Towards climate-based irradiation recommendations for optimal solar design: insights from a parametric study

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Summary

In the early phases of the building design process, decisions are made on certain geometrical parameters, which strongly dictate the future performance of the building. To support decision-making, an understanding of the relation between design parameters and performance is essential. This paper presents the results of two parametric studies conducted to investigate the impact of specific design parameters on three performance indicators related to solar potential and thermal and visual comfort. Results indicate which parameter has the strongest impact on each indicator and provide useful and potentially non-intuitive insights into the dynamics of building performance.

Keywords: solar potential, comfort, parametric study, early design parameters, passive zone concept

1. Introduction

In the field of sustainable architecture, a rising interest is being given to the study of solar radiation and its potential for decreasing energy demand – via passive means (e.g. daylighting) – and increasing building autonomy – via active systems (e.g. photovoltaic). For buildings located in a climate characterized by an extensive heating period, the most commonly adopted method to achieve these goals consists in maximizing the solar exposure of the buildings [1, 2]. This, however, gives little consideration to the potential negative impacts of high solar radiation levels on the total energy consumption and occupant comfort. Indeed, overheating occurs even – and at an increasing rate – in cold climates due to higher internal gains especially in modern buildings characterized by considerable glazing and insulation levels [3]. Hence, it is important that both environmental (energy) and social (comfort) domains of sustainability be considered simultaneously in the conception of buildings.

At the early design phase, practitioners must take decisions on various design parameters, such as building height and orientation [4]. Such decisions dictate to a large extent the future performance of the building in terms of energy consumption [1]. This study aims at investigating the implications of such early design parameters with respect to three performance criteria: (i) solar potential (for passive and active exploitation), and (ii) thermal and (iii) visual comfort of occupants.

The present paper proposes a first step towards the ultimate development of a comprehensive evaluation method that will provide *climate-based* recommendations in the form of irradiation thresholds for optimal performance both comfort and energy wise. An interactive, early design decision support methodology will be developed towards this end for improving the solar potential of urban district and neighbourhood designs. Prior to doing so, it is important to gain insight into the impact of specific early design parameters on comfort and solar exposure. The current study attempts to do so by addressing the following question: Do changes in early design parameters impact all performance indicators in the same manner (i.e. in an overall favourable or unfavourable way)? A review of the literature comprising studies assessing building performance provides first elements of answer. The a priori hypothesis is that certain changes (e.g. increase in the building height) will cause diverging performance variations (e.g. visual comfort decrease versus thermal comfort increase).

2. Related work

An extensive amount of research has been done on the evaluation of building performance regarding energy consumption, daylighting or solar radiation.

For example, by evaluating solar radiation incident on a building, Lobaccaro et al. [1] investigated the influence of footprint, covering ratio and height for a building of constant volume located in Milan. Optimal shapes and orientations were obtained, maximizing the solar exposure. Although relevant for the implementation of active solar systems, this method ignores possible repercussions on occupant comfort.

Hygh et al. [5] conducted a sensitivity analysis over a set of early design parameters such as orientation and aspect ratio (length/depth), identifying the most influential parameters per orientation over building energy consumption (heating, cooling and total energy). Such results provide guiding information for practitioners, but no consideration is given to the solar potential of the building.

Another set of studies evaluated the energy consumption associated to designs differentiated by their compactness (area of envelope over volume or floor area) [6,7]. Building compactness is a common heuristic used as an indicator of energy consumption: the more compact a building is (less exposed surface area for the same volume), the lesser are its heat losses. However, compactness was proven not to be an adequate indicator for all climates [6], or for whole energy consumption (including for instance cooling requirements) [7].

Ratti et al. [8] introduced and tested the passive zone concept at the urban scale, concluding it was a better energy indicator than compactness. A passive zone, defined as the area falling within 6 m of an exposed façade, can exploit daylight, natural ventilation and passive heating significantly more than a non-passive zone, located further inside the building.

Although the previous studies provide useful insights that can be used to support early phase decision-making, their common shortcoming is that they address a limited set (if not a unique) performance criteria. The current study aims at relating the three performance indicators previously introduced (solar potential and thermal and visual comfort) by simultaneously evaluating them. This approach represents a step towards the development of a sustainable and holistic evaluation method.

3. Methodology

3.1 Design of experiments

To study the impact of early design parameters on the three performance criteria, two parametric experiments were conducted. Each experiment consisted in a set of design iterations, referred to as scenarios, and characterized by specific parameter values. Each scenario was modelled and evaluated in an iterative process using the DesignBuilder [9] software. The base case model for each experiment consisted in a virtual generic office building of one floor (4 m high) located in Geneva, Switzerland, with a brick façade, a flat roof, dimensions of 20 m by 20 m (exp. 1) and 45 m by 40 m (exp. 2), and default construction values as given by DesignBuilder.

3.1.1 Experiment 1

The first experiment focused on three early design parameters: height, window-to-wall (w:w) ratio, and roof inclination [4,10]. Two values were defined for each parameter to create the eight scenarios listed in *Table 1*. Fig. 1 illustrates the base case design. A large interval was chosen between the two values defined, so as to make the differences significant and impacts more apparent.

Table 1: Experiment matrix 1. Values assigned to the 3 variable design parameters (factors) at each iteration (scenario).

	Factors (design parameters modified)		
Scenario	Height [m]	Window:Wall (surface ratio)	Roof
1	4	0.3	flat
2	20	0.3	flat
3	4	0.7	flat
4	20	0.7	flat
5	4	0.3	pitched
6	20	0.3	pitched
7	4	0.7	pitched
8	20	0.7	pitched

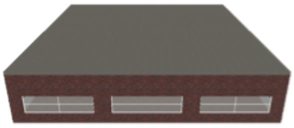

Fig. 1: Building design for scenario 1 of experiment 1

3.1.2 Experiment 2

The second experiment investigated the passive zone concept (introduced earlier [8]) in relation with building orientation. Assigning two values to each parameter created the four scenarios described in *Table 2*. The basic design, applied to all iterations, was given a flat roof and a height of 4 m (one level), while the glazing proportion was defined based on a reference value of 15% of the energy reference floor area [11], leading to a 40% window-to-wall ratio for scenarios 1 and 3, and a 21% window-to-wall ratio for scenarios 2 and 4. Fig. 2 illustrates scenario 2.

Table 2: Experiment matrix 2. Values assigned to the 2 variable design parameters (factors) at each iteration (scenario).

	Factors (design parameters modified)	
Scenario	Passive zone (% space within 6 m of façade)	Orientation (alignment of longer side of building)
1	48.7	N-S
2	100	N-S
3	48.7	E-W
4	100	E-W

Fig. 2: Building design for scenario 2 of experiment 2

3.2 Evaluation of performance criteria

The evaluation of each performance criteria was done using a specific indicator. The solar potential was evaluated based on the average irradiation received on all exposed surfaces (walls and roof) throughout the year, expressed in kWh/m^2. Expressing this value per exposed surface area (m^2) allows comparing results for buildings of different sizes. Higher irradiation values are favoured as they increase the potential for harvesting solar energy through active systems (photovoltaic and collectors).

Thermal comfort was evaluated based on the operative temperature of the building and its deviation from the comfort zone calculated using the ASHRAE adaptive comfort model [12] illustrated in *Fig. 3*. The operative temperature recorded corresponds to the free-running temperature, as all scenarios were modelled as free running buildings (i.e. no heating, cooling or mechanical ventilation systems were implemented). By doing so, it is possible to estimate the level of autonomy of a building, that is to say the level of comfort achieved solely through passive measures. The thermal comfort indicator employed is the number of discomfort hours over the year, i.e. the hours for which the operative temperature falls outside the comfort zone.

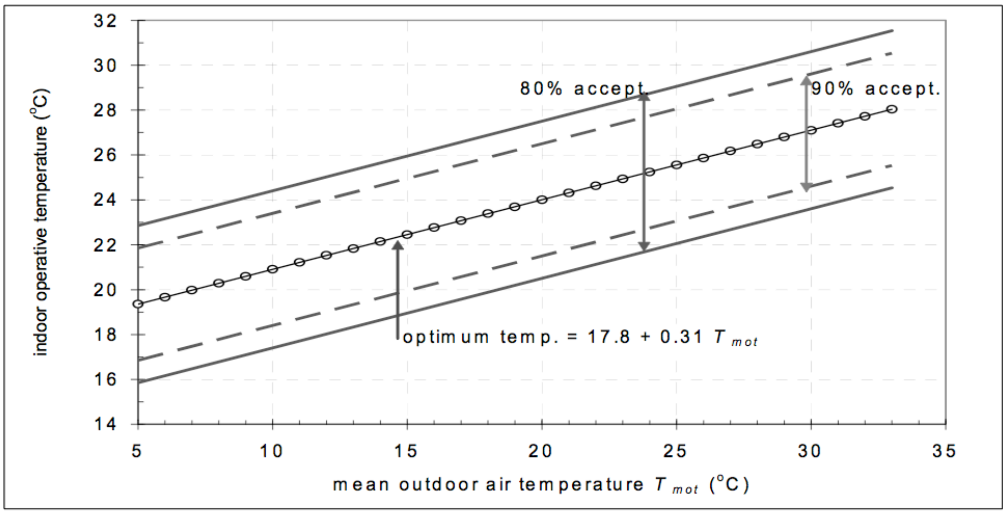

Fig. 3: ASHRAE adaptive thermal comfort model [12]. The optimum indoor operative temperature is a function of the mean outdoor air temperature. In the current study, the 80% acceptability band (optimal temperature ± 3.5 °C) has been adopted to define the comfort zone.

Visual comfort was evaluated using the daylight autonomy indicator provided by the LEED v3 NC 2009 IEQ 8.1 report outputted by DesignBuilder [13]. The LEED daylight autonomy represents the percentage floor area that has an illuminance value between 25 fc (269 lux) and 500 fc (5382 lux). The evaluation is done at 9am and 3pm and then averaged. Finally, to quantify the impact of each parameter on the three performance indicators, an analysis of variance [14] was conducted using Matlab [15].

4. Results and discussion

4.1 Experiment 1

Fig. 4 illustrates the results for experiment 1. The bars (left vertical axis) indicate, for each scenario, the number of discomfort hours over the year. A distinction was made between hours for which the temperature exceeds the upper limit of the comfort zone (referred to as “positive hours”, light grey bars) and hours for which the temperature falls below the lower limit of the comfort zone (referred to as “negative hours”, dark grey bars). Diamonds and stars respectively correspond to the irradiation and daylight indicators defined earlier.

Positive discomfort hours and daylight indicators occur for scenarios characterized by a higher w:w ratio (scenarios 3, 4, 7 and 8), which leads to higher internal heat and light gains. While positive discomfort hours and the daylight indicator are in good agreement, no such correlation is observed between the irradiation indicator and any other performance indicator. However, the irradiation indicator is predominantly dictated by the height of the building: a low height (4 m) leads to a positive irradiation indicator (scenarios 1, 3, 5 and 7).

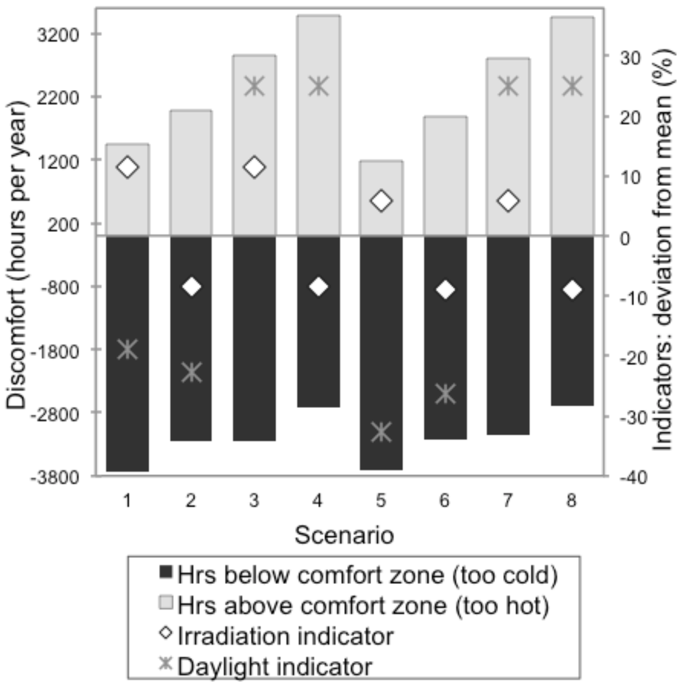

Fig. 4: Results from experiment 1 – Thermal comfort (bars), solar potential (diamonds) and daylight (stars) indicators for each scenario. Higher (positive) values for the indicators mean better performance.

Table 3 gives the numerical values for each indicator and scenario. Numbers in bold font indicate the best performances obtained. It can be seen that scenarios of lower height have less discomfort hours, while having a higher mean irradiation. These results provide useful and possibly unintuitive information to practitioners.

Table 4 presents the percent contribution resulting from the analysis of variance conducted. A high value (in bold font in the table) indicates a strong influence of a factor over the corresponding performance indicator, in comparison to the other factors examined. Results point to two possibly non-predicted phenomena: building height dictates to a large extent the irradiation level, while this level is practically unaffected by the roof inclination, thus a parameter of no significant importance in the studied context when it comes to designing for active solar system installation.

Table 3: Result matrix for experiment 1. Responses for thermal comfort (ratio of discomfort hours over total hours in a year), irradiation (average annual solar radiation on all exposed surfaces per m^2) and daylight autonomy (average from 9am and 3pm measures) at each iteration (scenario).

		Percent contribution		
		Discomfort	Mean irradiation	Daylight autonomy
Main effects	Height	10.4	95.1	0.02
	W:W	84.7	0.0	98.0
	Roof	2.4	2.9	0.7
Interaction	Height-W:W	2.3	0.0	0.02
	Height-Roof	0.07	2.0	0.3
	W:W-Roof	0.004	0.0	0.7

Table 4: Analysis of variance for experiment 1. Percent contribution from each factor and combination of factors (interactions) with respect to each performance indicator. A high value indicates a strong influence of the factor over the performance indicator

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	W:W-Roof	0.004	0.0	0.7

4.2 Experiment 2

Fig. 5 illustrates the results for experiment 2. Positive irradiation indicators are associated to scenarios 1 and 3, which have a smaller passive surface. The daylight indicator is always positive except for the last case (100% passive, E-W orientation), also characterized by fewer hours of overheating. This last case suggests that the passive zone and orientation have a combined effect on daylight autonomy and cannot be assessed independently.

Another interaction can be observed from Fig. 6, which plots the total discomfort hours against the mean irradiation for each scenario. When increasing the passive zone surface (circles to squares), the effect on the discomfort level varies based on the orientation: an increase in the discomfort hours occurs for the N-S orientation, while a decrease is observed for the E-W orientation. These results demonstrate the existence of a significant interaction between these two parameters that affects thermal comfort performance.

Table 5 presents the numerical results for each scenario and indicator. Numbers in bold font correspond to the best performance obtained. As for experiment 1 (*Table 3*), results highlight the conflicting nature of the performance criteria analysed, favoured by distinct design parameters.

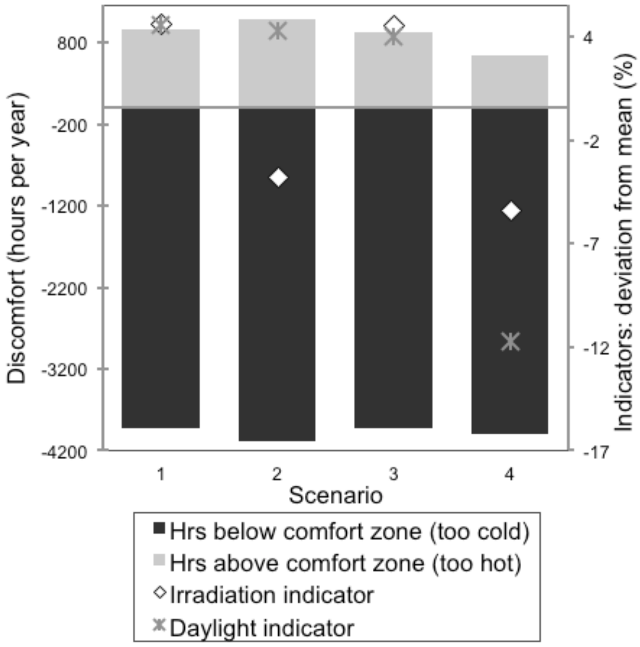

Fig. 5: Results from experiment 2 – Thermal comfort, solar potential and daylight indicators for each scenario. Higher (positive) indicator values mean better performance.

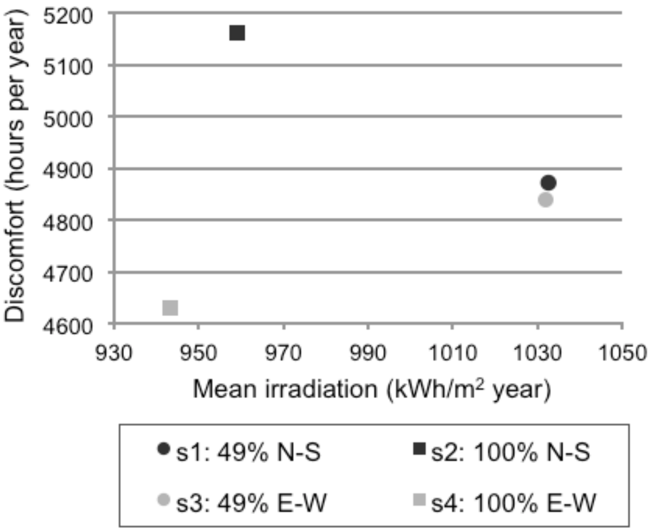

Fig. 6: Thermal comfort (discomfort hours) versus solar potential (mean irradiation) for each scenario of experiment 2.

Table 5: Result matrix for experiment 2. Responses for thermal comfort (ratio of discomfort hours over total hours in a year), irradiation (average annual solar radiation on all exposed surfaces per m^2) and daylight autonomy (average from 9am and 3pm measures) at each iteration (scenario).

	Responses (analysis outcome)		
Scenario	Discomfort [% time]	Mean irradiation [kWh/m^{2}yr]	Daylight autonomy [% space]
1	56	1032.4	36.0
2	59	958.9	35.9
3	55	1031.7	35.8
4	53	943.0	30.7

5. Conclusion and future work

Two parametric studies were conducted on a virtual office building located in Geneva. The outcomes suggest that specific early design parameters, namely orientation and proportion of passive zone, cannot be considered independently when assessing their impact on specific building performance criteria, while others (height, roof inclination and window-to-wall ratio) do not present any such interaction. Moreover, the solar potential varies according to height and passive zone ratio in a possibly non-intuitive fashion. These preliminary results provide a motivation to pursue the development of a comprehensive evaluation method joining conflicting performance criteria relating to solar potential and comfort.

This study is to be followed by further experiments extended to the urban scale, allowing the identification of the most influencing design parameters in such situations where buildings affect each other (e.g. through shading). Results will also provide a basis for the climate-based recommendations to be developed as a first milestone in the establishment of an early decision support method.

6. References

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