Multi-objective optimization objectives for building envelopes: a review study

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Abstract: This study organizes a systematic review of sixty studies on multi objective optimization related to buildings envelopes. The main objective of this paper is to investigate the most adopted building types, locations, and objectives presented in the literature. The study found that office buildings were the most represented in building optimization studies, while a majority of building locations were in Europe. The optimization objectives could be categorized into five types; visual comfort, energy consumption, thermal comfort, cost, and emissions. Energy related objectives were found to be predominant in building optimization studies, specifically cooling energy, followed by visual comfort objectives represented in a number of daylight metrics. This study can aid the designers and building scientists in pinpointing reliable objectives for optimizing their respective envelope designs.

Keywords: Genetic algorithm; façade; building envelope; multi-objective optimization.

1. Introduction

Building envelope is a core element in the life cycle of any building, starting from early design stages up to construction and operation stages. In addition to the definitive effect of the building envelope on the aesthetics and user perception (Magliocco et al., 2015), it is also considered the membrane separating the indoor and outdoor environments of a building. In general, building envelope comprises two main systems; the opaque and the transparent system. The opaque elements include walls, floors, roof, and insulation, while transparent elements include windows, skylights, and glass doors (Mirrahimi et al., 2016). Thus, the specification of such elements have a major role in determining the energy efficiency and indoor environmental quality within the building. In addition, building envelope design can considerably effect the project's structural design and cost. Numerous studies have addressed the impact of the envelope design on various aspects (Elghamry and Hassan, 2020; Mirrahimi et al., 2016) . As most of the decisions related to building envelope are taken at an early stage of design, architects and engineers used to rely on rules of thumb and past experience to identify best candidate envelope solutions based on various predefined information, such as building function and location (Granadeiro et al., 2013). However, as the morphology of building envelope is tending towards more sophisticated

Imaginable Futures: Design Thinking, and the Scientific Method. 54th International Conference of the Architectural Science Association 2020, Ali Ghaffarianhoseini, et al (eds), pp. 775–784. © 2020 and published by the Architectural Science Association (ANZAScA).

forms, materials, and flexibility, finding the best solution became a very complicated task that include a large pool of parameters. This includes the shape of the building, wall construction, insulation, glazing type, area, thermal mass of the used materials, and shading strategies. On the other hand, the competing nature of the end objectives of the envelope design (e.g. daylight availability versus solar heat gains) make it even harder to alter these variables towards a win-win solution.

Building simulation tools are used to achieve balance between the proposed solutions and efficiency thresholds in different aspects. For instance, tools such as DOE-2 (Winkelmann et al., 1993) and EnergyPlus (Crawley et al., 2001) enable designers to verify the energy performance of their designs through spatiotemporal simulations, while DIVA for Rhino (Solemma, 2014) can run climate based daylight simulations, and calculate various daylight performance indicators such as spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) (Heschong et al., 2012). While simulations offer definitive validation to the performance of the building at an early stage of design, having to test the outcome of every set of parameters individually then altering them to achieve better results can lead to an unintuitive design process, particularly when simulation time is long (Jones et al., 2012).

In this context, coupling the simulation tools with optimization algorithms can help the designers to explore large number of computationally generated solutions based on the performance metrics required. Mathematically defined, optimization is the process of finding the maximum or minimum value of a given function by selecting the best values for a set of variables (Fang and Cho, 2019). Thus, an optimization process would requires variable parameters and objective functions as two main inputs , where the parameters represent values of different building design elements, and the objective functions are the building performance indicators calculated in simulation tools (Machairas et al., 2014). If two or more conflicting optimization goals are involved, Multi-Objective Optimization Algorithms are used. In this case, the optimization process does not output one best solution, but a set of best win-win solutions known as “non-dominated” or “Pareto Optimal”. While there are many types of optimization algorithms, building performance optimization frequently adopts stochastic population-based algorithms, including genetic algorithm and particle swarm (Fang and Cho, 2019).

In this paper, sixty peer-reviewed studies on building envelope optimization published in the last twenty years were reviewed and analyzed, with a specific focus on the representation of daylighting-related objectives compared to other optimization aspects. In addition, optimized building type, location, design parameters, simulation and optimization tools used were thoroughly investigated for each reviewed paper. The contribution of this study lies in pinpointing the most addressed optimization objectives in building performance research, as well as effective parameters within the building envelope. The study can also guide building scientists and designers towards different simulation tools and optimization algorithms and their respective applications in daylight performance optimization.

2. Methodology

A methodology comprised of four phases was followed in the selection and analysis of the relevant works in this review study. First, a set of keywords related to the building simulation, optimization and envelope was used as search terms. The selected keywords were evolutionary design, multi-objective, optimization, façade, window, building envelope, building simulation, parametric design, and generative design. As this study investigates the representation of different parameters and objectives in the literature, terms directly related to optimization objectives (e.g. daylighting, energy, comfort) were avoided to prevent potential bias towards one objective over the other. Second, using a combination of the selected keywords, an extensive survey on relevant work was conducted within various related databases, including Google Scholar, Web of Knowledge, Jstor, and CuminCAD index. In addition,

databases of major publishers (Elsevier, Taylor & Francis, Sage, Springer, Wiley) were also scanned for relevant work.
As a large volume of candidate papers came out of the initial survey, a third phase was applied to screen the selected works based on fulfillment of a number of criteria; the work should be either a peer- reviewed journal or conference paper, the proposed optimization approach should showcase a case study rather than a theoretical framework, the variable parameters should be directly related to building envelope, the optimization process should be applied through Stochastic algorithms in principal, and published between 2000-2020. Subsequently, sixty papers were found to fulfill the discussed criteria and were selected for further analysis. Finally, for each of the selected works the following information was extracted; publication date, building type, building location, optimization objectives, building parameters, simulation tools, and optimization tools.

3. Results and discussion

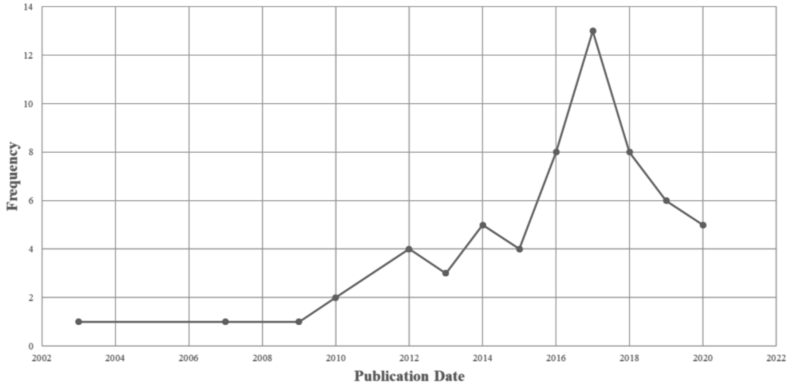

Figure 1: Reviewed studies by publication date.

Based on the previously discussed methodology, sixty journal and conference papers were selected as relevant works related to optimization of building envelope. A historical tracking of the publication dates of the selected works was conducted. While the selection criteria set 2000-2020 as the historical range of a paper, the oldest relevant work was found to be published in 2003. In this early study, Holst (2003) used a genetic optimization program coupled with an energy simulation tool to minimize building’s energy consumption by 22%. The optimized solution also offered better daylight availability and thermal comfort levels. On the other hand, in one of the most recent reviewed studies, Sun et al. (2020) proposed an Artificial Neural Network (ANN) to optimize daylight availability, energy use, and envelope cost for a public building in China. The optimized solutions showed 11% increase in sDA, as well as noticeable reduction in energy use and envelope costs. The proposed method also greatly shortened optimization time. In general, the majority of the selected papers were published between 2016 and 2020, with a noticeably the highest volume of publications in 2017 (Figure 1). This finding closely aligns with the findings of an earlier review study by Shi et al. (2016) focusing on energy optimization, where an upward trend in the number of related papers from 2011 to 2015. Furthermore, this noticeable increase in publications related to building optimization were explained by two causes; first, the paradigm shift in building industry where all the stakeholders are realizing the importance of high- energy efficiency within building design. Second, the wide variety of simulation tools rapidly developed in the recent years, namely focusing on energy simulations.

3.1. Building types and locations

The reviewed researches primarily focused on the optimization of office buildings, where 55% of the case studies addressed were office spaces (Figure 2). However, the specifications and areas of such spaces varied widely between studies. For instance, Méndez Echenagucia et al. (2015) performed a multi-objective optimization on an open space office of an area of 280 m^2, to minimize the energy need for heating, cooling and lighting. On the other hand, Zhai et al. (2019) optimized window configuration for a small office room of an area of 9 m^2 to minimize energy consumption, overheating hours, and hours with daylighting below 500 lux. Residential buildings represented approximately 26% of the optimization case studies, ranging between public housing units (Yigit and Ozorhon, 2018), family houses (Ascione et al., 2016), and dorm rooms (Lartigue et al., 2014). Educational spaces were addressed in six studies, including classrooms (Futrell et al., 2015; Zhang et al., 2017) and libraries (Hong et al., 2019; Sun et al., 2020). Each of healthcare (Mangkuto et al., 2016; Sherif et al., 2015) and commercial spaces were represented in two studies. One study by Menconi et al. (2013) addressed an industrial facility, where a livestock housing model was optimized in terms of energy performance using genetic algorithm.

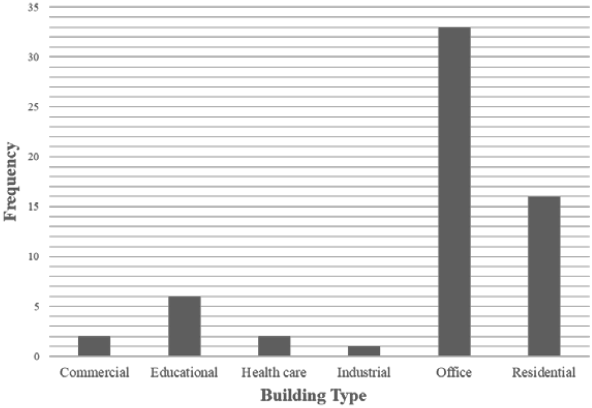

Figure 2: Building types considered in the reviewed studies.

As building optimization often includes climate-based simulation, the location of the building-and subsequently its climate zone- can have a major role in identifying the objectives and needed outcomes of the optimization process. In this survey study, about 15% of the locations featured within the reviewed literature were in the United States (Figure 3), citing the highest occurrence by country. It worth noticing that several climate zones were studied within the United States. For instance, Tuhus-

Dubrow and Krarti (2010) compared best parameters for minimal energy performance in five climate zones, comprising cities of Boulder, Phoenix, Chicago, Miami, and San Francisco. However, ranked by continent, cities in Europe accounted for 40% of the locations studied in the reviewed literature, led by locations in Italy. Rapone and Saro (2012) performed optimization analysis louvers and glazing in a typical office in five European cities; Stockholm, Vienna, London, Rome, and Athens, to minimize the annual carbon emissions. A considerable number of studies (34%) were conducted in Asia, led by locations in China. However, Japan, the only developed within the studied locations in Asia (United Nations, 2014), was included in only one early study. Torres and Sakamoto (2007) applied a genetic algorithm for the optimization of daylighting systems in an office room in Tokyo, to maximize energy savings and minimizing discomfort glare. Africa was the least continent represented in the optimization studies, with only four cases in Egypt and one case in Morocco (Sghiouri et al., 2018).

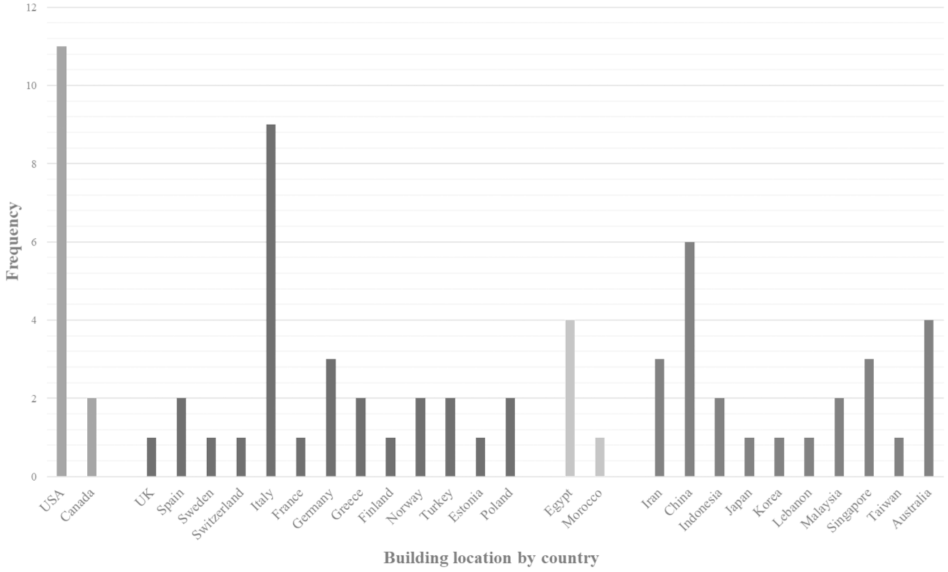

Figure 3: Building locations considered in the reviewed studies.

3.2 Optimization objectives

The sixty surveyed papers included a total of 131 objectives to be optimized. The objectives could be organized into five distinct categories; Visual comfort, Energy consumption, Thermal comfort, Cost, and Emissions (Figure 4). Energy-related objectives were found by far the most dominant (48%) among the reviewed studies. Moreover, minimizing the cooling energy consumption ($E_{cooling}$) (13%) and total energy consumption (E_{Total}) (13%) were also the most included objectives across all categories. To a lesser extent, minimizing lighting energy consumption ($E_{lighting}$) and heating energy ($E_{heating}$) were also considered. A total of 6 studies have used Energy Use Intensity (EUI) as a representative of building energy consumption. EUI can be defined as the total annual energy consumption of a given building divided by its total gross floor area, and has many important applications, such as energy bench marking and urban energy infrastructure planning (Ma and Cheng, 2016). In a recent study by Pilechiha et al. (2020), a multi-objective method was used to explore optimized window system designs to minimize EUI of an office room in Tehran while maximizing daylight performance metrics.

Visual comfort metrics came as the second highest number of objectives in the reviewed studies (27%) and where directly related to daylighting performance. The highest used daylight metric was the Useful Daylight Illuminance (UDI), which is defined as the annual occurrence of illuminances across the work plane where all the illuminances are within the range 100-2000 lux (Nabil and Mardaljevic, 2005). A number of studies have utilized different definitions of daylight availability as an indicator of visual comfort. For instance, Lartigue et al. (2014) developed a criterion of daylight availability proposed as Annual Deficient Daylight Time (ADDT), which is defined as the integrated time when the illuminance is below a threshold of 300 lux and artificial lighting is required. Mahmoud and Elghazi (2016) explored the performance of kinetic façade panels in terms of the percentages of daylit area for the Rotational motion different angles performed at four days of the year through three thresholds (partially daylit, daylit, and overlit). Chen et al. (2018) defined daylight availability as the ratio of the floor area receiving a mean annual illuminance more than 300 lx and lesser than 2000 lx over the gross floor area. Other studies used Daylight Factor (DF) (Lee et al., 2016; Mangkuto et al., 2016), (spatial) Daylight Autonomy (sDA) (Mangkuto et al., 2018; Sun et al., 2020), vertical and horizontal illuminance levels (Gagne and Andersen, 2012; Katsifaraki et al., 2017), and Light Uniformity (Mangkuto et al., 2016). A number of studies focused on minimizing glare through the use of Daylight Glare Probability (DGP) (Lavin and Fiorito, 2017; Wortmann, 2017) and Annual Glare Index (AGI)(Maltais and Gosselin, 2017). When it comes to daylighting, one of the challenges of optimization process is the subjectivity of the daylight related qualities. This challenge is evident in one study by Pilechiha et al. (2020), where a novel metric was developed as a quantitative indicator for the Quality of View (QV), defined by viewer position, view angle, view factor (Heschong et al., 2012), and view depth.

To a lesser extent, thermal comfort metrics were used as optimization objectives in the reviewed studies (13%). Predicted Percentage of Dissatisfied (PPD), followed by Predicted Mean Vote (PMV), were the most adopted thermal comfort metrics. The two metrics are directly related to human sensation of the surrounding thermal environment, and thus aims to predict occurrence of thermal discomfort in a given environment. Other studies have utilized physically based metrics such as Annual Solar Exposure (ASE) and Overall Thermal Transfer Value (OTTV). In one study, Gou et al. (2018) introduced Comfort Time Ratio (CTR) as an annual indoor thermal comfort indicator for naturally ventilated environments. The objective of the study was to maximize CTR and minimize energy demands through altering a number of facade parameters.

While minimizing energy consumption can positively minimize the cost of building operation as well as greenhouse gas emissions, a number of studies explicitly focused on the optimization of quantitative metrics for building cost and emissions. For instance, Ferdyn-Grygierek and Grygierek (2017) conducted a multi-variable optimization to minimize Life Cycle Costs (LCC) for a residential building in Poland. On the other hand Camporeale et al. (2017) and Hong et al. (2019) aimed to maximizing Net Present Value (NPV) by optimizing windows and glazing types of a social housing block and a library building, respectively. Sun et al. (2020) included Building Envelope Cost (BEC) as an objective to minimize in their optimization process of a library building in Changchun, China. Only four studies included objectives directly related to environmental pollution and emissions, represented in annual Green House Gas Emissions (GHG) (González and Fiorito, 2015; Rapone and Saro, 2012; Wu et al., 2017)and Global Warming Potential (GWP) (Hong et al., 2019).

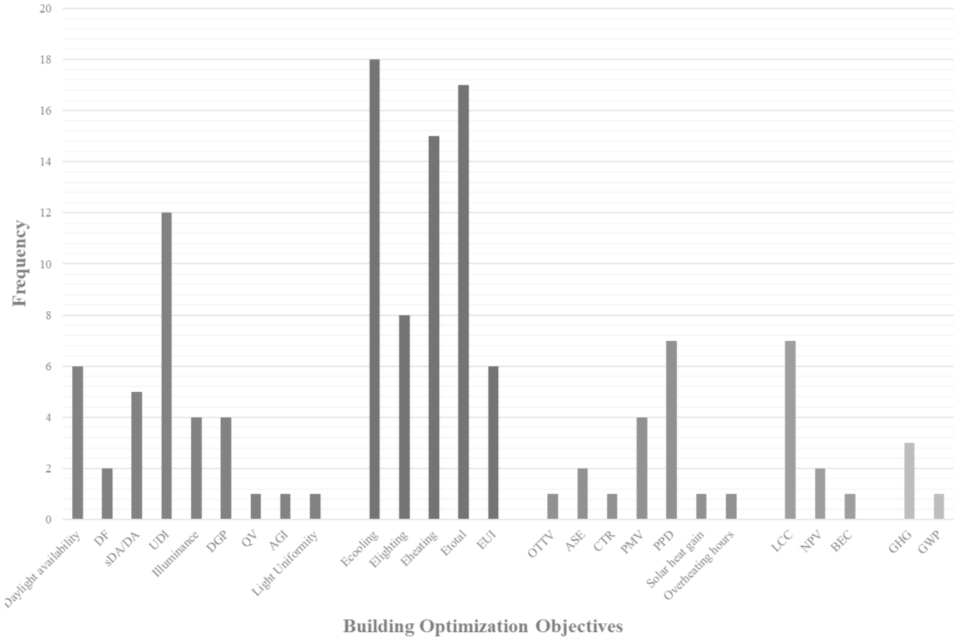

Figure 4: Optimization objectives in the reviewed studies.

4. Conclusions

Building envelope is the layer connecting the indoor environment with its natural and urban surroundings. Thus, the design of building envelope can definitely affect its performance on many levels, including aspects of occupant comfort, energy consumption, and operational costs. Due to the interweaving set of parameters that can control such performance outcomes, multi-objective optimization has seen an increase in the recent years among building scientists and designers to explore large number of envelope solutions based on fitness of their performance. In this study, sixty peer- reviewed papers addressing multi-objective optimization of building envelope were reviewed, analysed, and compared. The study concluded that the majority of literature focused on office and residential buildings, respectively. Among the reviewed studies, a majority of climate-based simulation were conducted for locations in the United States, followed by Italy, while locations in Africa were the least represented. An analysis of the optimization objectives could categorize them into five distinctive groups. Minimizing energy related objectives represented the major focus within the reviewed studies. The second most dominant group was visual comfort metrics, represented in daylight metrics such as Useful Daylight Illuminance (UDI) and Daylight Glare Probability (DGP). The three groups of thermal comfort, building costs, and emissions were also considered in a number of studies, specifically Predicted Percentage of Dissatisfied (PPD) and Life Cycle Cost (LCC). The contribution of this research lies in pinpointing the research gaps within the literature in terms of investigated building types, climates, and objective. It can also help designers and researchers to define a reliable set of objective within the optimization process.

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