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The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis

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HIGHLIGHTS

- A multi-objective search to minimise the building total energy need was performed.
- Number, position, shape and type of windows and the thickness of walls were varied.
- The analyses were performed for different climates and urban contexts.
- A post-Pareto analysis was performed through a box plot elaboration.
- A small area was found for non-south facing windows in all locations.

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ABSTRACT

The majority of decisions in the building design process are taken in the early design stage. This delicate phase presents the greatest opportunity to obtain high performance buildings, but pertinent performance information is needed for designers to be able to deal with multidisciplinary and contrasting objectives. In the present work, an integrative approach for the early stages of building design is proposed to obtain detailed information on energy efficient envelope configurations. By means of genetic algorithms, a multi-objective search was performed with the aim of minimising the energy need for heating, cooling and lighting of a case study. The investigation was carried out for an open space office building by varying number, position, shape and type of windows and the thickness of the masonry walls. The search was performed through an implementation of the NSGA-II algorithm, which was made capable of exchanging information with the EnergyPlus building energy simulation tool. The analyses were conducted both in absence and in presence of an urban context in the climates of Palermo, Torino, Frankfurt and Oslo. In addition, a preliminary analysis on the Pareto front solutions was performed to investigate the statistical variation of the values assumed by the input variables in all the non-dominated solutions. For the analysed case study, results highlighted a small overall Window-to-Wall Ratio (WWR) of the building in all locations. Pareto front solutions were characterised by low WWR values especially in east, west and north exposed façades. The area of the south facing windows was higher compared to the other orientations and characterised by a higher variability.

1. Introduction

The early stage of building design is characterised by multidisciplinary and contrasting objectives. In this phase, designers consider the largest number of design possibilities and have to make the majority of decisions in the entire process. It is traditionally accepted that end cost, energy efficiency and general performance of buildings are strongly determined in the early stages of design [1–3]. As a consequence, this phase presents the greatest opportunity to obtain high performance buildings. However, design decisions influence different aspects of the building which are often in contrast with one another. A good example of these contrasts is natural illumination versus solar shading. Designers therefore need to gather pertinent building performance information to be able to deal with contrasting objectives.

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Nomenclature

E	electric energy (kWh_e/m^2)
Q	thermal energy (kWh_t/m^2)
R	thermal resistance (m^2 K/W)
U	thermal transmittance (W/m^2 K)
c_p	specific heat (J/kg K)
g	solar energy transmittance (–)
t	thickness (m)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
τ_l	visible transmittance (–)

Subscripts

C	cooling
H	heating
L	lighting
e	east
g	glazing
n	north
nd	need
s	south
w	west

The building envelope is perhaps one of the most interesting subjects with regard to multidisciplinary design. Envelopes have a major role in the building's exposure to the elements; they have a great impact on energy efficiency and indoor environmental quality. Envelopes are also an important component in the building structure and are a big part of their budget.

Several articles detailing the use of various search, optimisation and design support algorithms in the building and construction industry have been published. A great variety of performance objectives can be addressed and many design variables can be optimised to reach the intended goals. Energy demand, system loads, construction and operating cost, thermal comfort, life cycle cost, life cycle environmental impact and CO_2 emissions are among the most investigated objectives in the building sector. Even though the majority of studies focused on building design, optimisation approaches are not limited to new constructions. They were also applied to optimise envelope and systems for refurbishing existing buildings [4–6].

Attia et al. presented a full review of current Building Performance Optimisation (BPO) tools for net zero energy building design [7]. Nguyen et al. [8] and Evins [9] reviewed simulation-based optimisation methods applied to building performance analysis and sustainable building design problems. Optimisation of passive solar design strategies were reviewed by Stevanović [10], who provided a summary with regard to building form, opaque envelope components, glazing and shading elements and whole building passive solar design optimisation. Machairas et al. presented a review on algorithms for optimisation of building design [11].

Search algorithms in combination with parametric models and dynamic energy simulation software were employed to determine optimal configurations of several building components including the building envelope. A literature review of building envelope design can be found in [12]. Some authors optimised the thermo-physical properties [13,14] or insulation thickness [15–19] of the opaque envelope. Other researches studied optimal Window-to-Wall Ratio (WWR) configurations [20,21] or combined an optimisation of thermo-physical properties and WWR [12,22–25]. Several researches focused on the optimisation of shading devices [26,27] or the combination of shading device and window area [28]. Building operation [29] and optimal scheduling strategies [30] were also investigated. An optimisation of both envelope and HVAC systems was performed in [23]. Even though a combined optimisation of envelope and HVAC systems was found to be preferable to a sequential approach where the HVAC systems are optimised after the envelope, only slightly better results were obtained at the expense of a considerable increase of the computational run time.

Size, number and position of windows were optimised for a south facing façade in terms of energy efficiency by means of a genetic algorithm in [20]. Building shape was investigated as part of the envelope optimisation in [31]. Building layout and shape for the initial design stage of a building with given envelope properties were respectively optimised in [32] and [2,33]. Curtain wall façade components were studied in terms of carbon emissions during the entire building operation in [34]. Glare and illuminance of several fenestration configurations were studied and optimised in [35]. A sensitivity analysis of the WWR was also studied in [36].

The present work proposes the use of Multi-Objective Genetic Algorithms (MOGAs) in the early stages of design of an office building. An integrative approach which involves the simultaneous optimisation of the façades is presented for the design of the building envelope. The building energy need for heating, cooling and lighting were chosen as objective functions. The analyses were conducted both in absence and in presence of an urban context in the climates of Palermo, Torino, Frankfurt and Oslo.

Parametric models were used to represent envelopes for the optimisation of number and type of windows, as well as their size, shape and position in each façade. The variation of window shape and position ensured that not only the WWR was studied, but also height to length ratios of the windows and their position along the building façades. In addition, the parametric models that were adopted could modify the thickness of the masonry walls to provide shading to the windows while keeping a fixed U-value.

Most of the existing research articles dealing with WWR analyses proposed a façade optimisation which was independent for each orientation. This approach is limited when it comes to the design of an entire building floor, because it is unlikely that the combination of optimised north, south, east and west orientations will produce an optimal result overall. Combining optimal window arrangements resulting from separate search processes is an approach that does not take the interaction of these windows in the same space into account. Moreover, searching for the optimal WWR is limited when the windows are set back from the outer edge of the walls and when the optimisation of the energy need for lighting is also involved. Even though the WWR has a major role in the energy efficiency of buildings [37], solar gains are not independent from the window shape when reveals provide shading to the windows [38]. In addition, the position of windows has an influence on the daylighting.

In the present work, the use of multiple fitness functions in a multi-objective optimisation is proposed as an HVAC-indepen dent search process. The use of multi-objective search algorithms has an important advantage from a design point of view. The data that is gathered during the process contains detailed information regarding the heating, cooling and lighting needs of each proposed solution. Even though aspects such as aesthetics or visibility towards the outside were not introduced as explicit search variables, they can nevertheless be considered in the final selection of a solution to pursue.