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A simulation-based optimization method for the integrative design of the building envelope

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Abstract

An effective design of green buildings requires a process of optimization to meet all the sustainability goals through an integrative design approach. The research focuses on the development of a replicable methodology for the optimization of the building features that affects specifically the energy demand and indoor comfort conditions.
Optimal design solutions are found following two steps: minimization of the total energy demand for heating, cooling and lighting coupling TRNSYS®, a dynamic simulation software, and GenOpt®, a Generic optimization program; a post-processing analysis considering thermal and visual comfort aspects. This optimization methodology was conducted on a school classroom case-study.

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Keywords: integrative design; optimization; total energy; thermal comfort; visual comfort; school classroom

1. Introduction

Within a specific set of constraints (climate conditions, building use and occupancy, availability of materials and technologies on the market…), the effective design of sustainable buildings results from an accurate optimization process of all the variables that are involved and interrelated in meeting all the sustainability goals in the field of energy, indoor environmental quality, water management, and sustainable materials. In this field, the application of the principles of the integrative design could help in effectively managing and optimizing synergies between the complex set of technical and living systems associated with design. To achieve cost effective and increasingly more

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effective environmental performance, it is necessary to shift from conventional linear design to design practices that focus on interrelated systems integration. The conceptual basis for the optimization methodology is that all relationships should be identified for optimal results, and value engineering should not focus on optimizing individual components. In fact, the conventional practice often tends to isolate design disciplines into silos (architects, energy engineers, lighting engineer, etc), creating fragmented solutions. These 'solutions' can, and do, create unintended consequences – sometimes they are positive, but mostly they are negative. Instead, integrating areas of practice allows the finding of performance and cost synergies and benefits [1].

To work this way requires a process that develops all major issues in parallel with each other, so that the entire design and construction team can identify cross-linked interrelationships and resultant benefits. Considering multiple variables and comparing design alternatives may be very complex [2]. In order to perform an accurate optimization, it is necessary to evaluate a great number of design options, which is often time-consuming: to achieve an optimal solution to a problem (or a solution near the optimum) with less time and labor, the computer building model is usually "solved" by iterative methods, which construct infinite sequences, of progressively better approximations to a "solution", i.e. a point in the search-space that satisfies an optimality condition. Due to the iterative nature of the procedures, these methods are usually automated by computer programming. Such methods are often known as "numerical optimization" or "simulation-based optimization" [3-4].

1.1. Scope of the work

Scope of the work is to set up a method able to support the integrative design process and test its potentialities on a simple case-study of a school classroom. This is done by the integration of several tools, aiming at identifying:

- The set of design options minimizing the total primary energy needs, intended as the sum of energy needs for heating, cooling and artificial lighting;
- Among the "energy optimal" solutions, the set of design options maximizing the thermal and visual comfort;
- The set of design options that satisfy at the same time the requirements related to energy efficiency and thermal and visual comfort for a sustainable school classroom.

2. Materials and methods

2.1. The case study model

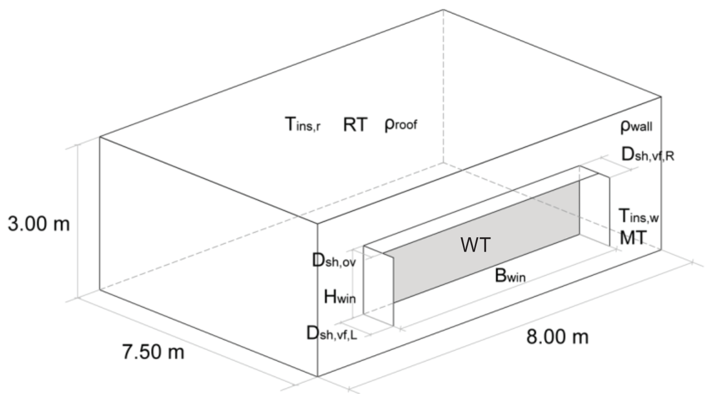

Figure 1 - Representation of the case study model with related design parameters, reported in details in Tables 1, 2, 3 -

The occupancy was set to 27 people and the related ventilation rate was set to 3.5 ach (UNI 10339).

Internal gains due to human's presence, lighting and appliance were set according to occupancy schedules for single days and for the whole year, according to typical occupancy rates and uses for school classrooms: the occupation time is set 8 am – 6 pm, Monday through Friday, in all months of the year except July and August.

External conditions were set using weather data of Turin, Piedmont, Italy. According to the Standard UNI/TS 11300, the set-point temperature for the conditioned space was set to 20°C in heating period, according to the climate zone E (from October, 15th to April, 15th) and 26°C in all other days of the year. The analysis was conducted for all the four main orientations (N, S, W, E). In this paper, only results related to the south orientation are reported and discussed.

Given these boundary conditions, a methodology was set up for optimizing the design variables of the presented case study from the energy and comfort point of views. The overall optimization methodology, from pre-processing to post-processing, is shown in Fig. 2.

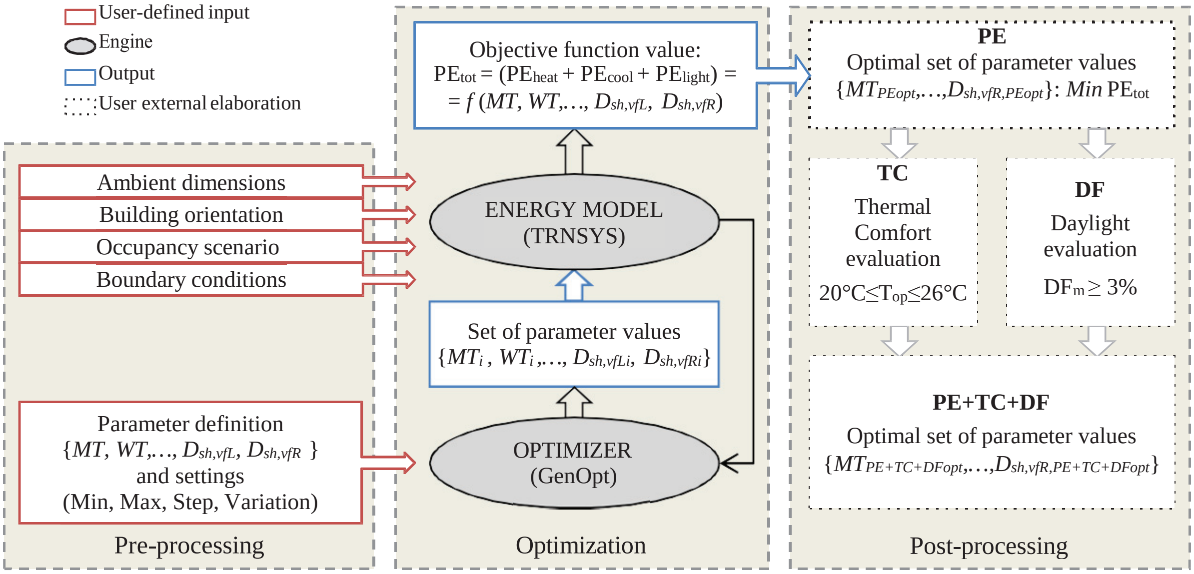

Figure 2. Pre-processing, optimization and post-processing phase of the proposed methodology for the integrative design process.

2.2. Pre-processing: parameter definition

The pre-processing stage of the methodology (Fig.2) deals with the optimization parameter definition. The identified parameters, reported in Table 1, are related to the classroom's components geometry, or its envelope options, and the range and the step of their variation were defined according to real construction practice. Geometry and material properties parameters follow a discrete step variation within a specific range, where the lower parameter values were set according to the current Italian regulatory requirements. Envelope typology parameters are defined as choice between options, which are described in details in Table 2 and Table 3.

2.3. Optimization

In order to ensure the easy and fast run of multiple simulations, the building simulation software TRNSYS was coupled with the general optimization software GenOpt, which allows setting parameters and constraints and performing the optimization. Among those available in GenOpt, the particle swarm optimization (PSO) algorithm was chosen. The process is shown in Fig.2: the optimization algorithm of GenOpt selects a set of parameter to be entered to TRNSYS, which performs the simulation and calculates the value of the objective function depending on that parameter set. After registering the objective function value and the related parameter values set, GenOpt, driven by the PSO algorithm, select another set to re-start the simulation, following this iterative process until the stopping criteria is met and the objective function minimized.

As already mentioned, the objective function is the total annual energy need of the case study, which is composed by heating, cooling and lighting needs. An ideal energy system was considered and the different energy needs were added together in terms of primary energy using the equation (1), where heating energy is weighted with a primary energy factor of 1 (gas boiler), cooling energy is reported into electricity considering an Energy Efficiency Ratio (EER) equal to 3 and then weighted with a primary energy factor equal to 2.18 (standard Italian conversion factor), lighting energy is multiplied by the conversion factor for electricity.

$$PE_{tot} = PE_{heat} + PE_{cool} + PE_{light} = Q_{heat} \cdot 1 + \frac{Q_{cool}}{3} \cdot 2.18 + Q_{light} \cdot 2.18 \quad (1)$$

Heating and cooling needs (Q_{heat} and Q_{cool}) were taken from outputs of TRNSYS Type 56, indicating the amount of sensible heating and cooling demand for the defined thermal zone, while the lighting energy (Q_{light}) required to fulfil the illumination function and purpose in the building were estimated as indicated in the Standard EN 15193 [5].

Table 1. Parameters: definition, variability range and step and initial scenarios

Parameter name and description		Unit	Variation	Range		Step
MT	Wall construction typology	[-]	Choice between options	M1 – M2		-
RT	Roof/ceiling construction typology	[-]	Choice between options	R1 – R2		-
WT	Window typology	[-]	Choice between options	W1 – W2 – W3 – W4		-
$T_{,ins,w}$	Thickness of external insulation on external wall	[m]	Discrete	0.01	0.21	0.02
$T_{,ins,r}$	Thickness of external insulation on roof	[m]	Discrete	0.01	0.21	0.02
ρ_{wall}	Reflection coefficient of external wall's outer face	[%]	Discrete	20	90	35
ρ_{roof}	Reflection coefficient of roof's outer face	[%]	Discrete	20	90	35
Bwin	Width of glazed area	[m]	Discrete	5.00	7.50	0.25
Hwin	Height of glazed area	[m]	Discrete	1.00	2.00	0.20
Dsh,ov	Depth of overhang shading system	[m]	Discrete	0.00	2.00	0.20
Dsh,vfL	Depth of left vertical fin shading system	[m]	Discrete	0.00	2.00	0.20
Dsh,vfR	Depth of right vertical fin shading system	[m]	Discrete	0.00	2.00	0.20

Table 2. Window type description

Type	Description		U-value [W/(m^{2}K)]	g-value	τ glass
W1	6/16/6	Double glazing, Argon gas, low emissivity	1.16	0.265	0.39
W2	4/16/4	Double glazing, Argon gas, without solar control	1.24	0.642	0.76
W3	6/12/4/12/4	Triple glazing, Argon gas, low emissivity	0.70	0.222	0.43
W4	4/16/4/16/4	Double glazing, Argon gas, without solar control	0.70	0.501	0.64

Table 3. Envelope type description

Type	Description	Layers (int - ext)
M1	Massive wall	Plaster (1 cm) + Concrete blocks (25 cm) + Insulation ((4 + $T_{ins,w}$) cm, λ=0,034 W/mK) + Plaster (1 cm)
M2	Lightweight wall	Plasterboard (2.5 cm) + Insulation (10 cm) + MDF (15 cm) + Insulation ($T_{ins,w}$ cm, λ=0,034 W/mK) + Plaster (1 cm)
R1	Massive roof	Plaster (1 cm) + Concrete (20 cm) + Insulation ((12 + $T_{ins,r}$) cm, λ=0,034 W/mK)
R2	Lightweight roof	Plasterboard (2.5 cm) + Insulation (12 cm) + MDF (2 cm) + Insulation ($T_{ins,r}$ cm, λ=0,034 W/mK)

2.4. Post processing: the comfort filters

The aim of the post-processing phase is to identify, among the resulted optimal solutions from the energy point of view, the solutions leading to optimal (or at least acceptable) comfort performance [6], by applying some "comfort filters" (Fig. 2). Concerning thermal comfort, the filter was applied to solutions leading to minimize the discomfort index (DI) which represents the ratio between the number of discomfort hours, occurring when the operative temperature (T_{op}) is outside the range 20°C – 26°C, and the total hours of occupancy.

On the other hand, the visual comfort filter was aimed to select solutions having an acceptable average level of daylight (daylight factor DF $\geq$ 3%), with a good internal distribution. The daylight analysis was conducted on a 60 cm spaced grid with 50 cm offset from the walls at a height of 80 cm above the finished floor considering standard LRV (Light Reflectance Value) of internal finishing (floor: 30%, ceiling: 75%, walls: 65%). A simplified calculation of the average value of the daylight factor was already involved in the estimation of Q_{light} (the D factor, defined in EN 15193), however, in order to perform spatial daylight analysis, Ecotect® was used.

3. Results

Results related to the case study optimization for the south orientation are shown in Fig. 3. All the 1000 design options that were evaluated during the optimization process are reported and ordered according to the objective function values, from highest to lowest. Each objective function value is split into heating, cooling and lighting energy needs. The black line indicates the total primary energy demands for each design option, while the grey line with little black dots is referred to the thermal discomfort index. It is shown that the optimization process was able to minimize the objective function value by 27% with respect to the highest evaluated design option. Moreover, it is interesting to note that similar values of PE_{tot} are composed by different share of cooling, heating and lighting needs. In Table 4, the values of parameters related to significant points of Fig.3, each representing a possible design option, are reported. The first point (point 1) is referred to the minimum value of the energy objective function (Eq. 1), which is equal to 64.5 kWh/m^{2}year. This "energy optimal" solution corresponds to a very insulated massive envelope. The window has the smallest dimension allowed by the parameters variation range and there is no horizontal shading, while there is a 20 cm width vertical fin both on the right and the left sides of the window. This solution is also good from the thermal comfort point of view, as the discomfort index DI = 45% is close to the minimum found during the optimization, that is DI=43%. However, the analysis performed in Ecotect revealed that this design configuration leads to a not acceptable average value of daylight factor (DF=2.31%) and a very bad daylight distribution in the ambient (in half of the grid points DF is lower than 1%).

Therefore, the point maximizing the daylight factor D resulted from the Q_{light} calculation was identified (point 2). It corresponds to 67.3 kWh/m^{2}year of energy consumption (5% higher than the PE_{tot} value related to point 1) and DI=50% (10% higher than the DI value related to point 1). The analysis performed in Ecotect leaded to an acceptable average value of daylight factor (DF=3.96%) and a good daylight distribution in the ambient (the minimum value of DF is equal to 1.7%, in the farthest points from the window).

The envelope typology and the insulation level of wall and roof to which point 2 corresponds is the same of point 1, the only difference is in the window dimension, which is 0.2 m higher and 2.5 m wider.

The higher amount of solar gains entering the ambient has a positive effect in winter, leading to decrease heating needs, while has a negative effect in summer, leading to increase cooling needs. The lighting needs, estimated through the LENI method [6], are equal in both points 1 and 2. This demonstrates the importance of performing a spatial daylight analysis for assessing the visual comfort with higher accuracy.

Table 4: Parameter values related to optimal design options

	PE_{tot} [kWh/m^{2}y]	PE_{heat} [kWh/m^{2}y]	PE_{cool} [kWh/m^{2}y]	PE_{light} [kWh/m^{2}y]	D.I. [%]	D.F. [%]	MT [-]	RT [-]	WT [-]	$T_{,ins,w}$ [m]	$T_{,ins,r}$ [m]	$\rho_{,wall}$ [-]	$\rho_{,roof}$ [-]	H_{win} [m]	B_{win} [m]	$Dsh_{,ov}$ [m]	$Dsh_{,vf,L}$ [m]	$Dsh_{,vf,R}$ [m]
1	64.5	23.3	11.1	30.1	45	2.31	M1	R1	W4	0.21	0.21	0.2	0.80	1.00	5.00	0.00	0.20	0.20
2	67.3	20.2	17.0	30.1	50	3.96	M1	R1	W4	0.21	0.21	0.90	0.20	1.20	7.50	0.20	0.40	0.20

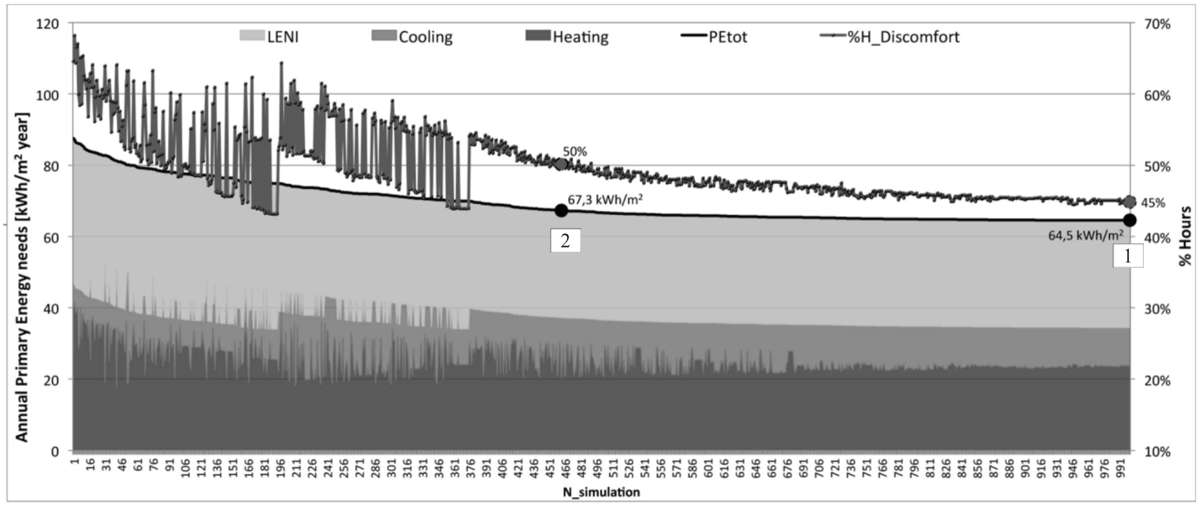

Figure 3. All design solutions evaluated by the optimization process, ordered from highest to lowest objective function values.

4. Conclusions

Beyond the numerical results, which provide some guidelines for an optimal design of a school classroom in the northern Italy area, this paper proposes a clear and replicable methodology to support designers in identifying the most suitable set of passive solutions to guarantee a comfortable indoor environment and hence to minimize the total energy needs.

This study shows the relevance of the integrative design approach in the research of optimal design solutions for green buildings, as the final optimal solution result from a trade-off between different objectives. Moreover, it is demonstrated that the use of such computing tools in a defined optimization methodology is able to effectively support the accurate evaluation of many different design alternatives and better control the interaction between all the involved design variables. In fact, this study found an optimal design solution for a school classroom that maximized the internal comfort with a very little increase of energy consumption. Further studies should be performed evaluating the coupling of other tools and software (Daysim, Contam, etc.) to better analyze indoor environmental quality conditions and including the energy system design (a real energy system is necessary for accurately assessing the thermal discomfort condition).

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