di Torino.

479

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561

- 1 Figure 1. Geometry of the simulated façade modules characterized by different WWR.
- 2
- 3 Figure 2. a) Plane concept of the office building. b) Subdivision of the volume building in two volumes
4 associated to two main orientations
- 5
- 6 Figure 3. Schematic illustration of the workflow and of the different simulations performed to determine the
7 optimal WWR for each orientation
- 8
- 9 Figure 4. Extra energy demand determined by non-optimal set-point values for the activation of solar shading
10 devices, for different transparent-to-opaque ratios: a) south-oriented façade; b) north-oriented façade
- 11
- 12 Figure 5. Extra energy demand determined by non-optimal set-point values for the activation of solar shading
13 devices, for different transparent-to-opaque ratios: a) west-oriented façade; b) east-oriented façade
- 14
- 15 Figure 6. a) Total energy demand E_{tot} for a south-oriented façade module. b) Total energy demand E_{tot} for a
16 north-oriented façade module. B2, SA:V = 0.25 m⁻¹
- 17
- 18 Figure 7. a) Total energy demand E_{tot} for a west-oriented façade module. b) Total energy demand E_{tot} for an
19 east-oriented façade module. B2, SA:V = 0.25 m⁻¹
- 20
- 21 Figure 8. a) Daylight Autonomy for different orientations; b) $UDI_{>2000}$ for different orientations; c) $UDI_{100-500}$ for
22 different orientations; $UDI_{500-2000}$ for different orientations, B2, SA:V = 0.25 m⁻¹
- 23
- 24 Figure 9 a) $UDI_{500-2000}$ for different WWR as a function of the distance from the façade (south-oriented façade
25 module); b) $UDI_{>2000}$ for different WWR as a function of the distance from the façade (south-oriented façade
26 module). B2, SA:V = 0.25 m⁻¹
- 27
- 28 Figure 10. Total energy demand E_{tot} for different building geometries B1, B2, B3: a) south-oriented façade
29 module b) north-oriented façade module
- 30
- 31 Figure 11. Total energy demand E_{tot} for different building geometries B1, B2, B3: a) west-oriented façade
32 module b) east-oriented façade module
- 33
- 34 Figure 12. a) Heating energy demand E_h for different building geometries B1, B2, B3 (south-oriented façade
35 module); b) Heating energy demand E_h for different building geometries B1, B2, B3 (north-oriented façade
36 module); c) Cooling energy demand E_c for different building geometries B1, B2, B3 (south-oriented façade
37 module); d) Lighting energy demand E_l for different building geometries B1, B2, B3 (south-oriented façade
38 module)
- 39

40 Figure 13. E_{tot} as a function of the transparent percentage in case of HVAC systems with different efficiencies:
41 a) south-oriented façade module; b) north-oriented façade module; c) west-oriented façade module; d) east-
42 oriented façade module. B2, SA:V = 0.25 m⁻¹

43

44 Figure 14. Total energy demand E_{tot} for different for different WWR, with and without internal loads (people
45 and equipment): a) south-oriented façade module; b) north-oriented façade module. B2, SA:V = 0.25 m⁻¹

46

47 Figure 15. Total energy demand E_{tot} for different for different WWR in a south-oriented façade module: a) with
48 and without solar shading systems; b) without solar shading systems and without internal loads (people and
49 equipment). B2, SA:V = 0.25 m⁻¹

WWR : 35%

transparent area: 4.32 m²
opaque area: 8.26 m²



a: 1.200 m b: 1.100 m
c: 3.600 m d: 3.700 m

WWR : 50%

transparent area: 6.30 m²
opaque area: 6.28 m²



a: 1.750 m b: 0.625 m
c: 3.600 m d: 3.700 m

WWR : 65%

transparent area: 8.28 m²
opaque area: 4.30 m²



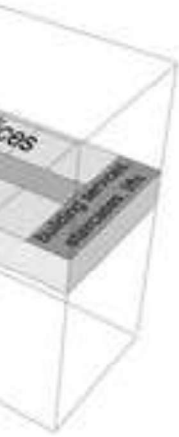
a: 2.300 m b: 0.550 m
c: 3.600 m d: 3.700 m

WWR : 80%

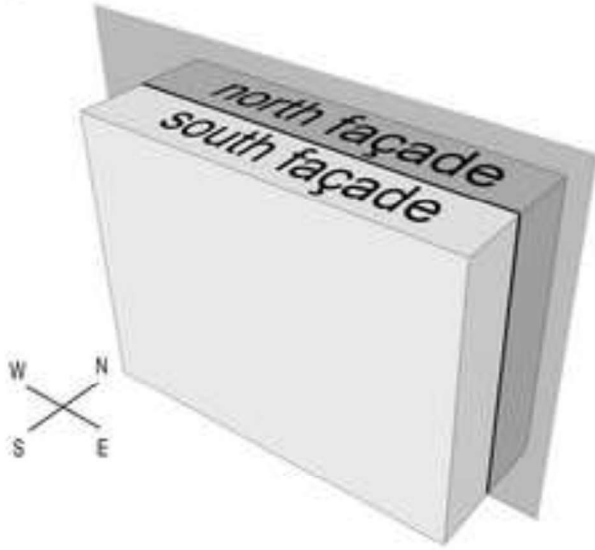
transparent area: 10.08 m²
opaque area: 2.50 m²



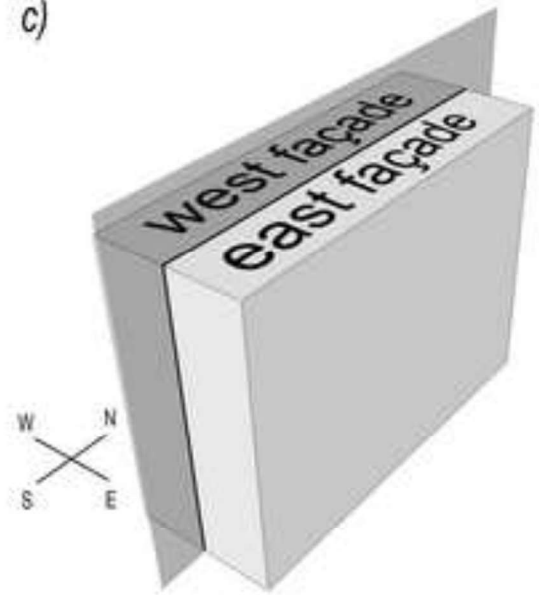
a: 2.800 m b: 0.300 m
c: 3.600 m d: 3.700 m



b)



c)



Figure_3

[Click here to download high resolution image](#)

Step I - Simulation on a single orientation

4 activation fluxes (100, 200, 300, 400 Wm⁻²) for each of the
5 WWR (20%, 35%, 50%, 65%, 80%), for each orientation

20 simulations for each orientation



Step II - Data analysis

determination of the optimal activation flux of the shading
device, for each of the 5 WWR and each orientation

$$f : \min \{E_{tot}\}$$



Step III - Simulation on the entire building

5 WWR for the front façade combined with
5 WWR for the back façade

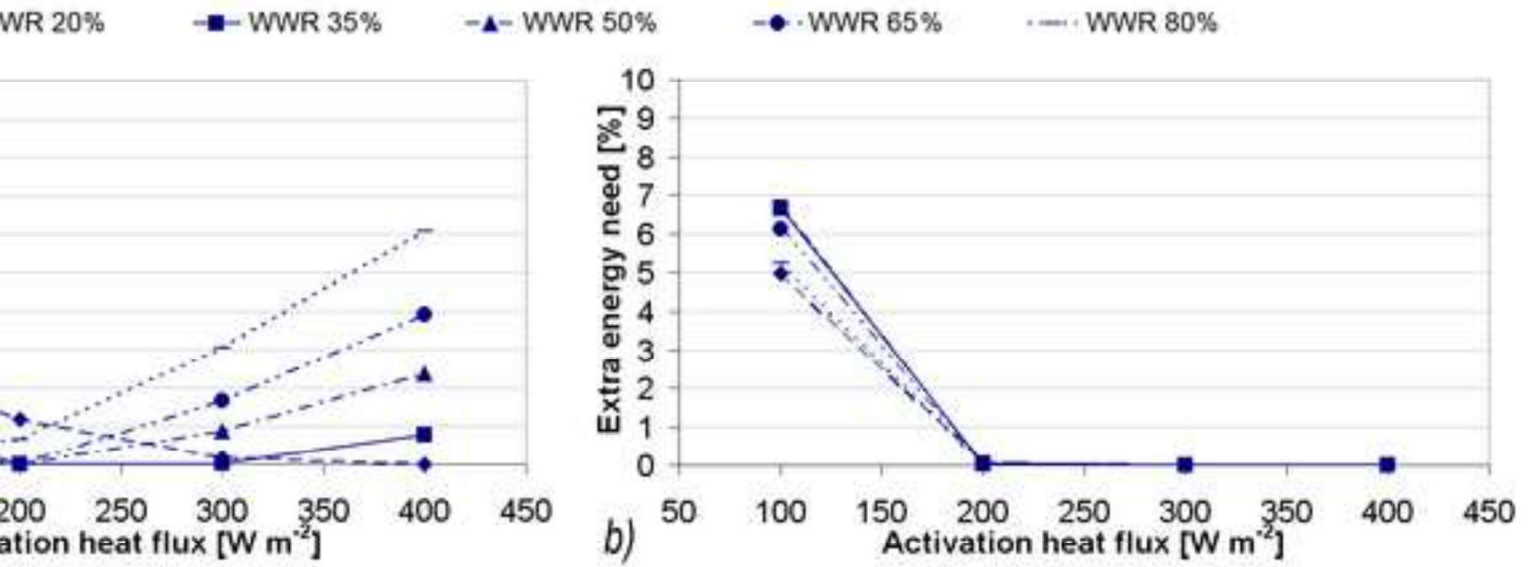
25 simulations for each building - two main façades: N-S or W-E

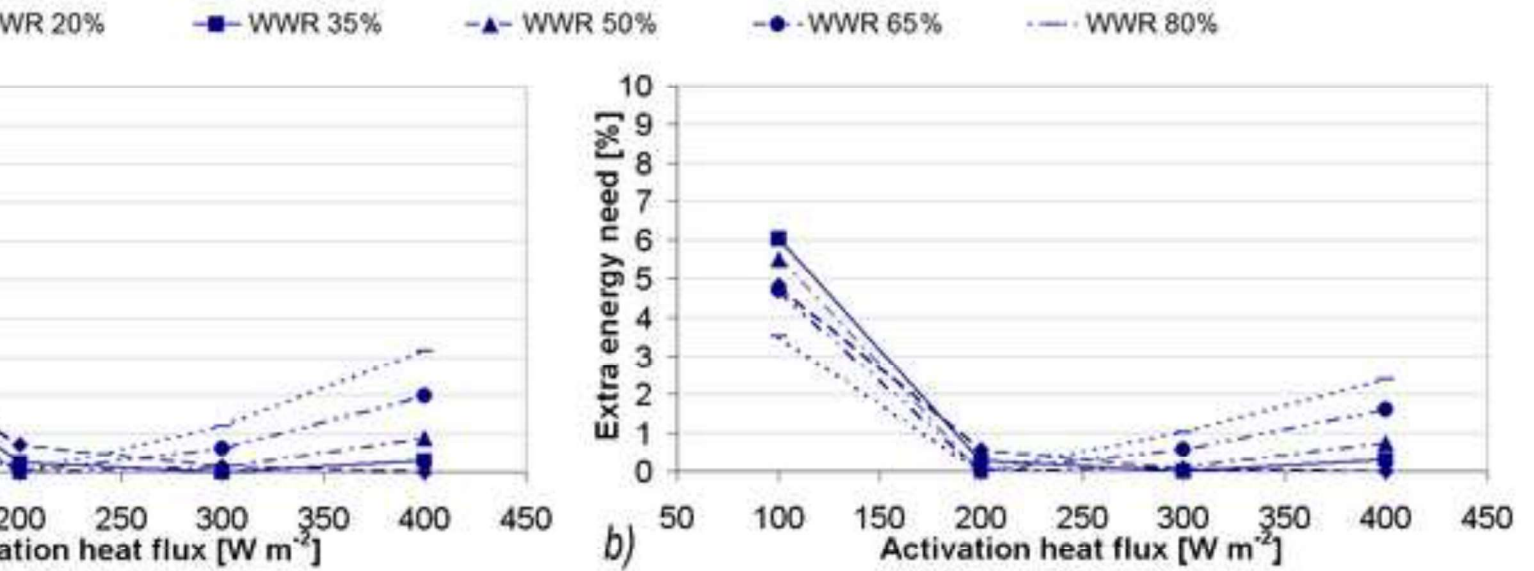


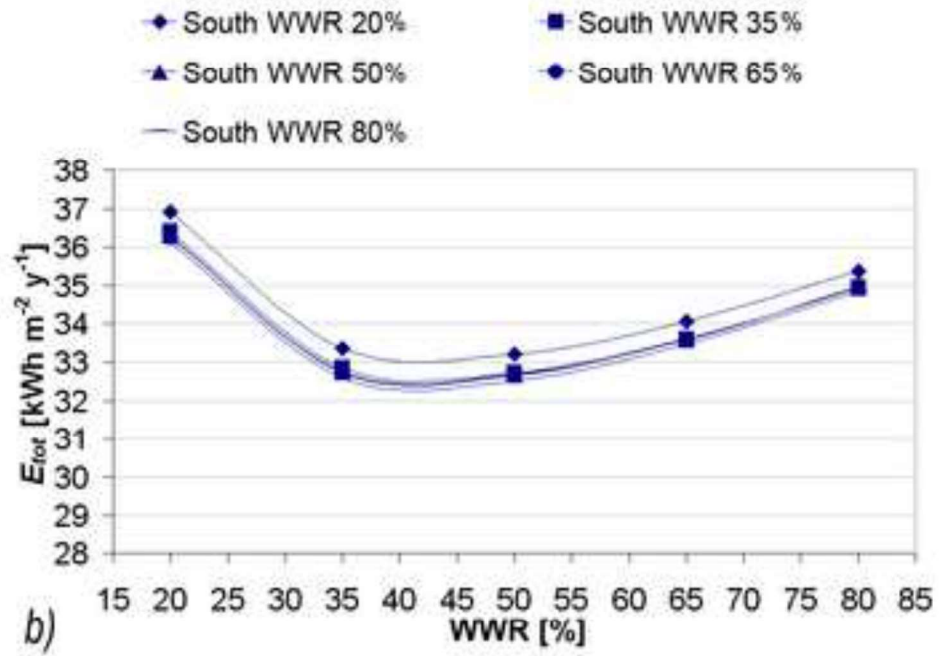
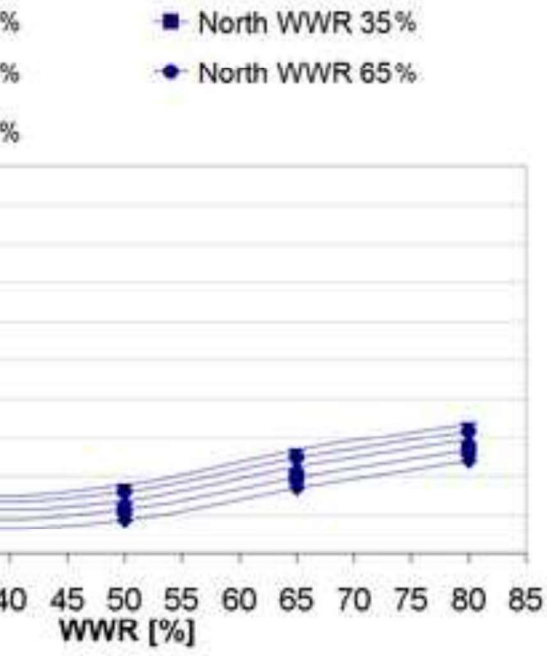
Step IV - Data analysis and final results

determination of the E_{tot} for each WWR and each façade
determination of the optimal WWR for the front and back façade

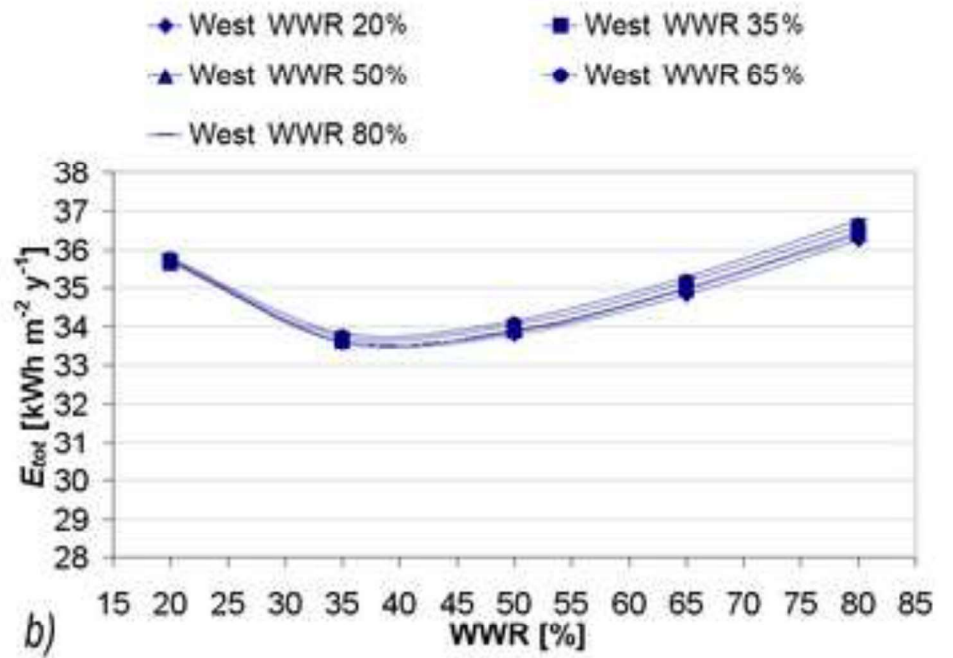
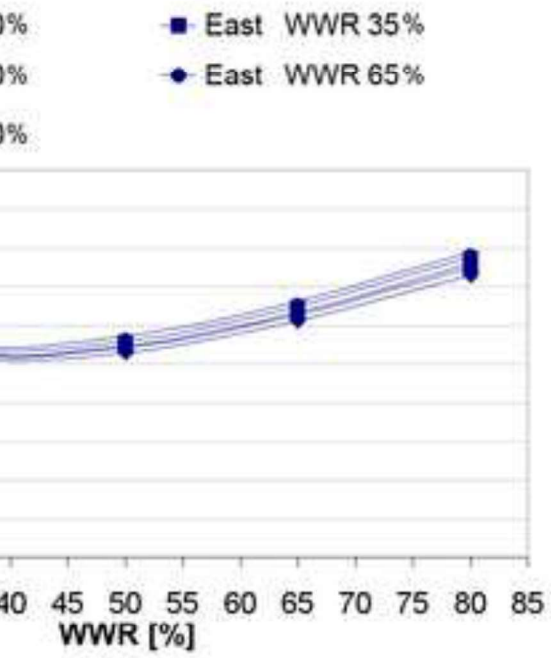
$$f : \min \{E_{tot}\}$$

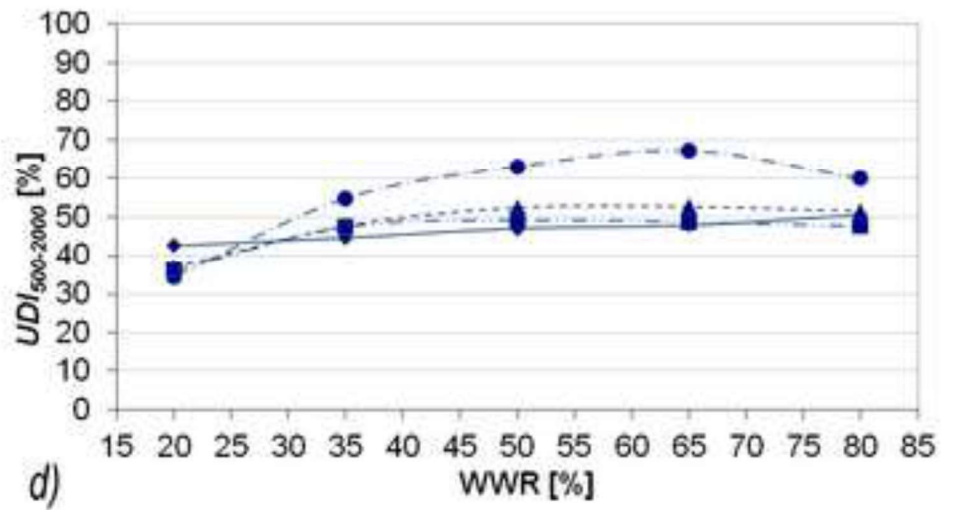
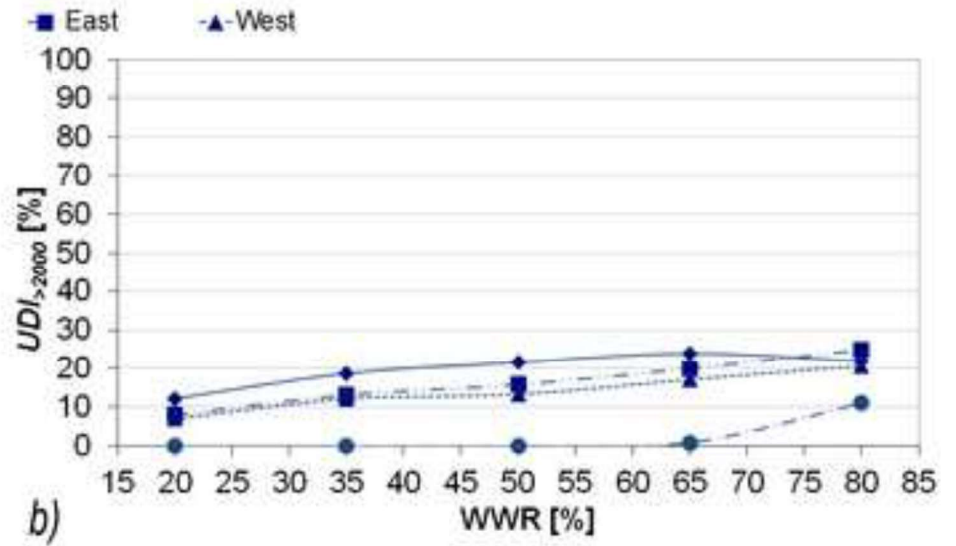
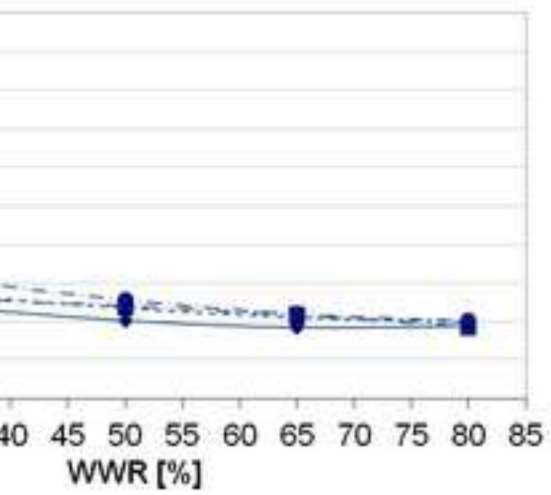
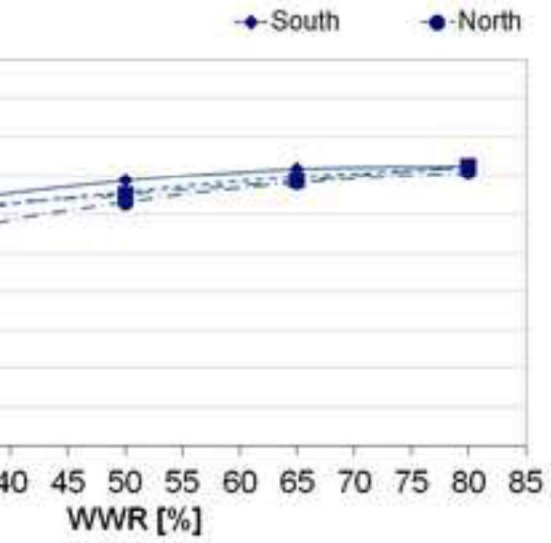


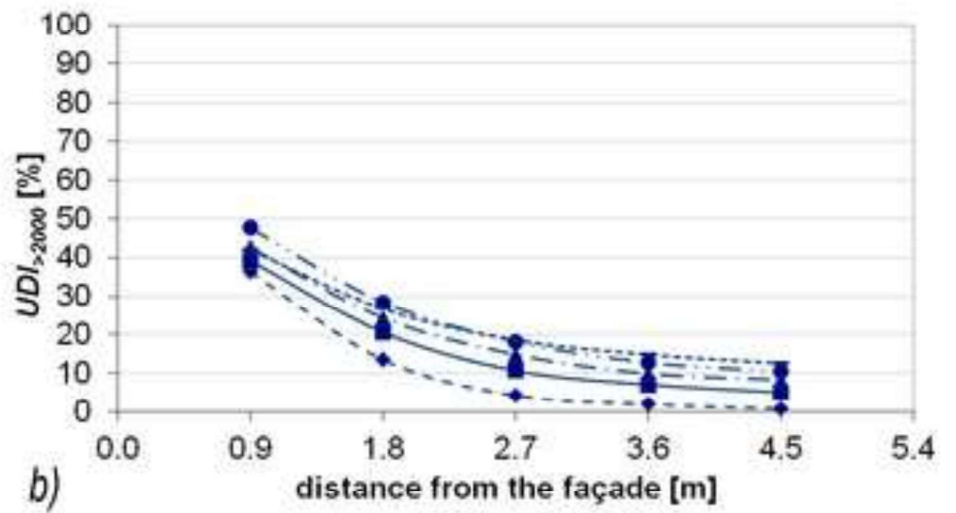
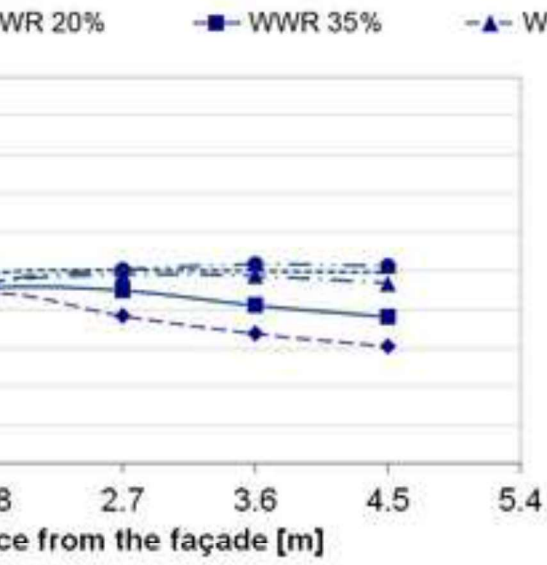


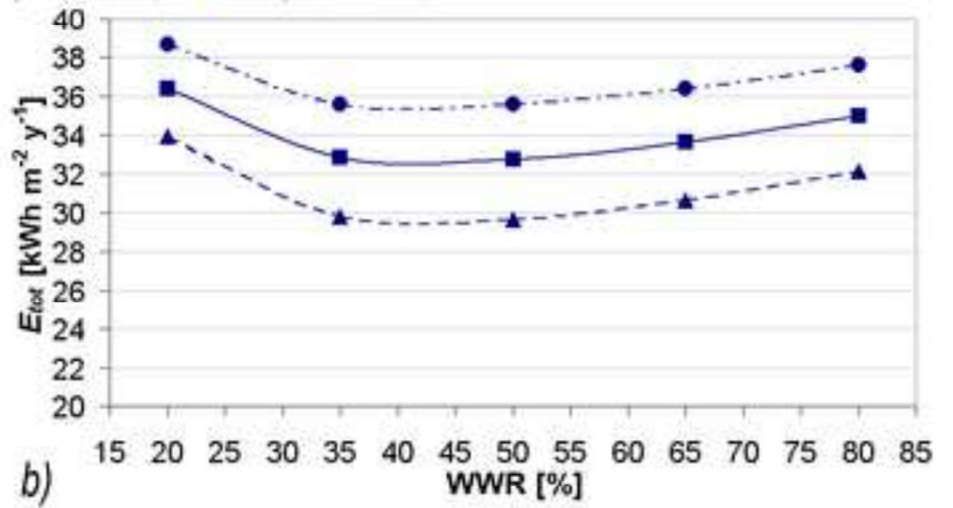
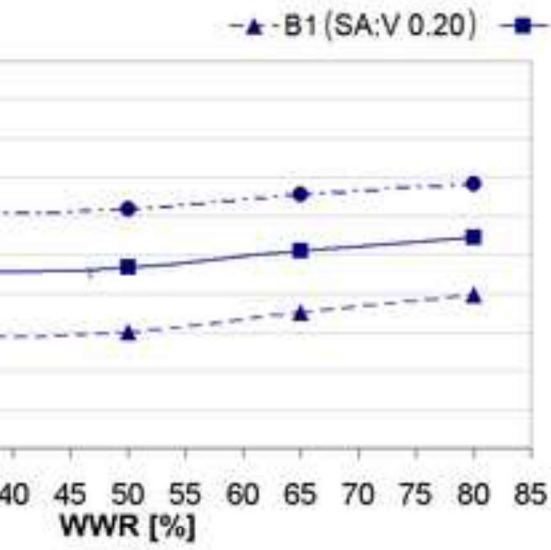


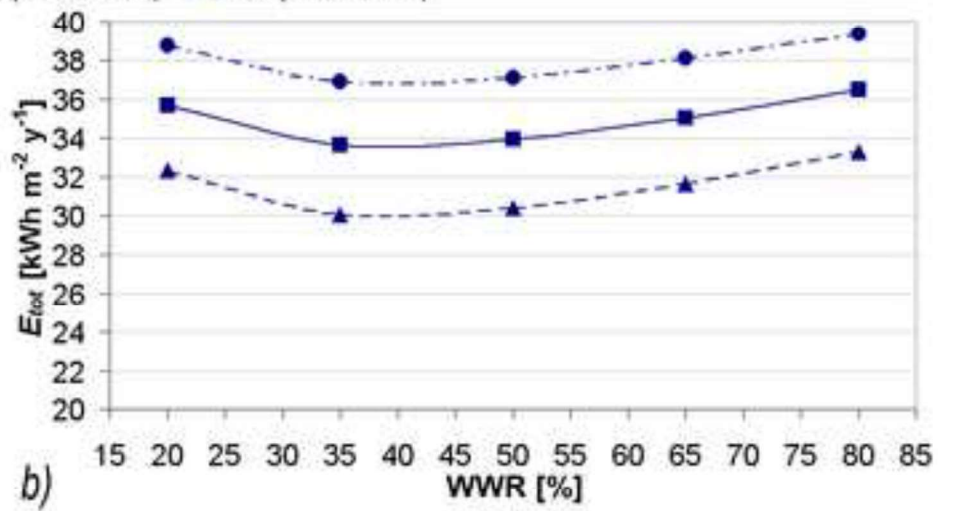
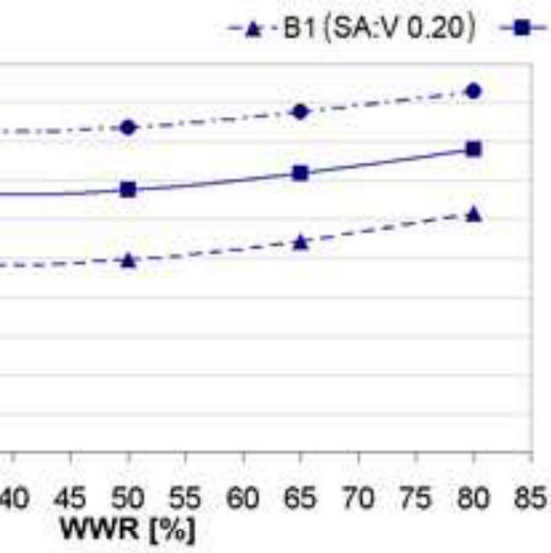
b)



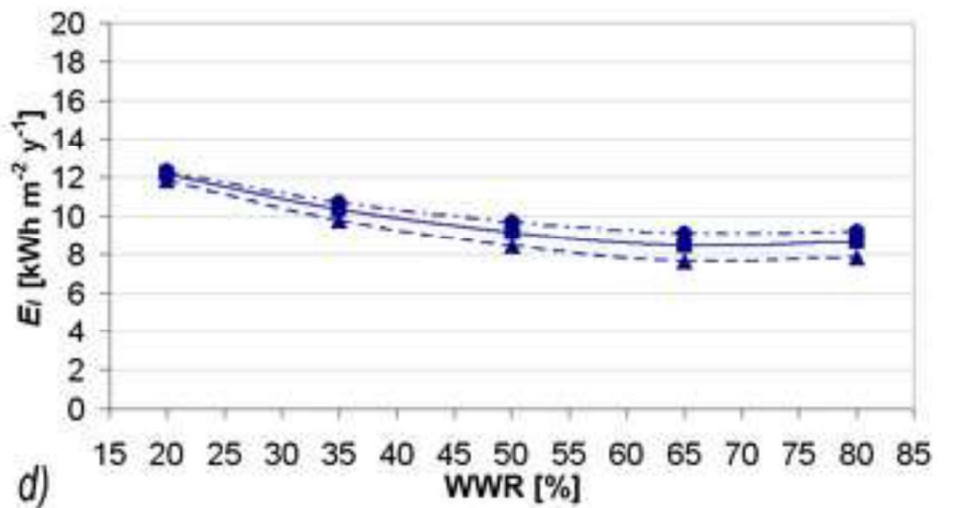
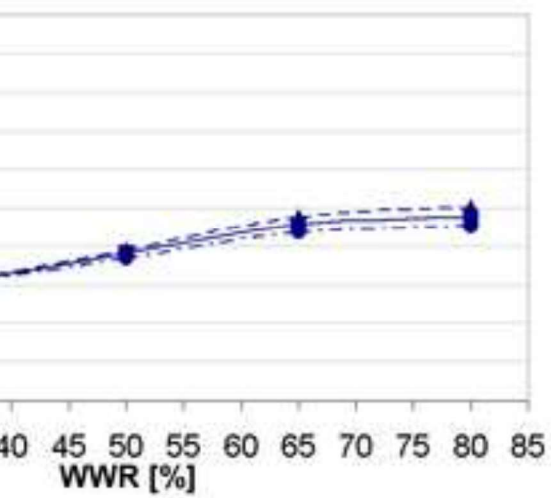
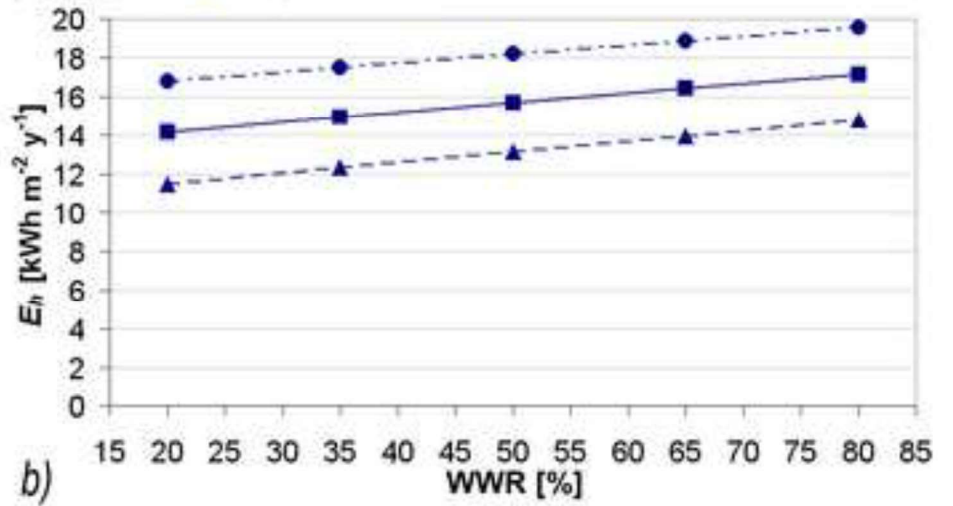
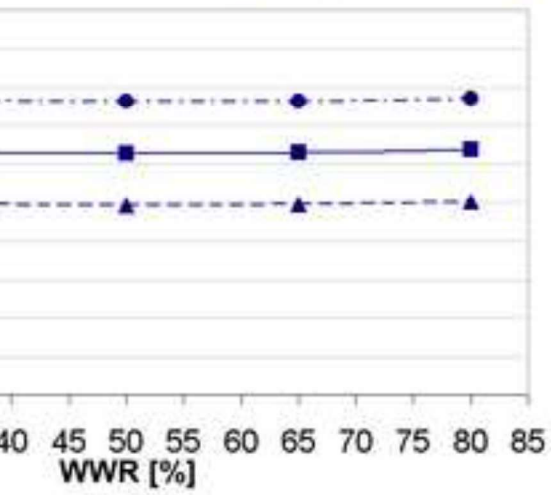


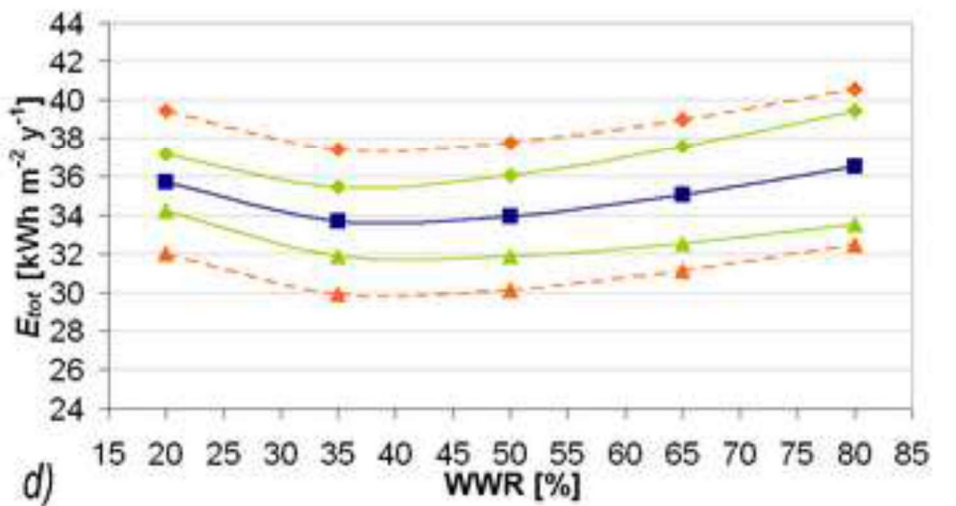
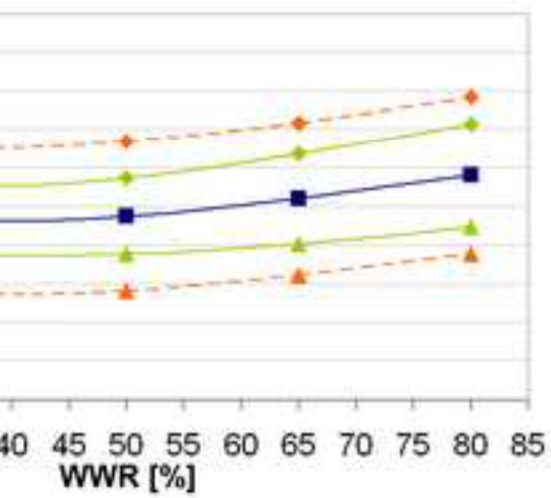
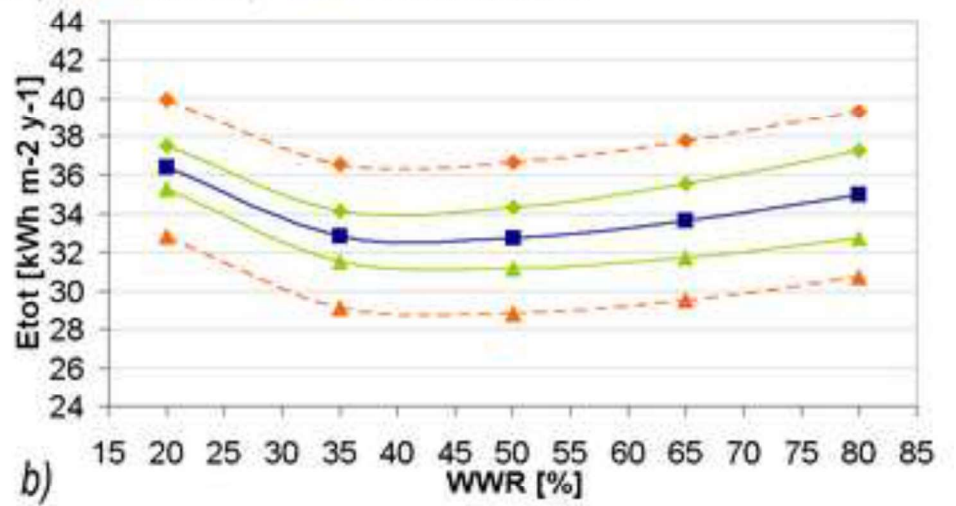
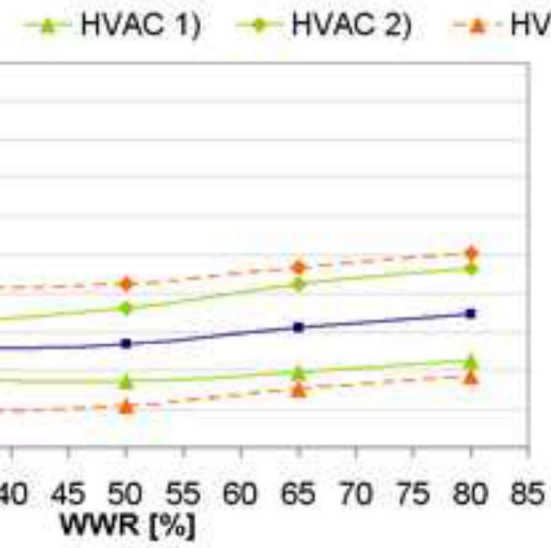


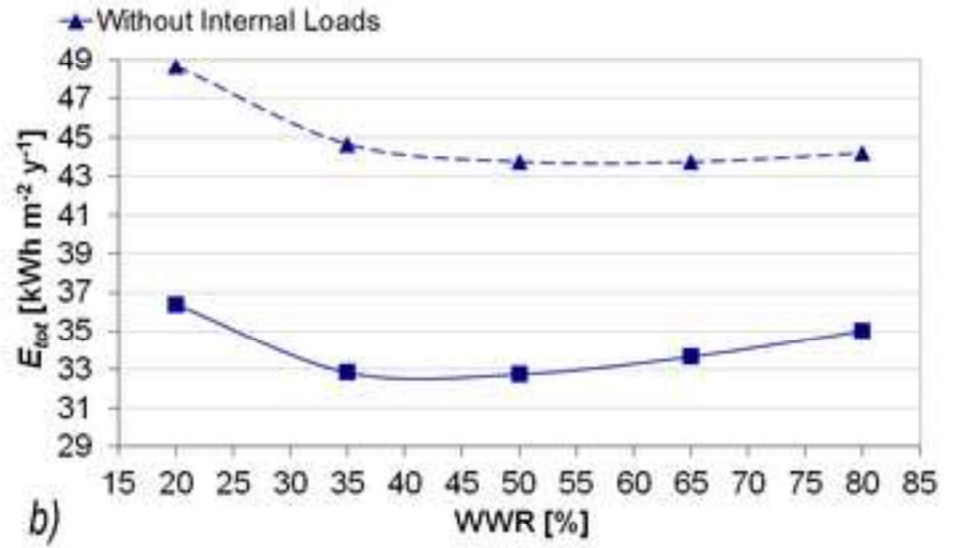
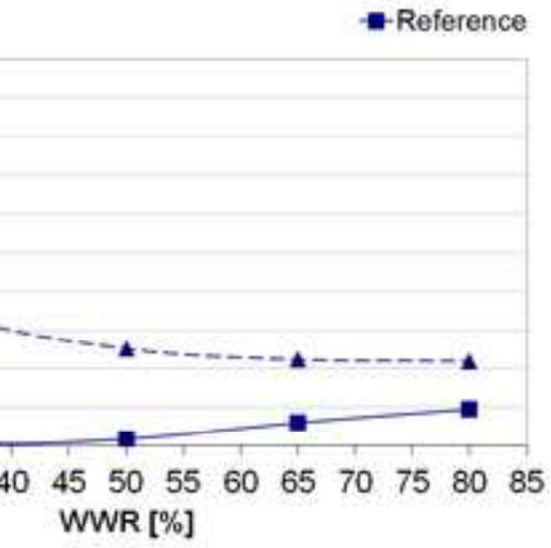




-▲- B1 (SA:V 0.20) -■- B2 (SA:V 0.25) -●- B3 (SA:V 0.30)







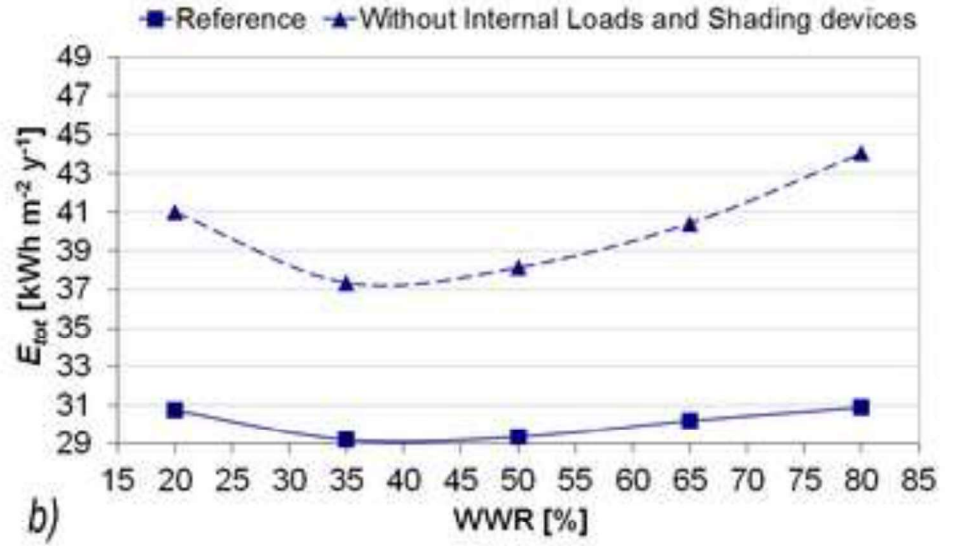
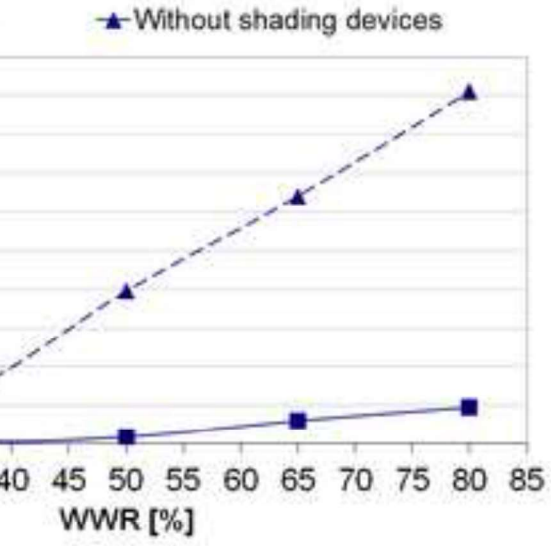


Table 1. HVAC system specifications

	Temperature set-point (heating/cooling)		HVAC specification				
	Summer	Winter	Mechanical ventilation	Heat Recovery Efficiency	Specific Fan Power	SCOP heating	SCOP cooling
	[°C]	[°C]	[l s ⁻¹ m ⁻²]	[-]	[kJ m ⁻³]	[-]	[-]
Occupancy <i>Mon – Fri</i> <i>8am – 5pm</i>	20 / 24	23 / 26	1.42	0.80	1.5	2.6	3.8
Non occupancy	17 / 27	20 / 29	0.70	0.80	1.5	2.6	3.8

Table 2. Internal loads and artificial light (office rooms only)

	Internal loads		Lighting	
	People [W m ⁻²]	Equipment [W m ⁻²]	Installed power [W m ⁻²]	Illuminance set-point [lux]
Occupancy <i>Mon – Fri</i> <i>8am – 5pm</i>	11.5	10.0	7.5	500
Non occupancy	0.0	1.0	7.5	0

1

Table 3. Dimensions of the three office buildings B1, B2 and B3

Code	SA:V [m ⁻¹]	Length (L) [m]	Width (W) [m]	Height (H) [m]
B1	0.20	53.3	14.4	90.1
<i>B2</i>	<i>0.25</i>	<i>45.9</i>	<i>14.4</i>	<i>28.9</i>
B3	0.30	38.5	14.4	18.7

2

Table 4. SCOP of the reference HVAC and of the more/less efficient systems

		<i>Reference HVAC</i>	More efficient HVAC (efficiency: +25%)	Less efficient HVAC (efficiency: -25%)
SCOP heating	[-]	2.60	3.25	1.95
SCOP cooling	[-]	3.80	4.75	2.85

Table 6. SCOP of the reference HVAC and of the more/less efficient systems

		HVAC 1)	HVAC 2)	HVAC 3)	HVAC 4)
SCOP heating	[-]	2.60	2.60	3.25	1.95
SCOP cooling	[-]	4.75	2.85	3.80	3.80

Table 6. Optimal set-point values for the activation of the solar shading device

		Façade orientation			
		South [Wm ⁻²]	North [Wm ⁻²]	West [Wm ⁻²]	East [Wm ⁻²]
WWR façade module	20%	400	(400)	400	400
	35%	200	(400)	300	300
	50%	200	(400)	200	200
	65%	100	(400)	200	200
	80%	100	(400)	200	200