Journal Pre-proofs

A critical review of fenestration/window system design methods for high performance buildings

Fan Feng[a], Niraj Kunwar[b], Kristen Cetin[c], and Zheng O'Neill[a,*]

[a]Department of Mechanical Engineering, Texas A&M University, College Station, TX, 77843
[b]Department of Mechanical Engineering, Iowa State University, Ames, IA 50011
[c]Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI 48824

*Corresponding Author
Zheng O'Neill, PhD, PE
J. Mike Walker '66 Department of Mechanical Engineering
Texas A&M University
College Station, TX, 77843
Ph: 979-845-4931 | Email: ZONeill@tamu.edu
https://hvac.engr.tamu.edu/

Abstract

Fenestrations allow for natural daylight and outdoor views, but also represent the least thermally efficient portion of the building envelope, and thus can be a source of unwanted direct sunlight and associated discomfort glare. A well-designed fenestration system operated with proper control strategies is capable of reducing building energy usage significantly while maintaining a both thermally and visually comfortable environment for occupants. This paper reviews and analyzes window design studies for high-performance buildings, which could be interpreted as decision-making processes to achieve the window performance goals by controlling a series of design variables (e.g., location and dimensions of windows, glazing type, etc.). An overview of available design options for window systems to date is introduced first, and then the decision-making methodologies of window system are categorized and analyzed to present a comprehensive review, where we present a detailed analysis of sequential knowledge-based design methods and simulation-based optimization methods. Last, potential challenges and future research trends are identified and analyzed to help promote all automatic simulation-based optimization design methods for high performance fenestration systems.

Keywords: Window technology; Fenestration system design optimization; Knowledge-based design; Simulation-based design

Journal Pre-proofs

1. Introduction

Fenestrations in a building serve multiple functions, including providing natural light, natural ventilation and/or outdoor views. They have long been viewed as instrumental parts of the building envelope, and, in most contexts, are also called windows. Fenestration components can include one or more of the following: (1) a glazing material, typically glass or plastic; (2) indoor, outdoor or built-in shading devices such as louvred blinds, roller shades, awnings, and metal grills; and (3) framing, mullions, dividers, and muntin bars [1]. Today, advanced techniques for manufacturing windows make it possible to have expansive views and daylight without sacrificing comfort or significant decreases in energy efficiency, unlike historical predecessors, where a window was an opening in the wall with an opaque cover or oiled paper [2].

One of the benefits of using windows to admit natural light to a building's interior is that they reduce energy demands by reducing the need for artificial lighting. In addition, biomedical literature over the past several decades has indicated that a deficiency of daylight in indoor environments relates to health problems such hormonal imbalance, sleep disorders, and depression [3]. Natural ventilation from open windows has also drawn considerable attention in literature, with the aim of providing a thermally-comfortable indoor environment while decreasing energy consumption from mechanical heating and/or cooling [4].

However, there are also tradeoffs when considering the presence and configuration of windows. Windows represent a major source of heat loss in winter as well as unwanted heat gain in summer, and consequently, their presence can result in an increase in heating and cooling energy consumption. A very large window, which brings sufficient daylight into a room to replace or significantly supplement artificial lighting, could also cause visual discomfort such as glare, and higher air conditioning energy demand requirements. Such tradeoffs are the subject of a significant number of research efforts, typically with the goal of either (1) minimizing energy use without compromising both thermal comfort and visual comfort or (2) optimizing occupants' health and/or comfort.

The benefits of fenestration systems are best realized if energy consumption, visual comfort needs, and thermal comfort criteria are carefully considered during the stages of building design with proper control strategies. In the past few decades, building science professionals have completed significant research efforts on the design methods of fenestration systems. To achieve a comprehensive understanding of the state-of-art in this field, we have conducted an extensive search of literature databases using search engines and journal web pages in Elsevier, American Society of Civil Engineers (ASCE), Institute of Electrical and Electronics Engineers (IEEE), Association for Computing Machinery (ACM), and Google Scholar. Figure 1 is a schematic of the most common keywords used in these publications. More detailed quantitative reviews of these publications will be presented in the following sections.

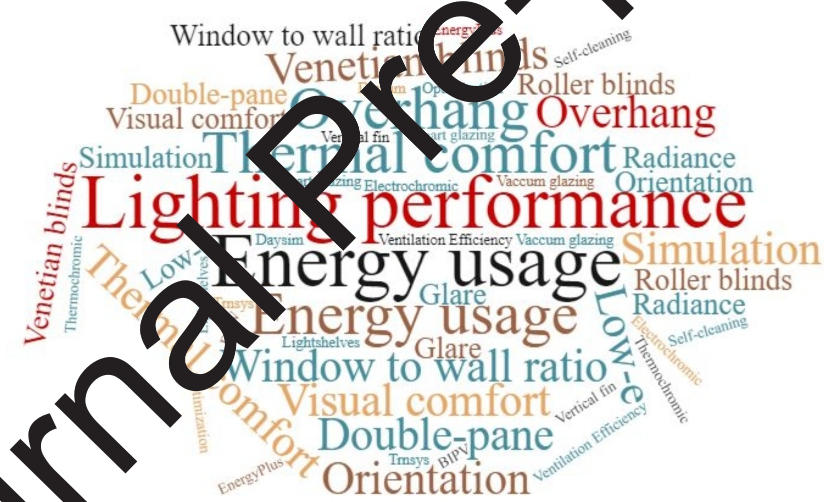


Figure 1. Word clouds of scattered areas of the current research on fenestration system

Despite the research and development progress in fenestration system design, little effort has been made to comprehensively review previous studies, to synthesize them qualitatively and quantitatively. Although there have been some relevant high-quality review studies in this field, these studies either cover a broader range of building systems (e.g., Nguyen et al. [5] presented a review of simulation-based optimization methods in the building sector, which includes windows) or focus on a specific aspect of the fenestration system (e.g., Wang [6] reviewed the design and implementation of innovative daylighting systems. To further improve the design methods of fenestration systems and move towards all automatic simulation-based optimization methods, this review activity aims to provide a holistic comparative review through a synthesis of recent

Journal Pre-proofs

literature in this area. Furthermore, potential challenges and future research trends are also identified and analyzed to facilitate further studies in this field.

It should be noted that aesthetics of fenestration systems is another important consideration, which may be assigned with a high priority by the designers. However, only studies that consider the functional purpose of window systems are reviewed and analyzed in this paper. Advanced daylighting systems [7], which are another mean to bring natural daylight into interior spaces via apertures in the building envelope, have gained increasing attention in modern buildings. A large amount of design options is available currently for advanced daylighting systems, like anidolic ceiling systems and sun pipes. Therefore, the review of advanced daylighting systems is not covered in this paper.

2. Overview of window technologies

Prior to discussions on the design method of fenestration systems, a brief overview of current and emerging window technologies is provided into facilitate the understanding of fenestration systems. Based on this, a design space could be derived, which contains the possible design solutions to be selected to fulfill the performance criteria by designers. Besides, there have been many high-quality review studies related to fenestration systems or components of fenestrations to date. Appendix A includes a summary of papers identified through an exhaustive search of review articles published to date. Therefore, more detailed information of a certain fenestration component could be obtained from the relevant review papers listed.

In Figure 2 a classification of fenestration components is illustrated. Among these five groups of fenestration components, the glazing could be considered as the most important, with shading devices being a common component to modulate or redistribute unwanted sunlight. Other components may also have a significant impact on the window performance, like frame or spacer. Taking fame as an example, some heavy wood frames could obstruct a large proportion of the total window opening, which would result in a significant obstruction effect for the direct sunlight. This obstruction effect could be mitigated by using more slender frames like vinyl frames, fiberglass frames, etc. Actually, these slender frames have become very prevalent nowadays. Jelle et al. [8] presented a review of spacers and frames. Many studies have also analyzed the effects of frames and spacers on windows [9], and develop new materials with lower U–values for spacers and frames [10].

Journal Pre-proofs

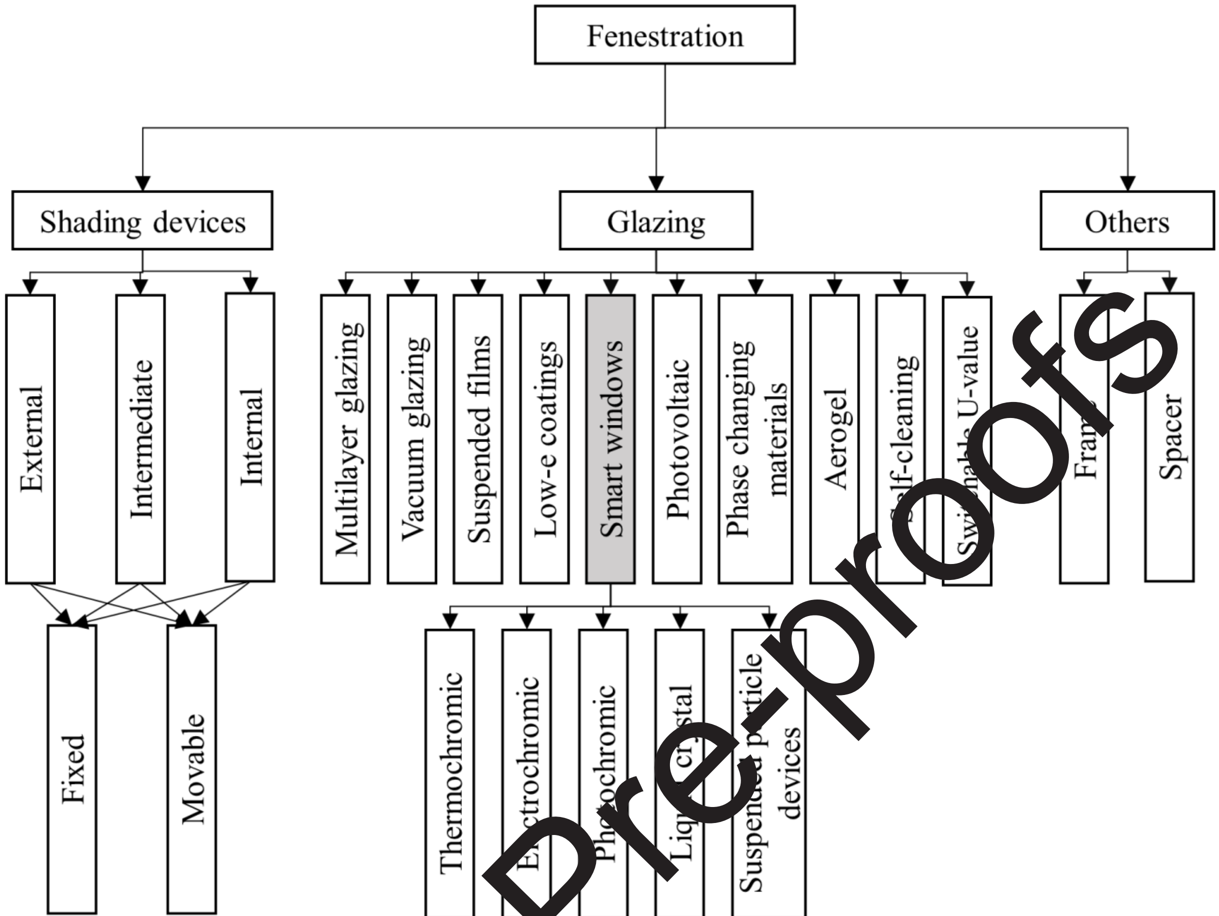


Figure 2. Classification of research topics related to fenestration systems

2.1. Design options for shading devices

Solar shading systems are mainly used to protect glazing components from solar radiation, thus reducing overheating and unwanted discomfort glare. As presented in Bellia et al. [11], shading devices can be divided into three categories, depending on where there are used: external, intermediate, and internal. Each of these categories can be either fixed or movable. A similar classification was also used in studying the design variables of solar shading devices[12, 13].

Fixed shading devices are generally designed to decrease incoming solar radiation, thus reducing the cooling loads during the cooling season. However, since they cannot be adjusted, fixed shading devices can also increase the need for heating during the heating period. Currently available fixed shading includes overhangs, horizontal and vertical louvers, eggcrates, and light shelves.

Movable shading devices are usually used to block detrimental direct summer sun, and to permit the beneficial winter sun, thus providing more advantages. However, sometimes in winter, blinds are also drawn to control the unwanted glare which will result in a decrease in desired solar gains. Therefore, the design of shading devices is clearly of great importance to find a balance between the unwanted glare and the desired solar gains. Widely used movable shading devices include

Venetian blinds, vertical blinds, and roller shades. Movable shading devices are most commonly controlled manually by occupants [14] but can be both manually or automatically controlled.

2.2. Design options for glazing

Glazing is an integral part of overall fenestration systems and has been the subject of research for centuries. The performance of glazing products is quantified using two sets of commonly used metrics: (1) U-values, the calculations of which can be found in Blanusa et al. [15], and (2) solar radiation glazing factors, e.g., visible solar transmittance, ultraviolet solar transmittance, solar heat gain coefficient, etc., the definitions and calculations of these metrics are found in Jelle et al.[16]. The classification of the glazing products is detailed in Figure 2. Jelle et al. [8]and Cuce and Riffat [17] performed comprehensive reviews on glazing products. Multilayer products, especially triple-glazing, provide low U-values; double-glazed units are the most common glazing used in modern buildings. Vacuum glazing and aerogel solutions are growing, with competitive U-values. Aerogels in particular have strong potential due to their low U-values, as discussed in several recent review articles, including Baetens et al. [18] and Buratti and Moretti[19, 20]. Aerogel products are already in use for translucent applications but are not currently suitable for conventional windows where transparent glazing most often is a requirement.

The category of smart windows is among the most common areas of research in recent literature. Compared to static glazing solutions, smart windows have the ability to adjust change one or more properties, such as visual transmittance, with the goal of meeting desired interior visible and/or thermal conditions. Smart windows can be subdivided into three categories: (i) thermochromic, photochromic, and electrochromic materials, (ii) liquid crystal materials, and (iii) suspended particle devices. Baetens et al. [21, 22] presented a review on currently available dynamic smart windows, their properties, and their potential for controlling daylight and solar energy loads in buildings. Based on their review, it is concluded that electrochromic windows are the most reliable and promising in this category based on existing technology. In addition, Granqvist et al. [23, 24] performed a series of reviews on chromic materials, which provide a clear picture of the research on chromogenic materials.

Photovoltaic glazing and phase change material(PCM)-integrated glazing are other types of glazing products that offer distinct advantages because of their ability to produce energy and store energy, respectively. Overviews of phase change material-integrated glazing may be found in work by Baetens et al. [25], Demirbas [26], and Silva et al.[27]. Their studies suggested that PCM-integrated glazing solutions have shown successful applications in increasing the indoor thermal comfort of the building and shifting peak energy demand. Photovoltaic glazing, as a category of building-integrated photovoltaic (BIPV), is a promising glazing solution that can be used to increase the installed capacity of PV systems on buildings. This is of particular significance in order to avoid additional land use. The available design options for PV glazing are systematically reviewed and analyzed in[28, 29]. Yang et al. made significant contributions to the numerical analysis, design, and control/operation of BIPV systems[30-32]. Once solar radiation is used in photovoltaic glazing and phase change material (PCM)-integrated glazing, it cannot be only exploited as the daylight source in buildings because a portion of the incoming solar radiation might be used to produce electricity or heat the PCM glazing. Therefore, various control schemes

Journal Pre-proofs

have been investigated on this topic to optimize its performance. For example, the study by Wang et al.[30] shows that the performance of a PV system can vary significantly with different control schemes.

Self-cleaning glazing products are discussed here because their ability to remove the need for cleaning chemicals, which runoff into water sources, will result in a positive environmental impact. Midtdal[33] presented a review of the self-cleaning glazing products available now and methods for measuring the self-cleaning effect as well as future research pathways and opportunities. Switchable thermal insulation has emerged as an effective method to regulate the indoor environment by alternating between different thermal states. Specifically, switchable thermal insulation can dissipate and/or absorb the heat, or reduce the heat flow on demand by switching between a conductive state and an insulated state. Pioneering research efforts have been conducted to investigate switchable insulation technologies and potential applications in building envelopes, a comprehensive review and analysis of which is in [34]. Although switchable thermal insulation technologies are still in their infancy, their applications as glazing solutions are projected to show strong thermal performance and provide substantial energy saving over static alternatives.

In terms of ongoing and future research, vacuum glazing, aerogel, electrochromic and photovoltaic windows have been found to have strong energy saving potential in terms of becoming part of future glazing solutions. There may be opportunities for utilizing several of these types of glazing technologies in combination, as a joint solution. This would enable the opportunity of combining the advantages offered by different glazing solutions. Moving forward, as existing buildings are renovated and new buildings are built, future fenestration solutions have the potential to revolutionize the industry, and contribute to a more dynamic and energy-optimal component of overall building systems.

3. Design methodologies for fenestration systems

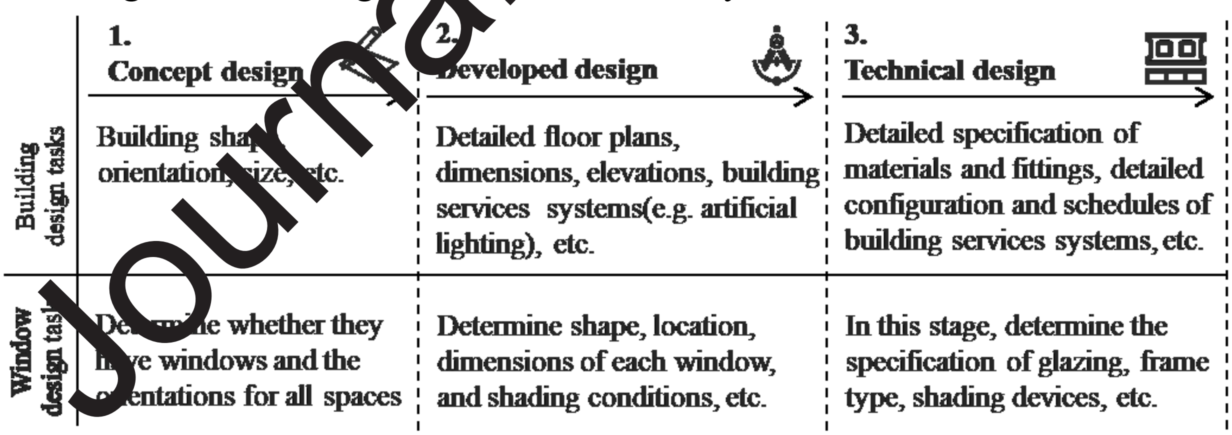


Figure 3. Plan of design tasks for fenestration systems in parallel with building design

Fenestration system design is complex and vaguely defined. One major area of difficulty encountered in the design process comes from a multitude of design criteria. Commonly used design criteria include indoor thermal comfort, visual comfort, daylighting ratio, energy-saving, and aesthetics, etc. More detailed discussion of these criteria is found in [12]. The challenges

Journal Pre-proofs

associated with these design criteria are two-fold. First, most criteria are influenced by several aspects and usually are easily quantifiable using a single metric. For instance, a visual comfort metric should address the following aspects: view of the exterior, glare, illuminance level, etc. Second, these criteria are often incompatible or even conflicting with one another. Therefore, designers must consider tradeoffs between these criteria or assign a different priority to each in the design process.

Another area of difficulty arises from the uncertainties of the design process, which stems from un(der)defined tasks, uncertain contextual information, and incomplete information. This is because fenestration system design, as a part of building design, is essentially a negotiation process among building owners, architects, construction teams, and other stakeholders. As a result, unless a design process begins to unfold, the design tasks and relevant information may not be clear.

To conduct a design project more effectively and efficiently, it is usually decomposed into several steps, where decisions need to be made in each step. This is shown in Figure 3, where the fenestration system design process is illustrated in parallel with the building design process since fenestration system design is inherently based on the building context in each step. The building design process in Figure 3 follows the plan of work defined by the Royal Institute of British Architects (RIBA)[35]. It should be noted that there are also several different definitions for plans of work from other institutes or sector bodies. Despite the difference, the decision-making methodologies discussed in the following sections are generally applicable.

In Figure 3, the design stage is divided into three steps: concept design, developed design, and technical design. These three steps usually occur in increasing order of detail and complexity while the decision-making methods for these three steps could be viewed in similar manners. Design efforts at each step are further illustrated in Figure 4. This starts with the preparation of three categories of information, including design context, performance objectives, and design variables. Establishing the design context is the process of establishing site conditions, climatic data, and usage, among other variables, which will be used as constraints when making decisions. Performance objectives mainly refer to the design project criteria discussed previously and design variables refer to the parameters which are selected by designers. Table 1 lists some commonly used design variables relevant to fenestration systems. It should be noted that this table is not an exhaustive list of all possible design variables. In certain cases, specific analysis methods should be used before the design space is established. Besides, the encoding methods employed that represent a fenestration system as a set of variables will affect the design space. For example, a conventional window design project will use a parameter set (e.g., width, height, location) to represent the geometry of a certain window, while in [36], a cellular encoding method was employed instead, which represents a windows as a *nc* by *nr* matrix of cells and for each cell a binary variable is employed to indicate if it is glazed or not.. Besides, the parameter set used should be independent. For example, a parameter set of only width, height, area, and location would be an ill-defined parameter set.

Then based on this information, decisions could be made to meet the design objectives. A variety of decision-making methods are used in current literature and can be classified into two categories: 1) knowledge-based methods, and 2) simulation-based optimization methods. The former has been

Journal Pre-proofs

and is still commonly used in practice while the latter arises as a result of the advancement of both mathematical optimization methods and computer science. The discussion of these two groups of methods is presented in the following sections. Last, the derived design solutions need to be evaluated before the design process proceeds to the next step. This is because the decisions made may raise some concerns, such as the feasibility and actual performance of the design solutions. New questions about the decisions in earlier steps could be asked in the later steps since design variables at these three steps are interdependent.

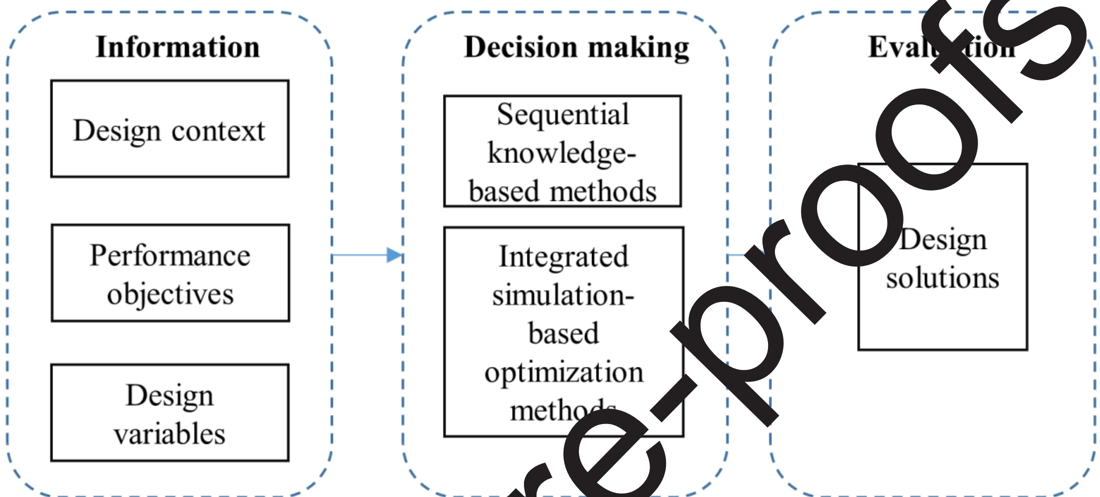


Figure 4. Decision-making process for fenestration system design

Table 1. Decision variables used in fenestration system design process

Category	Decision Variables
Geometry	Shape of windows, Location of windows (horizontal and/or vertical location), Dimensions of the windows, Window-to-wall ratio, Number of windows, Window orientation, Operability of window,
Glazing	U-value, Transmittance (Direct-diffuse transmittance, direct-direct transmittance) Solar heat gain coefficient, Glazing type (see Figure 2) • Design parameters for a certain glazing, such asemissivity for low-e glazing • Thickness • Control strategies for controllable glazing (e.g. electrochromic)

Journal Pre-proofs

Journal Pre-proofs

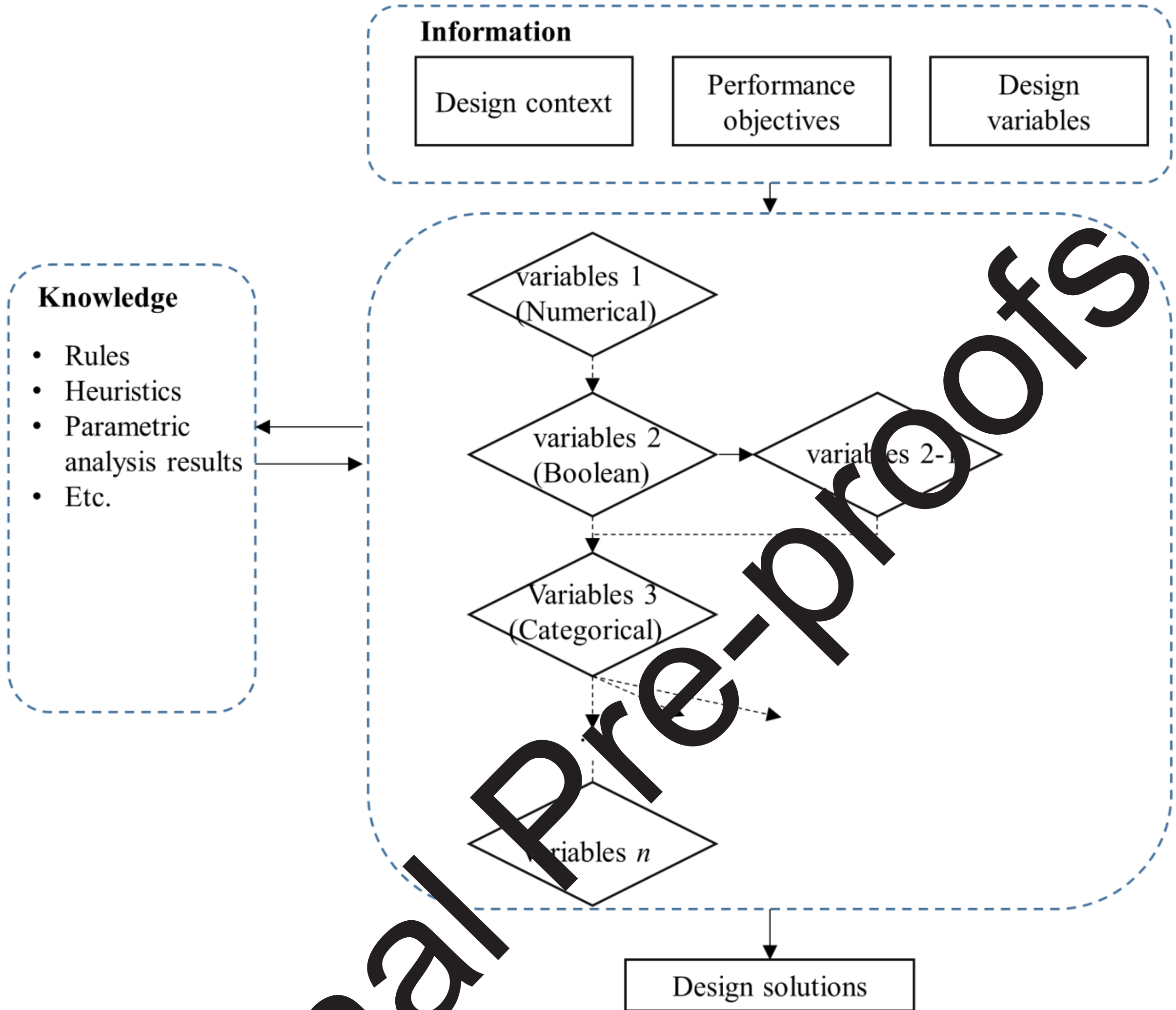
Shading	Shading techniques
	• Overhang
	  o Overhang projection factor
	  o Angle
	• Venetian blind
	  o Slat width
	  o Slat distance
	  o Slat properties
	Control
	• Manual
	• Automated
	Position
	• External
	• Internal
	• Between
	A detailed list of design variables of shading devices could be found in [12]

3.1. Knowledge-based methods

Similar to other design problems, designers have been designing fenestration systems using various knowledge, including prefabricated rules, understanding and heuristics, existing cases, and knowledge derived from parametric analysis. Based on these various knowledge sources, knowledge-based decision-making methods can be further divided into two groups: (1) sequential knowledge-based design(SKBD) methods, and (2) case-based design(CBD) methods.

Journal Pre-proofs

3.1.1. Sequential knowledge-based methods



Journal Pre-proofs

Figure 5. Sequential knowledge-based design(SKBD) process for fenestration systems

Based on these design conditions a designer could now proceed to determine each design variable to establish a set of design solution candidates. This design process is conventionally undertaken in a sequential manner. Figure 5 shows a conceptual flowchart for sequential methods. Usually, a designer only addresses one variable at a time, and available knowledge will be employed to facilitate decision-making. Then, after the current design variable is determined, the design process will proceed to address the next variable. This operation will be repeated until final design solutions are established.

As discussed previously, design variables can be in different forms: numerical values (e.g., window area), boolean values (e.g., operability of the window), categorical values (e.g., glazing types). The exact value of a design variable will usually affect the remaining design variables or the values of the remaining design variables. This is particularly true for categorical and boolean variables. For example, shading condition of a certain window can be represented as a categorical design variable. If this design variable takes the value—venetian blind, then design variables (such as the slat width, distance, and slat material) need to be determined before proceeding to the design variables. Otherwise, there is no need to consider these variables. In addition, for some variables, there is no strict rule specifying which design variable should be addressed first. This is also the reason why some blocks in Figure 5 are connected with black dashed lines. For example, if window location is assigned with the highest priority and determined first, its area will be addressed after the predetermined location is known. Alternatively, if the window area is determined first, and the window location would be next. Although these design variables could be addressed in a different order, then the derived design solutions will be different.

A good example of the sequential decision-making method is in [37], where window design knowledge for offices and schools in both cold and hot climates was used. The decision-making process was followed with consideration of the orientation first. Orientation was based on an analysis of the impact of window orientation on different criteria, including energy consumption, peak energy demand, and thermal comfort. For example, in a hot climate, north-facing windows have the least impact on energy usage compared with south-, west-, and east-facing windows when no overhang was employed. However, the difference became negligible when the solar heat gain coefficient of windows was substantially decreased. Then, the design process proceeded to determine whether there was a need for continuous dimming daylight controls. After daylight control strategies were determined, window area, shading conditions, and window type were established successively.

One key improvement proposed for the decision-making in [37] resides in that their knowledge base was established from a parametric analysis of the impacts of various design variables on the fenestration system performance. Instead of depending on parametric analysis results, conventional design methods are usually based on designers' domain-specific expertise, and heuristics. However, their design knowledge base tends to lack additional information on new technologies as new technologies are emerging at a rapid speed in the field. For instance, many designers would presume the orientation of windows would have a significant influence on energy consumption. This is correct for single-pane clear windows without any shading. For low U-value windows like low-E triple-glazed windows with proper shading, however, the impact of orientation becomes almost negligible.

Some researchers have also used a set of carefully generated simulation models as the source of the knowledge base. Andersen et al., in particular, completed a series of research efforts in this field [38–41], focused on daylighting-specific design problems. They proposed an interactive knowledge-based (also called expert system) and goal-driven systems using LightSolve Viewer (LSV) that was intended for use in the early design phase. This system consists of two major components: a daylighting knowledge base and a fuzzy rule-based decision-making logic.

First, to generate a detailed knowledge base, Design of Experiments (DoE) was utilized to populate a set of simulation models, which was based on the fenestration-related variables of interest. Next, the performance metrics for these models were calculated using simulation engines, from which the main effects of each design variable on the performance metrics were obtained. This information was used to build the daylighting knowledge base [40]. The second part of this

Journal Pre-proofs

Journal Pre-proofs

expert system was a rule-based decision-making algorithm that uses fuzzy logic to better emulate the human thought process. This fuzzy rule-based system can create a list of suggested fenestration design changes that improve the daylighting performance of a given design. Based on the user's choice of design suggestion(s), the system automatically modified the original model, and provided the results. The process is then repeated until the designer is satisfied with the design [41]. A user-based evaluation of this knowledge-based system was conducted afterward[39]. The results demonstrated that this system could generate designs that perform similarly to those generated by an optimization-oriented algorithm. In addition, by granting the designers more control, the acceptance of the designs generated by this knowledge-based system was significantly improved. In addition to allowing the users to be interactively involved in the design process, the expert system, such as the one developed by Hu and Olbina [42], can also provide informative figures demonstrating how the different design parameters influence design metrics. This system is anticipated to create higher flexibility for the designers compared to a list of modifications provided in the expert system by Andersen et al. [43].

One drawback of the SKBD methods is that design decisions are always made through relatively short-term thinking. For example, a designer may choose a small south-facing window to minimize the total solar energy entering a room in a hot climate. However, this decision ultimately is an improper design after a glazing with a low solar heat gain coefficient (SHGC) is employed since a small window will lead to less daylight entering the room and increase the demand for artificial lighting.

3.1.2. Case-based knowledge-based design methods

The previously successful design examples are also a valuable knowledge base for designers. The basic idea underlying case-based design methods is that the knowledge and experience embedded within previous successful design cases are useful and informative for new design solutions. Hiyama et al. proposed a new method for reusing existing design examples by taking the weighted average of values of design parameters for existing projects, for use as the default design solution for a new project [44]. The study showed a high similarity between a default window design generated through this method, and an optimal design. Although, as stated in their paper, the obtained design by this method could only serve as a starting point of the design process and further analysis is still required, this effort is still able to reduce the occurrence of mistakes by designers, and thus to shorten the overall design process.

The fundamental principles and current gaps of CBD approaches have been studied in several research efforts [45, 46]. Based on these studies, a typical CBD approach can be formulated, as shown in the flowchart in Figure 6. There are three core tasks in a CBD system. First, in order to extract the conceptual point, a proper representation approach should be developed. A commonly used representation method is to define a set of characteristics that could uniquely characterize a design. Usually, these characteristics cover the design information (such as the environment, geometries, materials, and control methods). This is also of great importance for the organization of the knowledge base.

Second, based on the characteristics of the design problem, a CBD approach will retrieve one design case or a group of design cases from the knowledge base. A typical retrieval method is to

Journal Pre-proofs

identify these cases with a high similarity or relevance to the design problem.To address the challenges of the similarity between two design cases should be measured? Roseman et al. proposed a fixed similarity measurement using previously defined characteristics [47].

The last task is to develop a new design solution based on these retrieved cases. One possible approach is to use the case of highest similarity with minor adjustments. As simple as this approach may be, this approach may not be adequate in most cases. Another approach is to generate a new design solution by adapting and combining these retrieved design cases. However, this is complex, with further research needed.

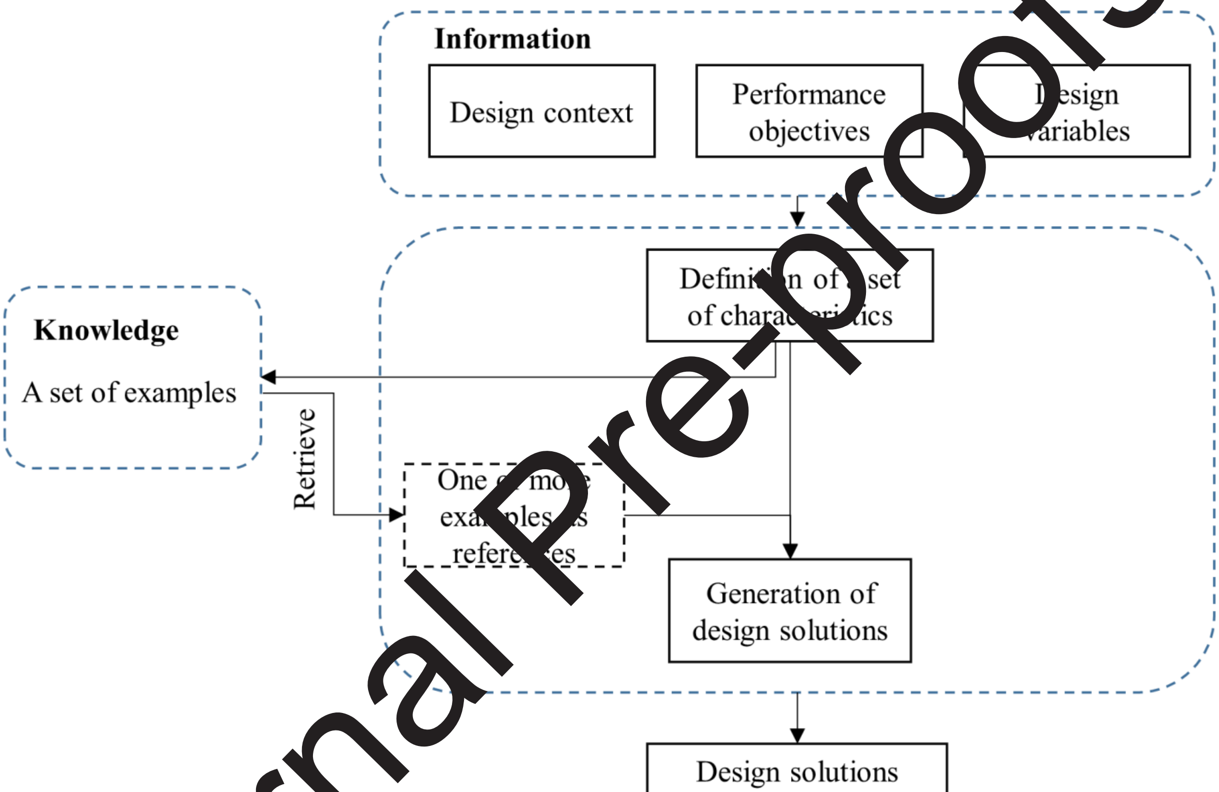


Figure 6. Case-based design(CBD) process for fenestration systems

Currently, CBD methods for the fenestration system are under-researched, and future research is desired before a convincing breakthrough occurring. It should be also noted that a simulation model is a useful simplification and an approximation from a realistic design project and uncertainties always exist [48], thus an ideal knowledge source for an expert system comes from realistic projects. Therefore, one direction of the future research is to build a fenestration design project database to facilitate the development of case-based methods.

3.2. Simulation-based optimization methods

3.2.1. Fundamental of SBO design for fenestration systems

As fenestration system design problems become more complex, the solution space of such a problem often increases exponentially with the problem dimensions. The progress in computer

Journal Pre-proofs

science has helped provide a number of efficient numerical optimization algorithms to explore all promising solution regions within a given time budget.

In fenestration system design, the term “optimization” does not always mean performing a mathematical optimization. Some authors may use sensitivity analysis methods as an approach to optimize system performance [49]. In this section, the focus our efforts is on publications that perform mathematical optimizations to identify optimal fenestration system design solutions. It should be noted that because of nature of the problems which are NP (non-deterministic polynomial-time)-hard in many cases [50], most studies can only obtain sub-optimal solutions.

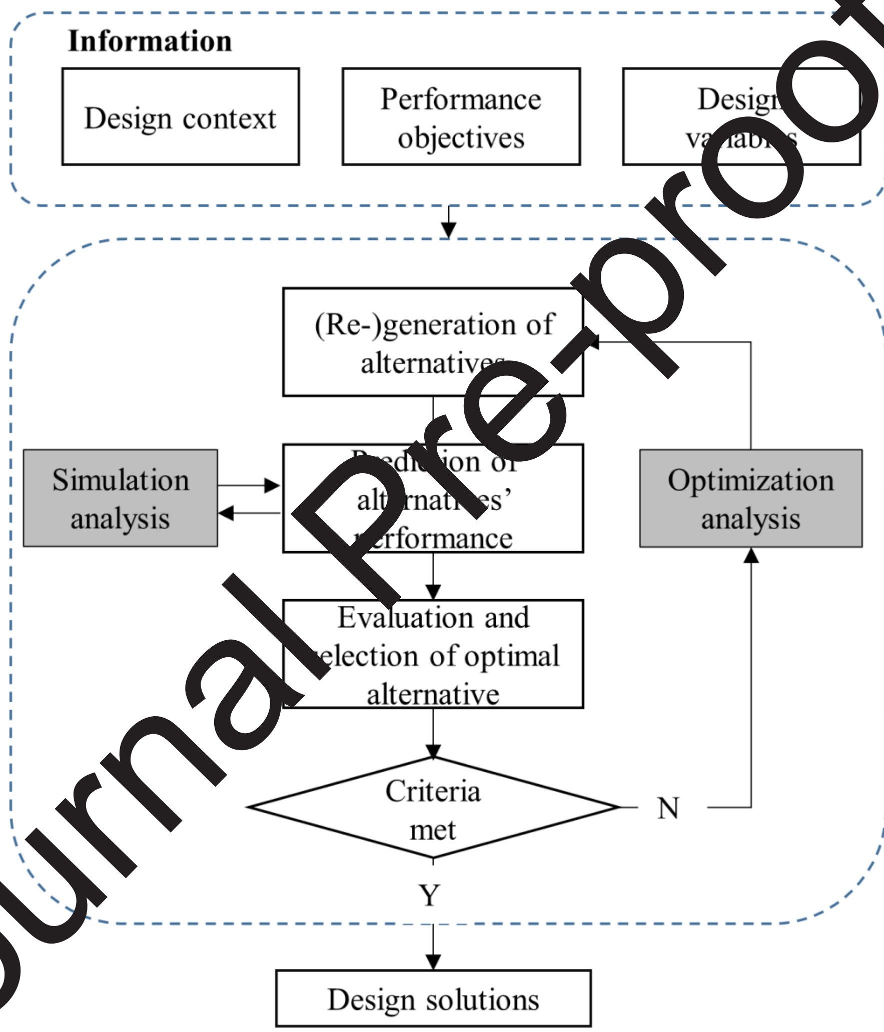


Figure 7. Simulation-based optimization design process for fenestration systems

The essential idea of SBOshows a generic process for SBO design of fenestration systems. In the first step, alternative fenestration design solutions can be (re-)generated by initialization methods used in some optimization algorithms, such as the random initialization used by Gagne and Andersen [51].

Journal Pre-proofs

Journal Pre-proofs

The second step determines the alternatives' performance using simulation analysis. Based on the objectives of the design problems and the scale of the current design step, appropriate simulation tools should be chosen and used . For instance, Radiance, as a ray-tracing lighting simulation program, can provide a detailed daylighting performance evaluation of the fenestration systems. However, it requires detailed modeling of system geometries and is not a good option for the conceptual design step [52]. A bibliometric review of the commonly-used simulation is presented in the following sections.

Based on the information obtained from the third step and the objectives of the design problems, a particular selection method is employed to select an optimum solution. A variety of selection methods are used in current literature and can be classified into two categories, based on the number of performance objectives. This includes a single-objective selection and a multi-objective selection. The single-objective method ranks the alternatives, thereby enabling the designer to select the optimum solution(s). For multi-objective problems, two selection methods are widely used, including the following: (1) according to the specified priorities among all performance objectives, a weighted sum is calculated and used as a single performance indicator; and (2) a Pareto optimal solution set is generated to facilitate the comparison of alternatives. However, this might be computationally expensive sometimes. Then, the SBO design process will proceed to the next step to check if the termination criteria are met or not. If not, the SBO design process will proceed to the first step to regenerate a new group of alternative design solutions from the selected design solutions in the third step. This iteration might be repeated several times until the termination criteria is met.

A good example of the SBO design of fenestration systems is provided by Wright et al [53]. This study described a multi-objective SBO design of a fenestration system. One key innovation of this study is that they proposed a cellular encoding method to represent the geometries of windows (e.g., shape, location, and dimensions) which divide the building facade into a matrix of rectangular cells and several matrices were used to represent the windows. External overhangs were also considered as design variables. EnergyPlus was used to calculate the illuminance results, which were then used for energy simulation. It should be noted that both windows and fixed overhangs were not controllable in their study, thus the only controls were to adjust the artificial lighting systems. Ideal dimming controls were employed to maintain the illuminance setpoint. Lastly, a multi-objective Genetic Algorithm was used to find the optimal design solutions. In addition, repeated optimizations and sensitivity analysis were also conducted to confirm the confidence in the optimality of the solutions.

One advantage of SBO design methods is that they allow the evaluation of multiple design variables at the same time, which is more likely to generate optimal design solutions compared with SKBD methods. The SBO design methods also provide a possibility for the use of an automatic design routine. However, although a great deal of work in this area has been conducted and published, many challenges still remain.

Journal Pre-proofs

3.2.2. Trends and challenges in optimization design studies

Error! Reference source not found. Figure 8 presents an increasing publication trend in this field. A pioneer study was presented by Caldas et al. in 2002 [54] where they proposed a design optimization tool using a Genetic Algorithm (GA) to investigate the placing and sizing of windows in an office building. Following this, since 2005, the number of publications has increased greatly, which shows an increasing interest in SBO design in the building research community.

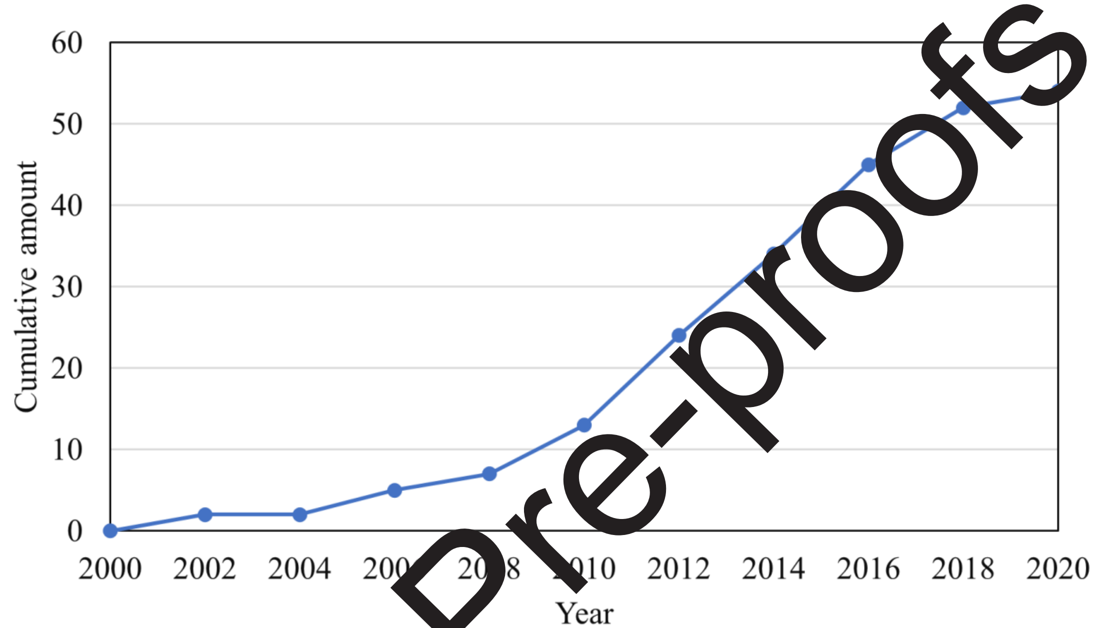


Figure 8. Cumulative number of SBO publications for fenestration systems

Challenges with computation speed

The computation time has long been viewed as a major feature to consider in the development of desirable SBO methods. As a non-ideal example, Magnier and Haghighat [55] found it took 10 years in the computational time to identify optimal solutions for a window design using Genetic Algorithms with TRNSYS simulations. In Wang et al. [56], a single optimization took approximately 70 hours. In practice, however, multiple optimization runs are required to either adjust hyper-parameters for the optimization process or compare multiple results to identify the best solution. This is because the most-used optimization algorithms (such as Genetic Algorithms) do not guarantee global optimal solution(s). Given such situations, the computation speed has received increased attention.

A review of recent literature reveals two main reasons for the prohibitive computation time for an optimization-based design of fenestration systems. First, while there are some other alternatives for daylighting simulations, Radiance is still preferred by most researchers due to its strong and flexible capabilities and accuracy (This will be discussed in the following section). Radiance uses ray tracing to perform all lighting calculations, which is well known for its high degree of virtual realism, but greater computational cost [52]. Cutler et al. [43] found that for their test scenarios,

Journal Pre-proofs

45-90 minutes were required to create a single highly accurate image using Radiance, and five minutes to produce a quick rendering. Secondly, as previously mentioned, the solution spaces for most fenestration design problems are large, particularly when more elements (such as heating, ventilation, and air-conditioning (HVAC) system operation setting) are taken into consideration. Although most advanced optimization algorithms can greatly reduce the number of runs, the number of simulations to be evaluated is still quite large. Wright et al. [36] showed that 5,000 unique solutions are required for the evaluation prior to the convergence of their GA-based optimization.

Such challenges establish a need for reducing the computation time of the SBO process. Several promising solutions have been tested in recent literature. These are summarized as follows.

(1) *Lower-Computational Intensity Tools*: Using a lower computational intensity daylighting simulation tool, which still provides a decent level of accuracy. One tool of interest is LightSolve by Andersen et al. [57]. However, more research should be conducted to show the general usefulness and feasibility of this simulation tool.

(2) *Surrogate Models*: Another way of alleviating the computational cost is by constructing an approximation model, known as a surrogate model, that mimics the behavior of the simulation model while being computationally inexpensive to evaluate. Many optimization studies have performed their design optimization using surrogate models [58-61]. Commonly-used surrogate models include the use of Artificial Neural Networks (ANN) and Multiply Linear Regression (MLR) in this application. Magnier and Haghighat [55] used ANN to characterize building behavior first. Then, a database of cases was created using TRNSYS to construct the ANN model. Next, the derived ANN model served as the simulation engine for the design optimization. This process is illustrated in Figure 9. Sampling methods are required to generate this database, and widely-used sampling methods include Monto Carlo sampling, and Latin Hypercube sampling, among others. Magnier and Haghighat [55] also have found that the time-saving associated with using surrogate models can be significant; reducing their computation period from more than 10 years to 7 minutes.

The development and performance evaluation of various surrogate methods have been an active area of research. Based on a review of the use of surrogate models in the building fenestration system field, there are several outstanding questions that remain to be answered consistently across the literature. These are as follows: (1) Is there a significant difference between optimization results obtained by a surrogate model and an actual simulation model? (2) What performance metrics are the best to use to evaluate the performance of a surrogate model? (3) Is it necessary to evaluate a surrogate model by embedding it in the optimization process (as embedded evaluation method) instead of evaluating it separately?

Figure 9. Flowchart for constructing surrogate models

Journal Pre-proofs

(3) *Adaptive Optimization with Multiple Simulation Tools*: Instead of using a single, time-consuming simulation tool throughout the optimization process, to improve the speed of computation, González and Coley [62] proposed a self-adaptive optimization method which used multiple simulation tools: LT-method, lumped parameter model, and EnergyPlus. The proposed method used the LT-method in the early stage of the optimization, and then as the optimization evolved, the lumped parameter model and EnergyPlus were used in sequence. The optimal solutions identified were found to be better than the solutions used only EnergyPlus, while also reducing the computational time to one third of other conventional methods. One major challenge for this self-adaptive method, however, is that termination and change criteria are needed to change between different simulation methods. As a result, more parameters are involved and the selection of these can have a significant impact on the performance of this self-adaptive method. Therefore, it is necessary to determine the criteria and associated values.

(4) *Micro-genetic algorithms*: Micro-genetic algorithms (micro-GA) are also found to be useful in some cases [51, 63]. A micro-GA is a genetic algorithm with a very small population, which consequently reduces the computational time required. In a study by Andersen et al. [51], after running a micro-GA process for 50 generations for 9 hours, a "perfect" solution was identified, although more "perfect" solutions may exist. The micro-GA process can get stuck at a local optimal solution or one "perfect" solution in a multi-modal problem. This problem can get worse when the dimensions of the design problem increase. Therefore, the micro-GA should be used with an understanding of its limitations.

(5) Other promising approaches include using high performance computer clusters to support high computation time needs, and performing dimension reduction methods (e.g., sensitivity analysis) to reduce the size of search space. Although there are no studies in the area of fenestration system design currently that utilize these methods, the use of these methods in other related fields provides motivation to consider their use in fenestration design applications.

Fenestration system design optimization under uncertainties

Like all scientific methods, optimization based fenestration system designs are also subject to various uncertainties, as an uncertainty is inherent as a part of the scientific method [64]. The uncertainty may arise from the simulation process, and objective functions. In current literature, uncertainties from simulation process are divided into two categories: aleatory and epistemic. Epistemic uncertainties can also be further divided into three categories, as discussed by Hopfe and Hensen [65]: physical, design, and scenario uncertainties. The uncertainties from the objective function arise from the specific formula since different designs can produce identical numerical performance values [66].

Journal Pre-proofs

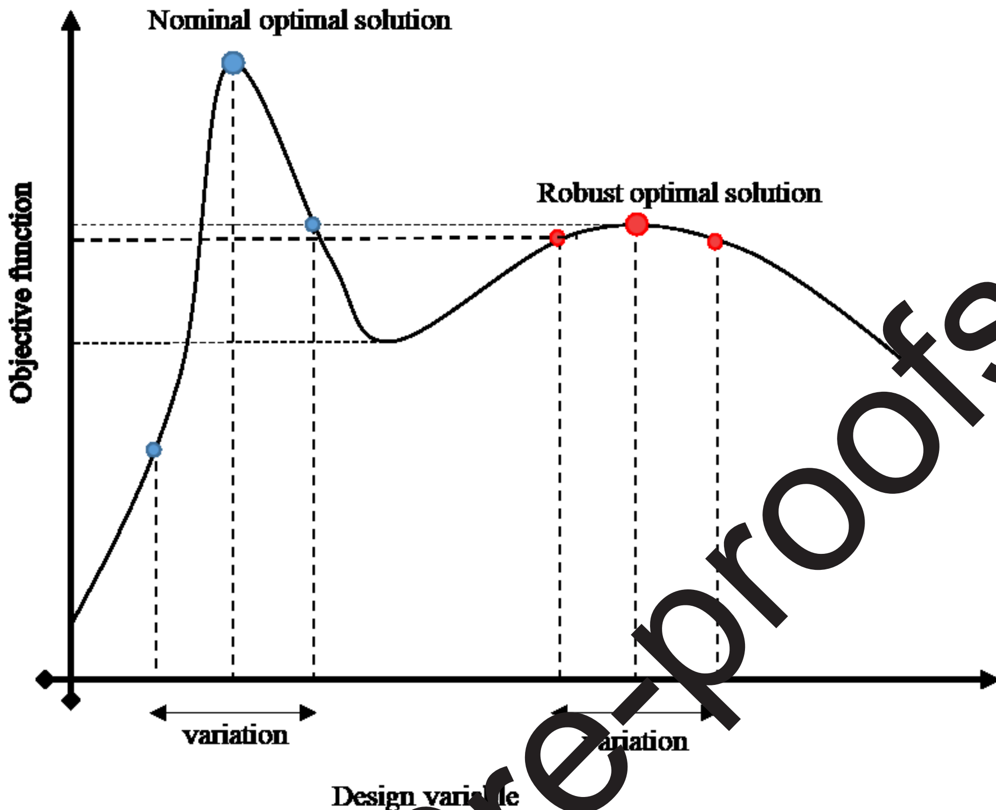


Figure 10. Robust optimal solutions of a single-variable function (adapted from [67])

To identify optimal solutions with the uncertainty, robust design optimization is required, which should be robust (or insensitive) to various uncertainties. Figure 10 is a widely-used illustration of robust design optimization. Instead of looking for a nominal sensitive optimization solution, the sub-optimal but robust solution should be found, which has a tolerance with respect to its uncertainty. An robust design optimization problem can be formulated as follows.

$$\text{Min} \quad F(X,\varepsilon_X,p,\varepsilon_p) = f(\mu_f(X,\varepsilon_X,p,\varepsilon_p),\sigma_f(X,\varepsilon_X,p,\varepsilon_p)) \quad (1)$$

$$\text{Subject to} \quad g(X,\varepsilon_X,p,\varepsilon_p) \leq 0 \quad \text{and} \quad X \leq X_R \; ;$$

Where X is a design variable vector, subject to the variable search space X_R; ε_X is the uncertain of X; p is a system parameter vector and ε_p is the corresponding uncertain. $\mu_f(\cdot)$ and $\sigma_f(\cdot)$ are the mean and standard deviation of the objective function, respectively. Based on Eq. (1), the robust design optimization problem could be viewed as finding a solution that provides the lowest mean objective function and the minimum standard deviation simultaneously, as discussed in [68, 69].

Robust design optimization is not a new challenge in many engineering applications. However, there are few research articles in building optimization design, or SBO design for fenestration systems. A pioneer study on the robust simulation-based optimization design was presented by Hopfe et al. [65]. In the case study presented, decision variables consist of values related to building geometry, glazing area, and building operation. A Kriging model was used for

Journal Pre-proofs

optimization and to examine the robustness of optimal Pareto fronts under input uncertainties. Results showed that with the support of the Kriging model, they successfully located a robust Pareto front for this multi-criteria optimization design. This study represents a starting point for further consideration of such methods, considering the necessity, significance, and practice of robust design optimization in SBO design for fenestration systems.

3.3. Other design schemes

3.3.1. graphical method

One commonly-used method for shading device design, specifically for static exterior shading device design, is the graphical method, which dates back to the middle of last century [70]. This design problem usually focused on the determination of the shading geometry to improve the system performance. Key graphical methods include the one point method [71], the point-cloud ray-trace [72], the cellular approach [73], and the SHADERADE method [74]. Such methods can be roughly divided into two categories. The first category of studies, including Olgyay's shading mask [70], Etzion's one point method [71], primarily account for the need of shading in the cooling period, rather than needs considerations in the heating season. To generate the shading solution, a shading period during which, over the course of a year, it is undesirable to have the solar radiation directly incident on a widow, is chosen. This period is bounded by "cut-off" dates at the start and end, and usually approximates the annual period of either mechanical cooling or potential overheating [74]. Then, the second step is to determine the type of shading device that provides complete shading of the window throughout the period. The emergence of these methods was earlier than the other category of methods, and the majority of these methods require less computation time because they were developed when limited computational capabilities were available. Here, Etzion's one point method [71] is explained to illustrate the fundamental philosophy of these methods.

Commonly used "cut-off" date selection methods include: (1) Equinox selection, which defines the shading period as that between the vernal and autumnal equinox; (2) Degree day selection, which uses heating and cooling degree days to identify the cooling period of a year; and (3) Thermal selection, which involves conducting a quick annual thermal simulation of the space under consideration without the use of a static shading device.

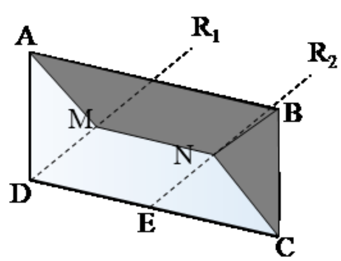


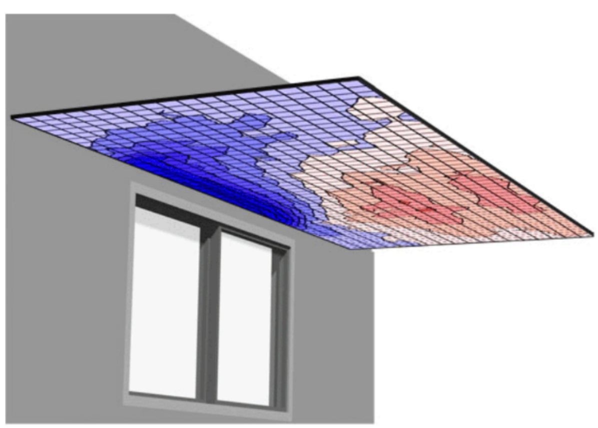
Figure 11.The shading device AMNCB completely blocks the sun rays, R_1 and R_2

Once a shading period has been identified using one of the above-mentioned methods, the one-point method is employed to find the shading form. A simple case of a shading device calculation is shown in Figure 11. This is the shading device derived for a rectangular window ABCD at a

Journal Pre-proofs

certain time. All the sun rays which are parallel to R_1 and R_2 would only be able to hit the lower window sill. The size and dimensions of shading device AMNCB would be determined only by the position of point *M* given a rectangular window. For other times, when the solar altitude and azimuth are different, the one-point method is still valid for the rectangular windows with few exceptions. The shape of the shading device for the entire shading period will be the result of the superposition of all shading devices needed to shade the window at any instant. This is discussed further in [71, 75]. In summary, there are several limitations of these methods, including that (1) they consider only shading needs rather than solar gain needs; (2) they are unable to handle complex geometry; (3) they consider only direct solar rays rather than diffuse radiation, and (4) they are unable to take other design performance objectives into consideration, such as aesthetics, cost, and artificial lighting.

The other category of graphical methods, including Kaftan's cellular shading method [73], Marsh's point-cloud ray-trace [72], and Sargent's SHADERADE method [74], do not only focus on the shading needs in cooling periods. For instance, the cellular shading method [73] enables designers to optimize shading devices based on predicted indoor thermal requirements for both shading and solar gain (i.e.., hourly sensible heating and cooling loads). These methods employ a range of approaches to address the limitations of "cut-off" data methods, which are not detailed herein. Here, we present a brief review of the cellular shading method, which is used in Ecotect[76]. This method begins by dividing the proposed shading devices into numerous theoretical cells. The cell's degree of importance to provide either shading or solar penetration during a certain time is calculated, as illustrated in Figure 12. The cell's overall importance is then calculated as the accumulated sum for an analysis period. Finally, the final shading form resulting from this method, could be optimized based the accumulated information and other specific design needs (e.g. cost, structure, etc.). In summary, graphical methods in this category consider the shading and solar gain needs in both the winter and summer periods. These methods usually can accommodate geometries of any complexity, and enable a high level of flexibility in considering design needs. In addition, simulations are required by these methods to obtain detailed performance information. For instance, in the SHADERADE implementation [74], EnergyPlus is used as the energy simulation engine. However, while shading device design is ultimately a trade-off between a variety of performance objectives (energy consumption, thermal comfort, visual comfort, cost, environmental impact, etc.), graphical methods focus mainly on thermal performance.



Journal Pre-proofs

Figure 12. Cellular shading method model [77]

4. Design tool analysis

We have conducted an extensive search for the studies using simulation tools to conduct the parametric analysis and simulation-based control design. In total, 97 papers were found. Based on these studies, a bibliometric review of energy simulation tools, daylight simulation tools, and optimization algorithms (for SBO design methods) is presented and discussed in detail in the following sections. However, it should be noted that because our analysis is based on research studies in these papers, most conclusions resulting from this analysis are more applicable to research-focused efforts and may have more limited applicability in industry.

4.1. Energy system simulation tools

Figure 13 shows the percent utilization of Figure 7. Simulation-based optimization design process for fenestration systemsthe energy system simulation tools used by these research articles. The overwhelming share (i.e., 54% of articles) use EnergyPlus (E+) [78]. Openstudio [79], DesignBuilder [80] and jEplus [81] were developed to provide an easy-to-use graphical user interface (GUI) to interface with EnergyPlus, therefore these were categorized as variants of EnergyPlus in this analysis. Figure 14 also shows the cumulative usage of EnergyPlus over time. The first study using EnergyPlus as a design analysis tool was published after 2000. This is because the original version of EnergyPlus was released in 2001, which was followed by several other studies. In 2015, EnergyPlus surpassed DOE2 [82] and became the most popular energy simulation program. This remains the case currently. As we previously mentioned, this is the case in research while in practice and industry, DOE2/eQuest are still the most popular one. The distribution of the usage of energy simulation tools across countries is shown in Figure 15. This suggests that EnergyPlus has become prevalent around the world.

TRNSYS [83] accounts for the second largest share of use among these programs. Some potential reasons for the popularity of Energy and TRNSYS are as follows: their abundant modeling features and capabilities, strong technical support, broad user base, and timely version updates make them powerful and viable. EnergyPlus' dominant share is also likely because it is open-source and free. DOE2 accounts for a smaller share , and it was generally more popular before EnergyPlus took much of the usage share. However, the engineering industry continues to use DOE2 and eQUEST, while most researchers have switched to EnergyPlus. Besides, based on the papers included in this study, DOE2 is mainly used in the United States and is rarely used in other countries (see the red circle in Figure 15).

Matlab, IES-VE [84],and IDA ICE [85] are also used by some researchers. "Others" in Figure 13 refers to others simulation tools used in these articles, including Lumped Parameter Models, LT-methods [86], the ASHRAE toolkit for building load calculations [87], and Autodesk Green Building Studio (with a simulation backbone of DOE2) [88], Ecotect [76], ESP-r [89], Capsol[90], COMFEN [91], DEROB-LTH [92], EDSL TAS [93], iDbuild [94], IENUS [95], SIBIL [22], SUNCODE-PC [96],etc. These programs are used by only a small number of studies or in a certain area, and account for 20% of these papers. For instance, ESP-r was developed as general-purpose building performance energy modeling software by the University of Strathclyde, and has been under development for more than 30 years. Currently, it is still widely used by some researchers in Europe (see Figure 15) to compute the thermal performance of fenestration and shading systems [97].

A further quantitative analysis should be conducted to compare the performance of these programs. Currently, a valuable review was provided by Crawley et al. [98], which presents more information about most of these simulation tools, including their capabilities, strengths and weakness.

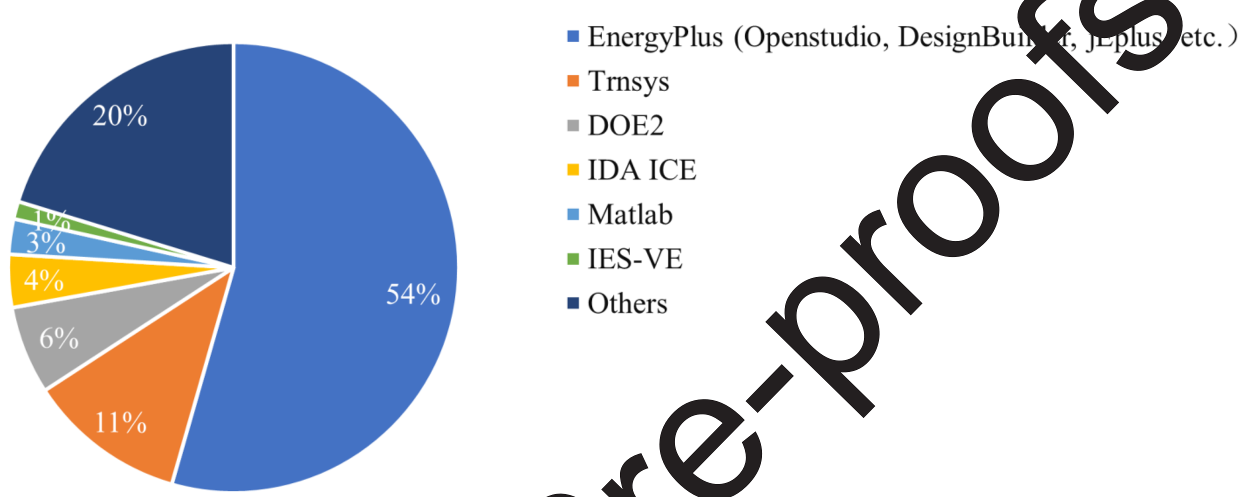


Figure 13.Utilization share of major energy system simulation programs for fenestration systems

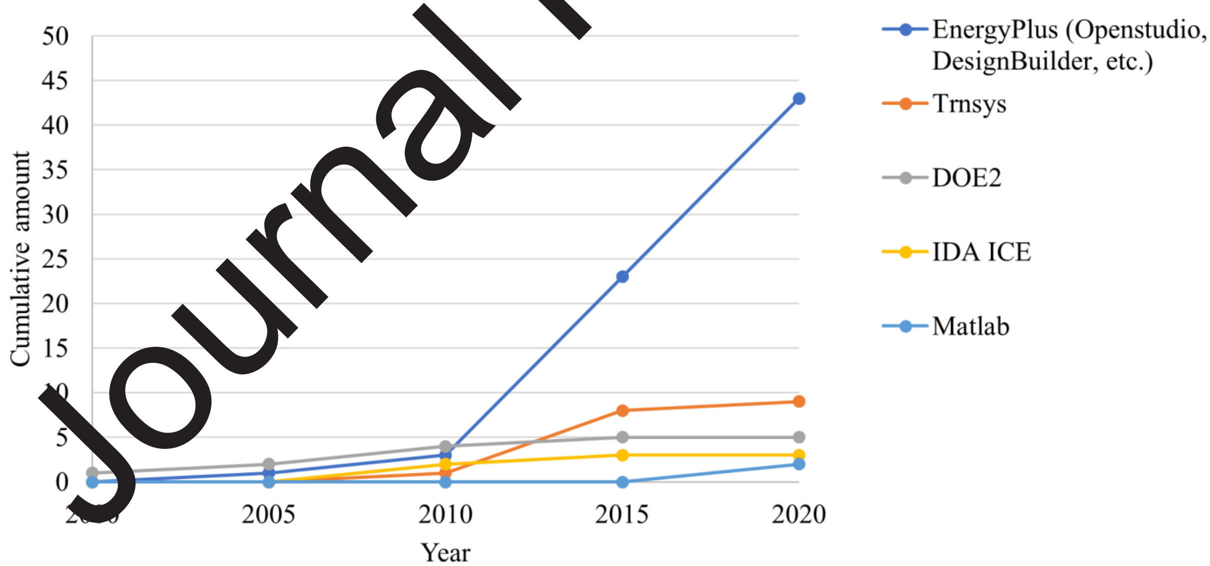


Figure 14. Cumulative usage of the top 5 energy simulation tools

Journal Pre-proofs

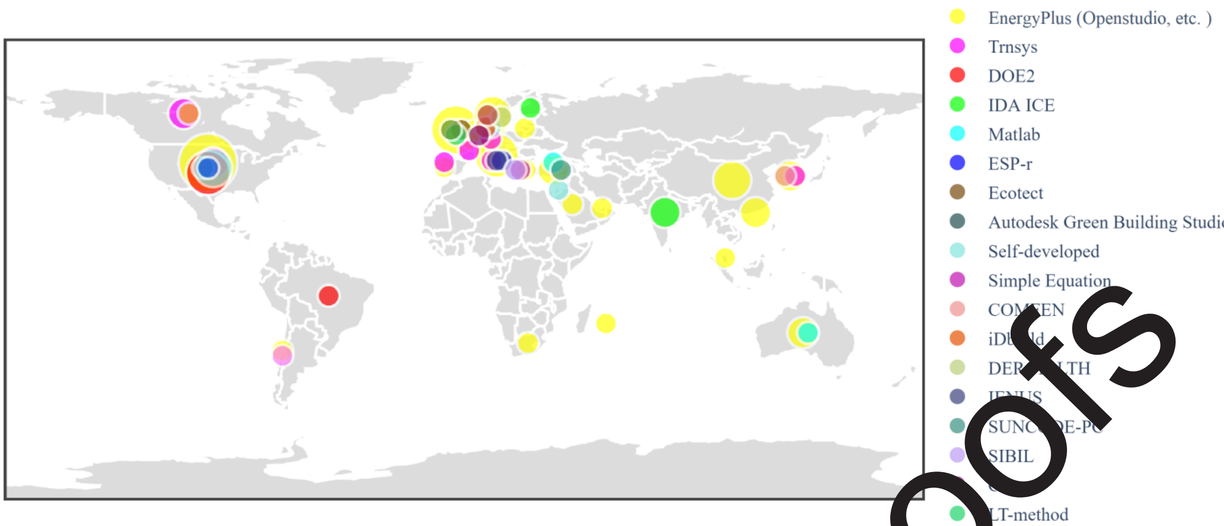


Figure 15. Spatial distribution of the total usage amount of all energy simulation tools

4.2. Daylighting system simulation tools**Error! Reference source not found.**Figure 16 shows an approximation of the utilization share of the major daylighting simulation engines. Radiance is the most popular simulation engine among those tools. First developed in 1985 [99], Radiance is generally considered to be the most accurate and flexible tool for lighting simulation. In addition, similar to EnergyPlus for energy simulation, Radiance often serves as the underlying simulation engine for other daylighting simulation packages (e.g., DIVA for Rhino [100],DaySim [101], OpenStudio [79]). A number of studies have been conducted to integrate Radiance with an optimization analysis to provide the design guidance regarding daylight performance of windows [97, 102, 103]. Motamedi et al. [104] used Radiance to identify an optimal design of the skylight for a one-story building through implementing EnergyPlus as the energy simulation engine, and Grasshopper to couple EnergyPlus and Radiance. The decision variable considered was the skylight floor area ratio; and they applied both a gradient descent method and an exhaustive search method to identify optimal solutions. Results indicated the ability to obtain energy-saving design solutions while meeting targeted daylighting performance requirements. Vera et al. [105] successfully used Radiance to optimize a fixed exterior complex fenestration system. The decision variables in their study included three variables related to the fenestration system. It should be noted that most studies which use Radiance as the daylighting simulation engine only consider a relatively small amount of decision variables, as Radiance is highly computation-intensive, thus a large search space might make the Radiance-based optimization design computationally prohibitive [106]. With this said, Radiance has maintained its number one rank since 2010 as shown Figure 17. One most possible explanation for this is due to the great advancement in optimization algorithms and computer science. In addition, Figure 18 shows that although its main users are located in the United States, Radiance is widely used by the users from different areas around the world.

EnergyPlus is also used for daylighting simulation in some studies, however its features are limited as compared to stand-alone methods discussed in the previous sections. EnergyPlus provides two daylight calculation methods: Delight (Radiosity) and Split-flux which is derived

Journal Pre-proofs

from DOE2. Both methods provide an approximation of particular daylighting simulation outputs. Wright et al. [36, 107] used EnergyPlus to calculate illuminance results, which were then used to run energy simulations. As discussed in Yoon et al. [108], the Delight method was able to provide relatively accurate results when compared to experimental data, when used for simple windows without shading devices. The Split-flux method was found to be accurate only for shading windows using blinds. These results suggest the daylighting calculations used by EnergyPlus are not generally accurate if more complex window components are applied. However, since EnergyPlus supports more rapid calculation of certain daylighting metrics, it is still has been used in some research efforts when the computational resources are of concern, the fenestration system is simple, and the desired daylighting metrics are limited.

In addition, DOE2 was once one of the most popular daylighting simulation program used until 2010 (see Figure 17) [109], where the daylighting simulation algorithm implemented is Split-flux. Several researchers used DOE2 to conduct simulation-based optimizations and parametric analysis for fenestration systems [54, 110, 111]. One key feature of DOE2 at that time is that it provided an environment to easily integrate thermal and daylighting simulation for a single building model. However, because most of its simulation characteristics including its daylighting simulation module are inherited by EnergyPlus, EnergyPlus has taken its place after 2010 and become the second most popular lighting simulation program.

Lightsolve Viewer (LSV) is a academic focused modeling software developed by EPFL, which combines forward ray tracing with radiosity and shadow volumes rendering [43] and offers an alteratives to Radiance with a lower computational intensity. A study found a rendered scene in LSV took 3.3% of the time required by Radiance, while displaying a relatively similar result [43]. LSV has been implemented in the studies by Andersen et al. [38, 43, 51, 57, 106], and shows strong performance for certain applications. The usage of LSW is limited to its development team currently.

Applications of COMFEN, a specific simulation tool for fenestration systems based on EnergyPlus is also be found in current literature [112]. As a specific tool for fenestration systems, it helps to easily define fenestration facade details and conduct a comparative façade analysis. Some other simulation tools include RUMLITE [113], IENUS, SIBIL, iDbuild, and Daylihgt visualizer [114]. These programs are used by only a small number of studies or in a certain area of the world as well, and account for 19% of these papers covered.

Journal Pre-proofs

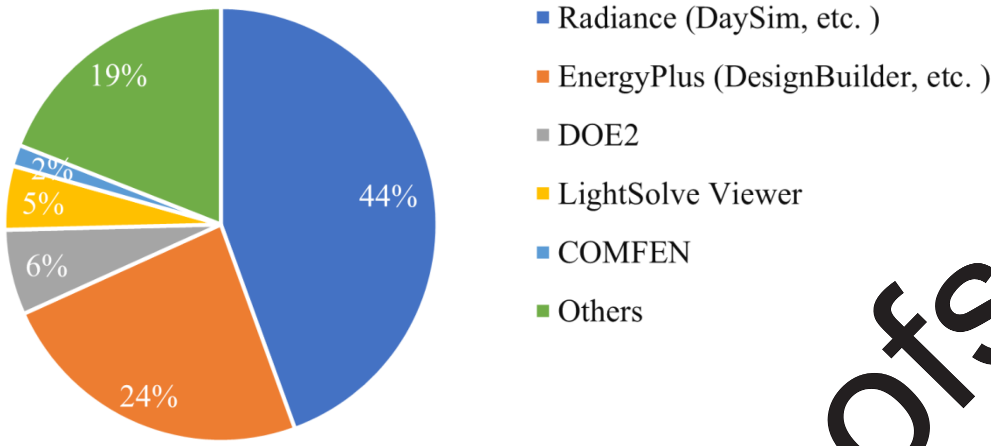


Figure 16.Utilization share of major daylighting system simulation programs

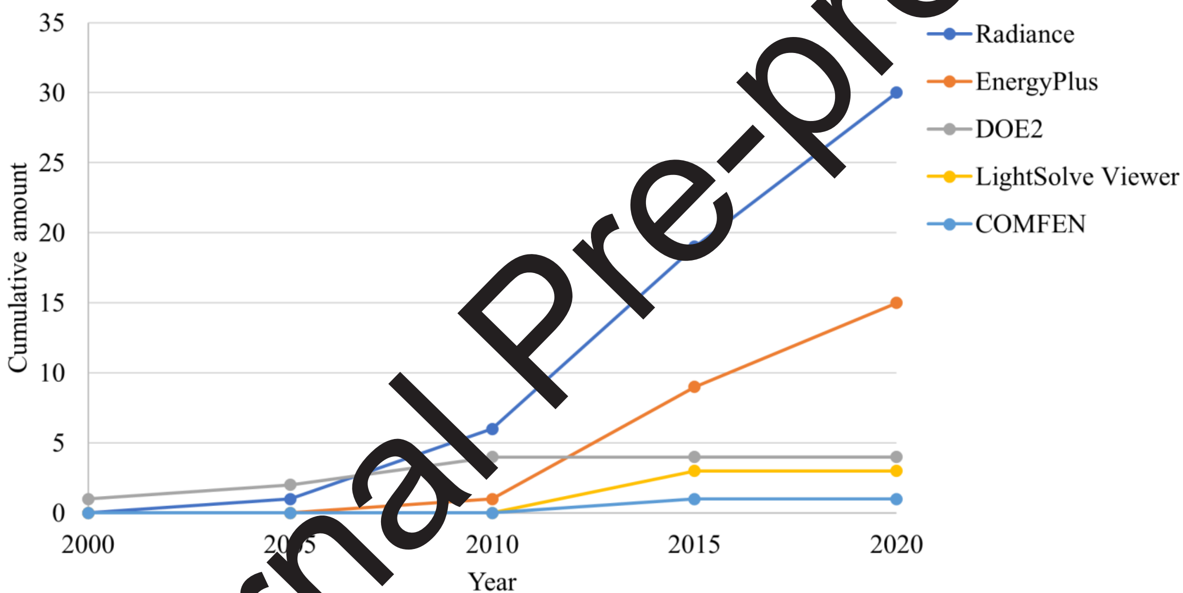


Figure 17. Cumulative usage of the Top 5 energy simulation tools in the surveyed literature

Journal Pre-proofs

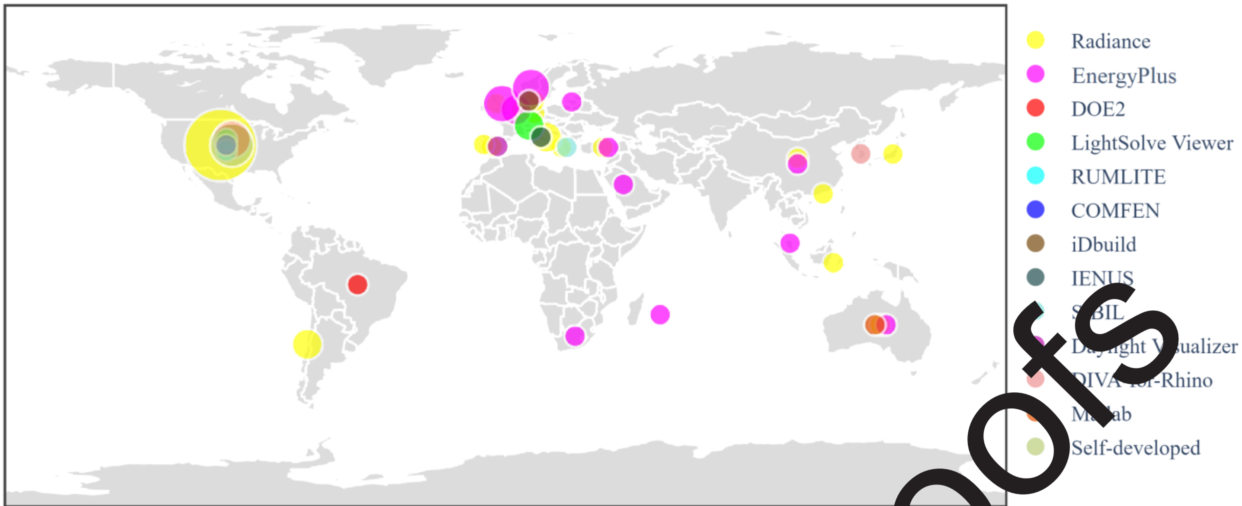


Figure 18. Spatial distribution of the total usage amount of all daylighting simulation tools in the surveyed literature

4.3. Optimization algorithms and programs

The choice of optimization algorithms for fenestration systems and the corresponding parameter settings is crucial to yielding the best design solutions. The optimization algorithms used in the reviewed articles are summarized in 19. Meta-heuristic methods, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO), are the most popular methods for SBO of fenestration systems. These meta-heuristic methods have a key feature of stochastic operations, which allows them to efficiently overcome problems associated with local optimal solutions and large discontinuous search spaces. Such a feature is desirable for fenestration optimization problems, which usually have the following characteristics: discontinuous decision variables (e.g., type of glazing [115]), large search space (i.e., size of search space increases exponentially with the number of decision variables; ten decision variables results in more than one million potential alternatives [116]), multimodal and multi-objective optimization. Wright et al. [53] conducted a comparison of the performance of five algorithms (IBEA, MOCell, NSGA-II, SPEA, and PAES) for a multi-objective window optimization problem, finding that NSGA-II (one multi-objective GA) performed the best in constrained and unconstrained cases in terms of both result quality and computation performance. Other studies (e.g., Futrell et al. [117]) have also provided insights into the comparison of the performance of different algorithms.

However, an exhaustive comparison of the performance of all existing algorithms is fundamentally ill-posed because there are many optimization algorithms available. In addition, the performance of certain algorithms is also strongly related to the context of the optimization problems. Therefore, it is necessary to test if the chosen method would be able to identify optimal solutions for the problem under consideration. There are several validation methods used in current literature: (1) test against a similar hand-worked example of a limited size [54]; (2) validation against the solutions derived from conventional design methods[107]; and (3) conducting a sensitivity analysis to understand to what extent the solutions may be optimal [36]. In addition, the

Journal Pre-proofs

computation speed of the chosen optimization algorithms is another key index when choosing proper algorithms. Stavrakakis et al. [118] and Motamedi et al. [104] applied a gradient descent search method to locate the optimal solutions, and both reached good-quality solutions in the target problems. This is largely because the size of search spaces in their studies was within in the capability range of gradient descent search methods.

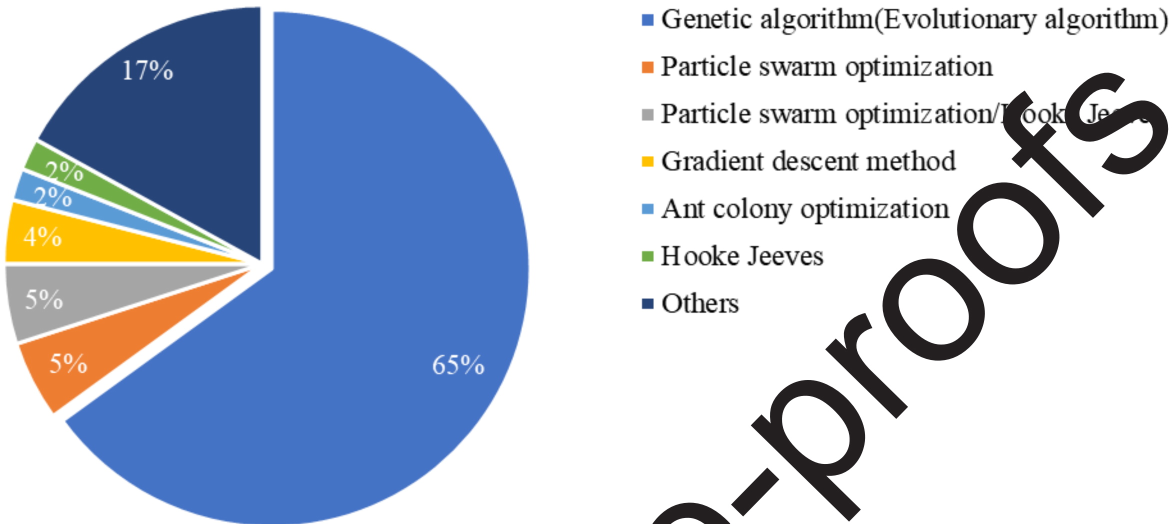


Figure 19. Utilization share of major optimization algorithms for SBO of fenestration systems

Other algorithms (e.g., Particle Swarm Optimization/Hooke Jeeves (PSO/HJ), Hooke Jeeves (HJ), graphical optimization) are also becoming more common [119, 120]. In summary, given the broad range of optimization algorithms, these should be carefully selected based on the characteristics of the problems under study. Further validation procedures are also highly recommended to understand the extent to which the solutions may be optimal.

A variety of optimization programs have been used in the fenestration optimization design literature, including GenOpt, Matlab, MultiOpt, GENE_ARCH, modelFRONTIER, Galapagos in Grasshopper, and DAKOTA. Among all these programs Galapagos [121], GenOpt [122], and Matlab are the most commonly used tools. GenOpt is a free, generic optimization tool specifically designed for building optimization problems. The optimization algorithms implemented include the Simplex algorithm, Pattern Search algorithm, PSO, and hybrid algorithms. Another advantage of GenOpt is that it allows an easy-to-use coupling with many building-related simulation programs (such as EnergyPlus and TRNSYS). However, to the best of authors' knowledge, the current GenOpt version does not support multi-objective algorithms. The Maltab optimization toolbox is a generic multi-domain optimization tool that could provide a high-level flexibility to the users with a user-friendly coupling function to integrate with simulation programs. Galapagos is a generic optimization tool in the Grasshopper environment [121]. Grasshopper provides a convenient platform to couple many simulation engines and has a number of plugins to combine other functions. A good example is the study by Motamedi and Liedl, in which they have proposed an algorithm to find optimal design of skylight for a one-story office building using Galapagos [104].

Journal Pre-proofs

Other useful optimization tools (such as jEPlus+EA [123], AMPL [124], Opt-E-Plus [125]) also have promising capabilities for using in SBO based design of fenestration systems although they have not been used in the reviewed 54 papers in this study.

5. Conclusions

In this review, we have systematically reviewed the current state of research on the design of fenestration systems. Fenestration system design have been the focus of building community for several decades, but the recent advances of system simulation and computational science have introduced a new paradigm into the study of fenestration systems.

Current fenestration design methods are divided in three categories: (1) knowledge-based methods; (2) simulation-based optimization methods; and (3) other methods which mainly comprise graphical methods. Simulation-based optimization is a promising and the most prevalent approach to achieve fenestration design targets. An overview of simulation tools, optimization methods, and optimization tools employed is also presented. There is a clear growth in the popularity of simulation-based optimization studies. As the capability of the simulation programs and optimization packages, either standalone or integrated, continues to expand, commercial application of simulation-based optimization is anticipated to be widely used.

Towards automatic simulation-based optimization methods, major challenges and future research opportunities are also presented, including issues related to computation speed, and uncertainty of factors during optimization. Computation speed is a key challenge in commercial applications, as fenestration system design covers many detailed variables. Perhaps cloud computing simulation-based optimization may be used more often moving forward. In order to perform fenestration design that is both environmentally- and economically-conscious, uncertainty and robustness should be better accounted for. Future research should focus on addressing these challenges. Fenestration system design is a process which requires the efforts of generations to answer: how to conduct a system design to generate the best result.

Acknowledgements

This study is supported by the NSF project #2011296 and #2013093 " Collaborative Research: Adaptive, Multi-Layered Fenestration Elements for Optimum Building Energy Performance and Occupant Comfort."

Journal Pre-proofs

Appendix A.

Table A. State-of-art review articles related to fenestration systems or parts of fenestrations

Ref.	Year	Subject related to fenestration systems	Keywords	No. of ref.
Carmody et al. [37, 126]	2004	Review of window materials and assemblies, and a decision-making process for window design along with several case studies.	Window material	N/A
Baetens et al. [22]	2010	Currently available dynamic smart windows (e.g. electrochromic windows, liquid crystal devices, and suspended-particle devices, etc.), their	Smart window	155

Journal Pre-proofs

		properties and potential for daylight and solar energy control in buildings		
Baetens et al. [18]	2010	Aerogel insulation in general and for building applications (*Note: both opaque and translucent aerogel insulation materials are covered, while we are only interested in the latter for this research)*	Aerogel insulation	85
Chow et al. [127]	2010	Developed and emerging innovative solar window technologies for cooling-demand climates	Glazing	41
Granqvist et al. [24]	2010	Advances in chromogenic materials and devices (*including thermochromic, and electrochromic)* and their impacts on energy saving and occupant comfort	Chromogenic	76
Jelle et al. [8]	2011	Best performing, state-of-the-art fenestration productions (*excluding mechanically operated fenestration parts, e.g. blinds, shades and etc.*) available; research and development being performed; possible research opportunities and potential future products	Glazing, Spacers, Frames, Phase change materials	89
Granqvist [128]	2012	Oxide-based electrochromics, including applications, device design, and critical materials issues	Electrochromic	218
Li et al. [129]	2012	Three challenges with VO_2-based materials and research to meet the challenges	Thermochromic	159
Buratti and Moretti [20]	2013	Nanogel windows and their properties and potential for energy saving in building applications	Nanogel	N/A
Midtdal [33]	2013	Self-cleaning glazing products currently available; methods for measuring the impact of self-cleaning; future research pathways and opportunities	Self-cleaning glazing	48
Jelle [16]	2013	Measurements and calculations of the most important solar radiation glazing factors	Glazing, Metrics	207
Ye et al.[130]	2013	Energy saving performance and corresponding theoretical limitations of the active/passive smart windows	Smart window	32
Bellia et al. [11]	2014	Solar shading systems, specifically external and intermediate devices; analysis of thermal, daylight and energy impacts of these shading systems	Shading	20
Granqvist [131]	2014	Electrochromics and their application in smart windows; references to current literature of particular relevance and provides good introduction to the research field	Electrochromic	1173
Granqvist [23]	2014	Oxide-based thermochromics; electrochromics with particular attention to recent advances	Electrochromic, Thermochromic	100
Cuce and Riffat [17]	2015	Existing glazing technologies; future research opportunities	Glazing	170
Hee et al. [132]	2015	Impact of window glazing types on the thermal, visual and energy aspects on the building; optimization techniques used in choosing a glazing	Glazing	74
Kirimtat et al. [133]	2016	Shading device types used in the building sector; previous studies for designating the performance aspects of different shading	Shading, Simulation tool	119
Silva et al.[27]	2016	Review of the use of phase change material in fenestration components, including glazing, shading device, etc.	PCM, Glazing, Shading	135
Kunwar et al .[134]	2018	Review of laboratory testing methods of dynamic shading devices and related literature	Dynamic shading	57

Journal Pre-proofs

Cui and Overend[34]	2019	Review of switchable thermal insulation technologies for glazing	Glazing with switchable U-value	137
Kuhn et al[28]	2020	Review of technological design options for building integrated photovoltaics	Glazing-integrated PV	173

Journal Pre-proofs

Appendix B.

Table B Literature involving daylight simulation or energy simulation of fenestration systems

Ref.	Publish Date	Country and area	Energy Sim Tool	Daylighting Sim Tool	Optim
[113]	01/1977	United States	Manual	RUMLITE	
[135]	01/1984	United States	DOE2	DOE2	
[136]	01/2000	Turkey	SUNCODE-PC	N/A	
[54]	11/2002	United States	DOE2	DOE2	
[137]	03/2003	Italy	IENUS	IENUS	
[56]	01/2005	Canada	ASHRAE toolkit for building load calculation	NA	
[110]	01/2005	Brazil	VisualDOE	VisualDOE	
[138]	01/2005	India	IDA ICE	NA	
[139]	01/2006	Greece	NA	Radiance	

[103]	01/2006	United States,	NA	Radiance	ant c
[140]	03/2006	Sweden	DEROB-LTH	N/A	
[141]	01/2007	Canada	Trnsys	NA	
[63]	01/2007	Japan	NA	Radiance	
[142]	01/2007	Germany	NA	DaySim	
[143]	01/2007	Netherlands	Capsol	DaySim	
[144]	03/2007	United States	Self-developed	NA	
[111]	06/2007	United States	DOE2	DOE2	
[145]	08/2007	Greece	SIBIL	SIBIL	
[146]	05/2008	Turkey	E+	E+	
[147]	10/2008	India	IDA ICE	N/A	
[107]	01/2009	United Kingdom	E+	E+	
[55]	01/2010	Canada	Trnsys	NA	
[148]	01/2010	Finland	IDA-ICE	NA	
[149]	01/2010	United Kingdom	Ecotect	Radiance	
[49]	02/2010	China	NA	NA	
[150]	06/2010	Lithuania	E+	E+	
[151]	08/2010	Jordan	Self-developed	NA	
[106]	08/2010	Switzerland	NA	LightSolve Viewer	
[152]	01/2011	Norway	IES-VE	NA	
[153]	01/2011	France	Trnsys	NA	
[58]	01/2011	United Kingdom	jEPlus	NA	
[154]	01/2011	Italy	E+	NA	
[155]	01/2011	United States	DOE2	NA	GA,PS
[156]	02/2011	United States	NA	DaySim	
[51]	03/2011	Switzerland	NA	LightSolve Viewer	
[157]	04/2011	Italy	Trnsys	N/A	
[158]	05/2011	Denmark	iDbuild	iDbuild	
[159]	07/2011	Reunion	E+	E+	
[160]	11/2011	Germany	Trnsys	N/A	
[53]	12/2011	United Kingdom	E+	E+	GA,
[119]	01/2012	Netherlands	E+	E+	Grap
[161]	01/2012	United States	Autodesk Green Building Studio		
[115]	01/2012	Italy	E+	NA	
[118]	01/2012	Greece	NA	NA	Gradi
[38]	01/2012	United States	NA	LightSolve Viewer	
[162]	02/2012	United States	Self-developed	Self-developed	
[163]	04/2012	Chile	EDSL TAS	DaySim	
[164]	06/2012	Greece	E+	NA	
[165]	07/2012	Portugal	E+	DaySim	
[102]	01/2013	United States	E+	Radiance	Br
[166]	01/2013	Greece	Simple Equation	NA	

Journal Pre-proofs

[167]	01/2013	Italy	E+	NA	
[168]	01/2013	China	E+	Radiance	
[169]	01/2013	United States	Self-developed	Self-developed	
[112]	02/2013	United States	E+	COMFEN	
[170]	02/2013	South Korea	DesignBuilder	N/A	
[36]	03/2013	United Kingdom	E+	E+	
[171]	04/2013	United States	Trnsys	DaySim	
[172]	06/2013	United States	E+	N/A	
[173]	08/2013	Norway	E+	E+	
[174]	09/2013	United States	NA	Self-developed	
[97]	01/2014	Italy	ESP-r	Radiance	
[175]	01/2014	Portugal	Trnsys	NA	
[176]	01/2014	United States	Trnsys	Radiance	
[62]	01/2014	United Kingdom	Lumped Parameter Model,E+,LT-method	NA	
[177]	04/2014	South Korea	COMFEN	N/A	
[178]	12/2014	Hong Kong	E+	DaySim	
[179]	12/2014	South Korea	E+	DIVA-for-Rhino	
[180]	01/2015	United States	E+	Radiance	"Hybrid
[181]	01/2015	United States	E+	Radiance	
[59]	01/2015	Turkey	E+	Radiance	
[117]	01/2015	United States	NA	Radiance	Algor Hooke
[132]	02/2015	Malaysia	OpenStudio	OpenStudio	
[182]	05/2015	Spain	NA	Daylight Visualizer	
[183]	05/2015	Denmark	Self-developed	NA	
[184]	05/2015	United States	N/A	Self-developed	
[185]	09/2015	Switzerland	E+	NA	
[186]	09/2015	Denmark	E+	DaySim	
[187]	10/2015	Norway	E+	E+	
[188]	12/2015	South Africa	E+	E+	
[189]	12/2015	Saudi Arabia	DesignBuilder	DesignBuilder	
[190]	01/2016	United States	NA	Radiance	
[191]	01/2016	Hong Kong	E+	NA	
[120]	02/2016	Indonesia	NA	Radiance	Grap
[192]	04/2016	Spain	N/A	DaySim	
[104]	06/2016	United States	E+	Radiance	Gradi
[193]	07/2016	Norway	E+	E+	
[194]	01/2017	Italy	E+	Radiance	
[195]	01/2017	Australia	E+	Radiance	
[105]	02/2017	Chile	E+	Radiance	"Hybrid
[196]	07/2017	United Arab Emirates	DesignBuilder	N/A	

Journal Pre-proofs

Journal Pre-proofs

[197]	09/2017	Australia	E+,Matlab	E+,Matlab
[60]	01/2018	South Korea	Trnsys	NA
[198]	01/2018	China	DesignBuilder	NA
[116]	08/2018	Turkey	Matlab	NA
[199]	04/2019	China	E+	E+
[200]	04/2020	United States	E+	Radiance

Journal Pre-proofs

Reference

[1] ASHRAE, ASHRAE handbook of fundamentals, 2013.

[2] J. Carmody, D. Arasteh, S. Selkowitz, L. Heschong, Residential windows: a guide to new technologies and energy performance, WW Norton & Company, 2007.

[3] J. Hraska, Chronobiological aspects of green buildings daylighting, Renewable energy, 73 (2015) 109-114.

[4] C. Allocca, Q. Chen, L.R. Glicksman, Design analysis of single-sided natural ventilation, Energy and buildings, 35 (8) (2003) 785-795.

[5] A.-T. Nguyen, S. Reiter, P. Rigo, A review on simulation-based optimization methods applied to building performance analysis, Applied Energy, 113 (2014) 1043-1058.

[6] L. Wong, A review of daylighting design and implementation in buildings, Renewable and Sustainable Energy Reviews, 74 (2017) 959-968.

[7] J.-L. Scartezzini, Advances in Daylighting and Artificial Lighting, Invited paper, in: 2nd International Conference Building Physics Conference, Leuven (Belgique), 2003.

[8] B.P. Jelle, A. Hynd, A. Gustavsen, D. Arasteh, H. Goudey, R. Hart, Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities, Solar Energy Materials and Solar Cells, 96 (2012) 1-28.

[9] A. Gustavsen, S. Grynning, D. Arasteh, B.P. Jelle, H. Goudey, Key elements of and material performance targets for highly insulating window frames, Energy and Buildings, 43 (10) (2011) 2583-2594.

[10] W.A.W.A. Rahman, L.T. Sin, A.R. Rahmat, Injection moulding simulation analysis of natural fiber composite window frame, Journal of materials processing technology, 197 (1-3) (2008) 22-30.

[11] L. Bellia, C. Marino, F. Minichiello, A. Pedace, An overview on solar shading systems for buildings, Energy Procedia, 62 (2014) 309-317.

[12] T.E. Kuhn, State of the art of advanced solar control devices for buildings, Solar Energy, 154 (2017) 112-133.

[13] T.E. Kuhn, C. Bühler, W.J. Platzer, Evaluation of overheating protection with sun-shading systems, Solar Energy, 69 (2001) 59-74.

[14] D.W. Kim, C.-s.S. Park, D.-w.K. Meng, C.-s.S. Park, Comparative control strategies of exterior and interior blind systems, Lighting Research and Technology, 44 (3) (2012) 291-308.

[15] P. Blanusa, W.P. Goss, H. Roth, P. Weitzmannn, C.F. Jensen, S. Svendsen, H. Elmahdy, Comparison between ASHRAE and ISO thermal transmittance calculation methods, Energy and Buildings, 39 (3) (2007) 374-384.

[16] B.P. Jelle, Solar radiation glazing factors for window panes, glass structures and electrochromic windows in buildings—Measurement and calculation, Solar Energy Materials and Solar Cells, 116 (2013) 291-323.

[17] E. Cuce, S.B. Riffat, A state-of-the-art review on innovative glazing technologies, Renewable and sustainable energy reviews, 41 (2015) 695-714.

[18] R. Baetens, B.P. Jelle, A. Gustavsen, Aerogel insulation for building applications: a state-of-the-art review, Energy and Buildings, 43 (4) (2011) 761-769.

[19] F.P. Torgal, M. Mistretta, A. Kaklauskas, C.G. Granqvist, L.F. Cabeza, Nearly zero energy building refurbishment, Nearly zero energy Building Refurbishment, (2013) 555-582.

[20] C. Buratti, E. Moretti, Nanogel windows, in: Nearly zero energy building refurbishment, Springer, 2013, pp. 555-582.

[21] B.P. Jelle, Electrochromic smart windows for dynamic daylight and solar energy control in buildings, in: Electrochromic Materials and Devices, Wiley Online Library, 2015.

[22] R. Baetens, B.P. Jelle, A. Gustavsen, Properties, requirements and possibilities of smart windows for dynamic daylight and solar energy control in buildings: A state-of-the-art review, Solar energy materials and solar cells, 94 (2) (2010) 87-105.

[23] C.G. Granqvist, Oxide-based chromogenic coatings and devices for energy efficient fenestration: Brief survey and update on thermochromics and electrochromics, Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena, 32 (6) (2014) 060801-060801.

Journal Pre-proofs

Journal Pre-proofs

[24] C.-G. Granqvist, S. Green, G.A. Niklasson, N.R. Mlyuka, S. Von Kraemer, P. Georen, Advances in chromogenic materials and devices, Thin Solid Films, 518 (11) (2010) 3046-3053.

[25] R. Baetens, B.P. Jelle, A. Gustavsen, Phase change materials for building applications: a state-of-the-art review, Energy and buildings, 42 (9) (2010) 1361-1368.

[26] M.F. Demirbas, Thermal energy storage and phase change materials: an overview, Energy Sources, Part B: Economics, Planning, and Policy, 1 (1) (2006) 85-95.

[27] T. Silva, R. Vicente, F. Rodrigues, Literature review on the use of phase change materials in glazing and shading solutions, Renewable and Sustainable Energy Reviews, 53 (2016) 515-535.

[28] T.E. Kuhn, C. Erban, M. Heinrich, J. Eisenlohr, F. Ensslen, D.H. Neuhaus, Review of Technological Design Options for Building Integrated Photovoltaics (BIPV), Energy and Buildings, (2020) 110381.

[29] P. Corti, P. Bonomo, F. Frontini, P. Mace, E. Bosch, Building Integrated Photovoltaics: A practical handbook for solar buildings' stakeholders, (2020).

[30] M. Wang, J. Peng, N. Li, H. Yang, C. Wang, X. Li, T. Lu, Comparison of energy performance between PV double skin facades and PV insulating glass units, Applied energy, 194 (2017) 148-160.

[31] J. Han, L. Lu, H. Yang, Numerical evaluation of the mixed convective heat transfer in a double-pane window integrated with see-through a-Si PV cells with low-e coatings, Applied Energy, 87 (11) (2010) 3431-3437.

[32] H. Yang, L. Lu, The optimum tilt angles and orientations of PV claddings for building-integrated photovoltaic (BIPV) applications, (2007).

[33] K. Midtdal, B.P. Jelle, Self-cleaning glazing products: A state-of-the-art review and future research pathways, Solar energy materials and solar cells, 109 (2013) 126-141.

[34] H. Cui, M. Overend, A review of heat transfer characteristics of switchable insulation technologies for thermally adaptive building envelopes, Energy and Buildings, 199 (2019) 427-444.

[35] D. Sinclair, Guide to Using the RIBA Plan of Work 2013, Routledge, 2019.

[36] J.A. Wright, A. Brownlee, M.M. Mourshed, M. Wang, Multi-objective optimization of cellular fenestration by an evolutionary algorithm, Journal of Building Performance Simulation, 7 (1) (2014) 33-51.

[37] J. Carmody, S. Selkowitz, E. Lee, D. Arasteh, T. Willmert, Window system for high-performance buildings, W. W. Norton & Company, 2004.

[38] M. Andersen, J.M. Gagne, S. Kleindienst, Interactive expert support for early stage full-year daylighting design: A user's perspective on Lightsolve, Automation in Construction, 35 (2013) 338-352.

[39] J.M. Gagne, M. Andersen, User-based evaluation of an interactive expert system for full-year daylighting design support, in: Proceedings of the Building Simulation and Optimization Conference BSO12, 2012.

Journal Pre-proofs

[40] J.M. Gagne, M. Andersen, A daylighting knowledge base for performance-driven facade design exploration, Leukos, 8 (2) (2011) 93-110.

[41] J.M.L. Gagne, M. Andersen, L.K. Norford, An interactive expert system for daylighting design exploration, Building and Environment, 46 (11) (2011) 2351-2364.

[42] J. Hu, S. Olbina, An Expert System Based on OpenStudio Platform for Evaluation of Daylighting System Design, in: Computing in Civil Engineering (2013), 2013, pp. 186-193.

[43] B. Cutler, Y. Sheng, S. Martin, D. Glaser, M. Andersen, Interactive selection of optimal fenestration materials for schematic architectural daylighting design, Automation in Construction, 17 (7) (2008) 809-823.

[44] K. Hiyama, S. Kato, M. Kubota, J. Zhang, A new method for reusing building information models of past projects to optimize the default configuration for performance simulations, Energy & Buildings, 73 (2014) 83-91.

[45] A. Heylighen, H. Neuckermans, A case base of case-based design tools for architecture, Computer-Aided Design, 33 (14) (2001) 1111-1122.

[46] N.O. Sonmez, A review of the use of examples for automating architectural design tasks, Computer-Aided Design, 96 (2017) 13-30.

[47] M.A. Rosenman, J.S. Gero, R.E. Oxman, What's in a case: the use of case bases, knowledge bases and databases in design, in: Computer-Aided Architectural Design Futures, 1991.

[48] F. Feng, Y. Fu, J. Hou, P. Xu, Optimizing the topologies of heating, ventilation, and air-conditioning water systems in supertall buildings: A pilot study, science and technology for the built environment, 24 (4) (2018) 371-381.

[49] X. Su, X. Zhang, Environmental performance optimization of window–wall ratio for different window type in hot summer and cold winter zone in China based on life cycle assessment, Energy and buildings, 42 (2) (2010) 198-202.

[50] R. Banos, F. Manzano-Agugliaro, F. Montoya, C. Gil, A. Alcayde, J. Gómez, Optimization methods applied to renewable and sustainable energy: A review, Renewable and sustainable energy reviews, 15 (4) (2011) 1753-1766.

[51] J. Gagne, M. Andersen, A generative facade design method based on daylighting performance goals, Journal of Building Performance Simulation, 5 (3) (2012) 141-154.

[52] G. Ward, R. Shakespeare, Rendering with Radiance: the art and science of lighting visualization, (1998).

[53] A.E. Brownlee, J.A. Wright, M.M. Mourshed, A multi-objective window optimisation problem, in: Proceedings of the 13th annual conference companion on Genetic and evolutionary computation, ACM, 2011, pp. 89-90.

[54] L.G. Caldas, L.K. Norford, A design optimization tool based on a genetic algorithm, Automation in Construction, 11 (2) (2002) 173-184.

Journal Pre-proofs

[55] L. Magnier, F. Haghighat, Multiobjective optimization of building design using TRNSYS simulations, genetic algorithm, and Artificial Neural Network, Building and Environment, 45 (3) (2010) 739-746.

[56] W. Wang, H. Rivard, R. Zmeureanu, An object-oriented framework for simulation-based green building design optimization with genetic algorithms, Advanced Engineering Informatics, 19 (1) (2005) 5-23.

[57] M. Andersen, A. Si, Lightsolve tutorial, (2010) 1-39.

[58] E. Tresidder, Y. Zhang, A.I. Forrester, Optimisation of low-energy building design using surrogate models, in: Proc. of the Building Simulation, 2011, pp. 1012-1016.

[59] E.E. Aydın, O. Dursun, I. Chatzikonstantinou, B. Ekici, Optimisation of energy consumption and daylighting using building performance surrogate model, in: 49th International Conference of the Architectural Science Association, 2015, pp. 536-546.

[60] S. Kang, S.g. Yong, J. Kim, H. Jeon, H. Cho, J. Koo, Automated processes of estimating the heating and cooling load for building envelope design optimization, building simulation, 11 (2) (2018) 219-233.

[61] B. Eisenhower, Z. O'Neill, S. Narayanan, V.A. Fonoberov, I. Mezić, A methodology for meta-model based optimization in building energy models, Energy and Buildings, 47 (2012) 292-301.

[62] A.P. Ramallo-González, D.A. Coley, Using self-adaptive optimisation methods to perform sequential optimisation for low-energy building design, energy and buildings, 81 (2014) 18-29.

[63] S.L. Torres, Y. Sakamoto, Facade design optimization for daylight with a simple genetic algorithm, in: Proceedings of Building Simulation, Citeseer, 2007, pp. 1162-1167.

[64] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, S. Tarantola, Global sensitivity analysis: the primer, John Wiley & Sons, 2008.

[65] C.J. Hopfe, J.L. Hensen, Uncertainty analysis in building performance simulation for design support, Energy and Buildings, 43 (10) (2011) 2798-2805.

[66] H. Rittel, Some principles for the design of an educational system for design, Journal of Architectural Education, 26 (1-2) (1971) 16-27.

[67] Y. Nomaguchi, K. Kawakami, K. Fujita, Y. Kishita, K. Hara, M. Uwasu, Robust Design of System of Systems Using Uncertainty Assessment Based on Lattice Point Approach: Case Study of Distributed Generation System Design in a Japanese Dormitory Town, international journal of automation technology, 10 (5) (2016) 678-689.

[68] W. Yao, X. Chen, W. Luo, M. Van Tooren, J. Guo, Review of uncertainty-based multidisciplinary design optimization methods for aerospace vehicles, Progress in Aerospace Sciences, 47 (6) (2011) 450-479.

[69] T. Chatterjee, S. Chakraborty, R. Chowdhury, A critical review of surrogate assisted robust design optimization, Archives of Computational Methods in Engineering, 26 (1) (2019) 245-274.

[70] A. Olgyay, Solar control and shading devices, (1957).

Journal Pre-proofs

[71] Y. Etzion, Design of shading devices using a one point method. A technical communication, Energy and buildings, 8 (4) (1985) 287-290.

[72] A. Marsh, Computer-optimised shading design, in: Proceedings of Building Simulation, Citeseer, 2003, pp. 11-14.

[73] E. Kaftan, A. Marsh, Integrating the cellular method for shading design with a thermal simulation, Passive and Low Energy Cooling for the Built Environment, (May) (2005) 965-970.

[74] J.A. Sargent, J. Niemasz, C.F. Reinhart, SHADERADE: Combining rhinoceros and energyplus for the design of static exterior shading devices, Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association, (November) (2011) 310-317.

[75] Y. Etzion, An improved solar shading design tool, Building and Environment, 27 (3) (1992) 297-303.

[76] A. Roberts, A. Marsh, ECOTECT: environmental prediction in architectural education, (2001).

[77] E. Kaftan, THE CELLULAR METHOD TO DESIGN ENERGY EFFICENT SHADING FORM TO ACCOMMODATE THE DYNAMIC CHARACTERISTICS OF CLIMATE, (2001).

[78] E.D. Team, EnergyPlus engineering reference: The reference to EnergyPlus calculations. EnergyPlus Version 9.3. , (2020).

[79] R. Guglielmetti, D. Macumber, N. Long, OpenStudio: an open source integrated analysis platform, National Renewable Energy Lab.(NREL), Golden, CO (United States), 2011.

[80] V. Garg, J. Mathur, A. Bhatia, Building Energy Simulation: A Workbook Using DesignBuilderTM, CRC Press, 2020.

[81] Y.Z.P. MASHRAE, Use jEPlus as an efficient building design optimisation tool.

[82] F. Winkelmann, B. Birdsall, W. Buhl, K. Ellington, A. Erdem, J. Hirsch, S. Gates, DOE-2 supplement: version 2.1 E,Lawrence Berkeley Lab., CA (United States); Hirsch (James J.) and Associates ..., 1993.

[83] U.o.W.-.-M.S.E. Laboratory., TRNSYS, a Transient Simulation Program., Madison, Wis. :The Laboratory, 1975.

[84] Integrated Envrionmental Solutions. 2011. VE-Pro. http://www.iesve.com/software/ve-pro in.

[85] T. Kalamees, IDA ICE: the simulation tool for making the whole building energy and HAM analysis, Annex, 41 (2004) 12-14.

[86] N. Baker, K. Steemers, LT Method 3.0—a strategic energy-design tool for Southern Europe, Energy and Buildings, 23 (3) (1996) 251-256.

[87] C.O. Pedersen, D.E. Fisher, R.J. Liesen, R.K. Strand, ASHRAE toolkit for building load calculations/Discussion, ASHRAE Transactions, 109 (2003) 583.

[88] G.B. Studio, Autodesk Green Building Studio, 2008.

[89] J. William, H. Sc, M. Arch, Strategies for Deploying Virtual Representations of the Built Environment aka The ESP-r Cookbook, (2014).

Journal Pre-proofs

[90] CAPSOL, v.4.0, Computer Program to Calculate Multi-zonal Transient Heat Transfer, © 2002 PHYSIBEL, in.

[91] R.J. Hitchcock, R. Mitchell, M. Yazdanian, E. Lee, C. Huizenga, COMFEN: A commercial fenestration/façade design tool, Proceedings of SimBuild, 3 (1) (2008) 246-252.

[92] H.J.L.U. Kvist, Lund, Sweden, User manual for DEROB-LTH, (1999).

[93] T.a.s.E.U.I. TAS, <http://www.edsl.net/>. .

[94] S. Petersen, S. Svendsen, Method and simulation program informed decisions in the early stages of building design, Energy and buildings, 42 (7) (2010) 1113-1119.

[95] F. Gugliermetti, L. Santarpia, F. Bisegna, Integrated energy use analysis in office spaces, in: Seventh International IBPSA Conference, Building Simulation, Proceedings. Edited by R. Lamberts, C. Negrao, J. Hensen. Rio de Janeiro, Brazil, 2001, pp. 991-998.

[96] M.J.E.I. DeLaHunt, Seattle, Wash, Suncode-PC, a program user's manual, (1985).

[97] M. Manzan, Genetic optimization of external fixed shading devices, Energy and Buildings, 72 (2014) 431-440.

[98] D.B. Crawley, J.W. Hand, M. Kummert, B.T. Griffith, Contrasting the capabilities of building energy performance simulation programs, Building and environment, 43 (4) (2008) 661-673.

[99] G.G. Roy, A comparative study of lighting simulation packages suitable for use in architectural design, School of Engineering, Murdoch University, Perth, Australia, (2000).

[100] J. Niemasz, Diva for Rhino, Since 2009.

[101] M.S.D. Lab, Daysim, since 2001.

[102] L. Ghobad, W. Place, S. Chen, Design optimization of daylight roofing systems: roof monitors with glazing facing in two opposite directions, in: Proc. International Conference on Building Performance Simulation (IBPSA), 2013.

[103] K. Shea, A. Sedgwick, G. Antonuntto, Multicriteria Optimization of Paneled Building Envelopes Using Ant Colony Optimization, Intelligent Computing in Engineering and Architecture, 13th EG-ICE Workshop 2006, (2006) 627-636.

[104] S. Motamedi, P. Liedl, Integrative algorithm to optimize skylights considering fully impacts of daylight on energy, Energy and Buildings, 138 (2017) 655-665.

[105] D. Uribe, W. Bustamante, S. Vera, Seasonal optimization of a fixed exterior complex fenestration system considering visual comfort and energy performance criteria, Energy Procedia, 132 (2017) 490-495.

[106] J.M. Gagne, M. Andersen, Multi-objective facade optimization for daylighting design using a genetic algorithm, Proceedings of SimBuild, 4 (1) (2010) 110-117.

[107] J.A. Wright, M. Mourshed, Geometric optimization of fenestration, (2009).

Journal Pre-proofs

[108] Y. Yoon, W. Jeong, K. Lee, Window material daylighting performance assessment algorithm: Comparing radiosity and split-flux methods, Energies, 7 (4) (2014) 2362-2376.

[109] S. Selkowitz, The DOE-2 and SUPERLITE daylighting programs, (1982).

[110] E. Ghisi, J.A. Tinker, An ideal window area concept for energy efficient integration of daylight and artificial light in buildings, Building and environment, 40 (1) (2005) 51-61.

[111] E.S. Lee, A. Tavil, Energy and visual comfort performance of electrochromic windows with overhangs, Building and Environment, 42 (6) (2007) 2439-2449.

[112] J.-W. Lee, H.-J. Jung, J.-Y. Park, J. Lee, Y. Yoon, Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements, Renewable energy, 50 (2013) 522-531.

[113] F. Arumi, Day lighting as a factor in optimizing the energy performance of buildings, Energy and Buildings, 1 (2) (1977) 175-182.

[114] Daylight Visualizer 2.6.7, Velux 2013. 〈http://viz.velux.com/daylight_visualizer/about〉, in.

[115] G. Rapone, O. Saro, Optimisation of curtain wall façades for office buildings by means of PSO algorithm, Energy and Buildings, 45 (2012) 189-196.

[116] S. Yigit, B. Ozorhon, A simulation-based optimization method for designing energy efficient buildings, Energy and Buildings, 178 (2018) 216-227.

[117] B.J. Futrell, E.C. Ozelkan, D. Brentrup, Optimizing complex building design for annual daylighting performance and evaluation of optimization algorithms, Energy and Buildings, 92 (2015) 234-245.

[118] G.M. Stavrakakis, P.L. Zervas, H. Sarimveis, N.C. Markatos, Optimization of window-openings design for thermal comfort in naturally ventilated buildings, Applied Mathematical Modelling, 36 (1) (2012) 193-211.

[119] C.E. Ochoa, M.B.C. Aries, E.J. van Loenen, J.L.M. Hensen, Considerations on design optimization criteria for windows providing low energy consumption and high visual comfort, Applied Energy, 95 (2012) 238-245.

[120] R.A. Mangkuto, M. Rohmah, A.D. Asri, Design optimisation for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: A case study of buildings in the tropics, Applied Energy, 164 (2016) 211-219.

[121] D. Rutten, Galapagos: On the logic and limitations of generic solvers, Architectural Design, 83 (2) (2013) 132-135.

[122] M. Wetter, GenOpt-A generic optimization program, in: Seventh International IBPSA Conference, Rio de Janeiro, 2001, pp. 601-608.

[123] jEPlus, jEPluse+EA, since 2012.

[124] A.O. Inc., AMPL, since 1985.

[125] NREL, Opt-E-Plus, since 2010.

Journal Pre-proofs

[126] E.S. Lee, S.E. Selkowitz, R.D. Clear, D.L. DiBartolomeo, J.H. Klems, L.L. Fernandes, G. Ward, V. Inkarojrit, M. Yazdanian, Advancement of electrochromic windows, Ernest Orlando Lawrence Berkeley NationalLaboratory, Berkeley, CA (US), 2006.

[127] T.-t. Chow, C. Li, Z. Lin, Innovative solar windows for cooling-demand climate, Solar Energy Materials and Solar Cells, 94 (2) (2010) 212-220.

[128] C.G. Granqvist, Oxide electrochromics: An introduction to devices and materials, Solar Energy Materials and Solar Cells, 99 (2012) 1-13.

[129] S.-Y. Li, G.A. Niklasson, C.-G. Granqvist, Thermochromic fenestration with VO2-based materials: Three challenges and how they can be met, Thin Solid Films, 520 (10) (2012) 3823-3828.

[130] H. Ye, X. Meng, L. Long, B. Xu, The route to a perfect window, Renewable Energy, 55 (2013) 448-455.

[131] C.G. Granqvist, Electrochromics for smart windows: Oxide-based thin films and devices, Thin solid films, 564 (2014) 1-38.

[132] W. Hee, M. Alghoul, B. Bakhtyar, O. Elayeb, M. Shameri, M. Alrubaih, K. Sopian, The role of window glazing on daylighting and energy saving in buildings, Renewable and Sustainable Energy Reviews, 42 (2015) 323-343.

[133] A. Kirimtat, B.K. Koyunbaba, I. Chatzikonstantinou, S. Sariyildiz, Review of simulation modeling for shading devices in buildings, Renewable and Sustainable Energy Reviews, 53 (2016) 23-49.

[134] N. Kunwar, K.S. Cetin, U. Passe, Dynamic Shading in Buildings: a Review of Testing Methods and Recent Research Findings, Current Sustainable/Renewable Energy Reports, 5 (1) (2018) 93-100.

[135] R. Johnson, R. Sullivan, S. Selkowitz, S. Nozaki, C. Conner, D. Arasteh, Glazing energy performance and design optimization with daylighting, Energy and Buildings, 6 (4) (1984) 305-317.

[136] M.N. Inanici, F.N. Demirbilek, Thermal performance optimization of building aspect ratio and south window size in five cities having different climatic characteristics of Turkey, Building and Environment, 35 (1) (2000) 41-52.

[137] F. Gugliermetti, F. Bisegna, Visual and energy management of electrochromic windows in Mediterranean climate, Building and environment, 38 (3) (2003) 479-492.

[138] H. Poirazis, Å. Blomsterberg, Energy and thermal analysis of glazed office buildings using a dynamic energy simulation tool, in: Proceeding of ninth international IBPSA conference, Montreal, Canada, 2005, pp. 945-952.

[139] A. Tsangrassoulis, V. Bourdakis, V. Geros, M. Santamouris, A genetic algorithm solution to the design of slat-type shading system, Renewable energy, 31 (14) (2006) 2321-2328.

[140] M.-L. Persson, A. Roos, M. Wall, Influence of window size on the energy balance of low energy houses, Energy and buildings, 38 (3) (2006) 181-188.

[141] R. Charron, Development of a genetic algorithm optimisation tool for the early stage design of low and net-zero energy solar homes, Concordia University, 2007.

Journal Pre-proofs

[142] J. Wienold, Dynamic simulation of blind control strategies for visual comfort and energy balance analysis, in: Building Simulation, 2007, pp. 1197-1204.

[143] R. Bokel, The effect of window position and window size on the energy demand for heating, cooling and electric lighting, in: Proceedings: Building Simulation, Citeseer, 2007, pp. 117-121.

[144] A. Tzempelikos, A.K. Athienitis, The impact of shading design and control on building cooling and lighting demand, Solar energy, 81 (3) (2007) 369-382.

[145] M. Assimakopoulos, A. Tsangrassoulis, M. Santamouris, G. Guarracino, Comparing the energy performance of an electrochromic window under various control strategies, Building and Environment, 42 (8) (2007) 2829-2834.

[146] N. Eskin, H. Türkmen, Analysis of annual heating and cooling energy requirements for office buildings in different climates in Turkey, Energy and buildings, 40 (5) (2008) 763-773.

[147] H. Poirazis, Å. Blomsterberg, M. Wall, Energy simulations for glazed office buildings in Sweden, Energy and buildings, 40 (7) (2008) 1161-1170.

[148] K. Siren, A. Hasan, M. Hamdy, Optimal Design of an Office Building for Low-Primary Energy Requirement and High-Indoor Thermal Comfort Level, in: presentation in Sustainable Community-buildingSMART conference, 2010, pp. 2010.

[149] S.H. Shikder, M. Mourshed, A.D. Price, Optimisation of a daylight-window: hospital patient room as a test case, (2010).

[150] V. Motuziene, E.S. Juodis, Simulation based complex energy assessment of office building fenestration, Journal of civil Engineering and Management, 16 (3) (2010) 345-351.

[151] K. Hassouneh, A. Alshboul, A. Al-Salaymeh, Influence of windows on the energy balance of apartment buildings in Amman, Energy Conversion and Management, 51 (8) (2010) 1583-1591.

[152] D. Chen, Z. Gao, A multi-objective generic algorithm approach for optimization of building energy performance, in: Computing in Civil Engineering (2011), 2011, pp. 51-58.

[153] F.P. Chantrelle, H. Lahmidi, W. Keilholz, M. El Mankibi, P. Michel, Development of a multicriteria tool for optimizing the renovation of buildings, Applied Energy, 88 (4) (2011) 1386-1394.

[154] G. Zemella, D. De March, M. Borrotti, I. Poli, Optimised design of energy efficient building façades via evolutionary neural networks, Energy and Buildings, 43 (12) (2011) 3297-3302.

[155] Y. Bichiou, M. Krarti, Optimization of envelope and HVAC systems selection for residential buildings, Energy and Buildings, 43 (12) (2011) 3373-3382.

[156] C.F. Reinhart, J. Wienold, The daylighting dashboard–A simulation-based design analysis for daylit spaces, Building and environment, 46 (2) (2011) 386-396.

[157] A. Gasparella, G. Pernigotto, F. Cappelletti, P. Romagnoni, P. Baggio, Analysis and modelling of window and glazing systems energy performance for a well insulated residential building, Energy and Buildings, 43 (4) (2011) 1030-1037.

Journal Pre-proofs

Journal Pre-proofs

[158] M.V. Nielsen, S. Svendsen, L.B. Jensen, Quantifying the potential of automated dynamic solar shading in office buildings through integrated simulations of energy and daylight, Solar Energy, 85 (5) (2011) 757-768.

[159] M. David, M. Donn, F. Garde, A. Lenoir, Assessment of the thermal and visual efficiency of solar shades, Building and Environment, 46 (7) (2011) 1489-1496.

[160] S. Jaber, S. Ajib, Thermal and economic windows design for different climate zones, Energy and Buildings, 43 (11) (2011) 3208-3215.

[161] D.J. Gerber, S.-H. Lin, B. Pan, A.S. Solmaz, Design optioneering: multi-disciplinary design optimization through parameterization, domain integration and automation of a genetic algorithm, in: Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design, 2012, pp. 1-8.

[162] H. Shen, A. Tzempelikos, Daylighting and energy analysis of private offices with automated interior roller shades, Solar energy, 86 (2) (2012) 681-704.

[163] A. Pino, W. Bustamante, R. Escobar, F.E. Pino, Thermal and lighting behavior of office buildings in Santiago of Chile, Energy and Buildings, 47 (2012) 441-449.

[164] K. Tsikaloudaki, K. Laskos, T. Theodosiou, D. Bikas, Assessing cooling energy performance of windows for office buildings in the Mediterranean zone, Energy and Buildings, 49 (2012) 192-199.

[165] P.C. da Silva, V. Leal, M. Andersen, Influence of shading control patterns on the energy assessment of office spaces, Energy and Buildings, 50 (2012) 35-48.

[166] C. Diakaki, E. Grigoroudis, Applying genetic algorithms to optimize energy efficiency in buildings, Multicriteria Decision Aid and Artificial Intelligence: Links, Theory and Applications, (2013) 309-333.

[167] M.E. Menconi, M. Chiappini, D. Grohmann, Implementation of a genetic algorithm for energy design optimization of livestock housing using a dynamic thermal simulator, Journal of Agricultural Engineering, (2013).

[168] X. Shi, W. Yang, Performance-driven architectural design and optimization technique from a perspective of architects, Automation in Construction, 32 (2013) 125-135.

[169] H. Shen, A. Tzempelikos, Sensitivity analysis on daylighting and energy performance of perimeter offices with automated shading, Building and environment, 59 (2013) 303-314.

[170] I. Susorova, M. Tabibzadeh, A. Rahman, H.L. Clack, M. Elnimeiri, The effect of geometry factors on fenestration energy performance and energy savings in office buildings, Energy and Buildings, 57 (2013) 6-13.

[171] B. Lartigue, B. Lasternas, V. Loftness, Multi-objective optimization of building envelope for energy consumption and daylight, Indoor and built environment, 23 (1) (2014) 70-80.

[172] S. Grynning, A. Gustavsen, B. Time, B.P. Jelle, Windows in the buildings of tomorrow: Energy losers or energy gainers?, Energy and buildings, 61 (2013) 185-192.

Journal Pre-proofs

[173] F. Goia, M. Haase, M. Perino, 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 (2013) 515-527.

[174] A. Tzempelikos, H. Shen, Comparative control strategies for roller shades with respect to daylighting and energy performance, Building and Environment, 67 (2013) 179-192.

[175] E. Asadi, M.G. da Silva, C.H. Antunes, L. Dias, L. Glicksman, Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application, Energy and Buildings, 81 (2014) 444-456.

[176] R. Shan, Optimization for heating, cooling and lighting load in building façade design, Energy Procedia, 57 (2014) 1716-1725.

[177] S.-H. Kim, S.-S. Kim, K.-W. Kim, Y.-H. Cho, A study on the proposes of energy analysis indicator by the window elements of office buildings in Korea, Energy and Buildings, 73 (2014) 153-165.

[178] Y. Huang, J.-l. Niu, T.-m. Chung, Comprehensive analysis on thermal and daylighting performance of glazing and shading designs on office building envelope in cooling-dominant climates, Applied energy, 134 (2014) 215-228.

[179] G. Yun, K.C. Yoon, K.S. Kim, The influence of shading control strategies on the visual comfort and energy demand of office buildings, Energy and Buildings, 84 (2014) 70-85.

[180] B.J. Futrell, E.C. Ozelkan, D. Brentrup, Bi-objective optimization of building enclosure design for thermal and lighting performance, Building and Environment, 92 (2015) 591-602.

[181] J. González, F. Fiorito, Daylight design of office buildings: Optimisation of external solar shadings by using combined simulation methods, Buildings, 5 (2) (2015) 560-580.

[182] I. Acosta, C. Munoz, M.A. Campano, J. Navarro, Analysis of daylight factors and energy saving allowed by windows under overcast sky conditions, Renewable Energy, 77 (2015) 194-207.

[183] M. Liu, K.B. Wittchen, P.K. Heiselberg, Control strategies for intelligent glazed façade and their influence on energy and comfort performance of office buildings in Denmark, Applied Energy, 145 (2015) 43-51.

[184] I. Konstantzos, A. Tzempelikos, Y.-C. Chan, Experimental and simulation analysis of daylight glare probability in offices with dynamic window shades, Building and Environment, 87 (2015) 244-254.

[185] T.M. Echenagucia, A. Capozzoli, Y. Cascone, M. Sassone, The early design stage of a building envelope: Multi-objective search through heating, cooling and lighting energy performance analysis, Applied energy, 154 (2015) 577-591.

[186] L. Vanhoutteghem, G.C.J. Skarning, C.A. Hviid, S. Svendsen, Impact of façade window design on energy, daylighting and thermal comfort in nearly zero-energy houses, Energy and Buildings, 102 (2015) 149-156.

[187] S. Carlucci, G. Cattarin, F. Causone, L. Pagliano, Multi-objective optimization of a nearly zero-energy building based on thermal and visual discomfort minimization using a non-dominated sorting genetic algorithm (NSGA-II), Energy and Buildings, 104 (2015) 378-394.

Journal Pre-proofs

[188] R. Singh, I.J. Lazarus, V. Kishore, Effect of internal woven roller shade and glazing on the energy and daylighting performances of an office building in the cold climate of Shillong, Applied energy, 159 (2015) 317-333.

[189] M.A. Fasi, I.M. Budaiwi, Energy performance of windows in office buildings considering daylight integration and visual comfort in hot climates, Energy and Buildings, 108 (2015) 307-316.

[190] K.S. Lee, K.J. Han, J.W. Lee, Feasibility study on parametric optimization of daylighting in building shading design, Sustainability, 8 (12) (2016) 1220.

[191] M.H. Wu, T.S. Ng, M.R. Skitmore, Sustainable building envelope design by considering energy cost and occupant satisfaction, Energy for sustainable development, 31 (2016) 118-129.

[192] I. Acosta, M.Á. Campano, J.F. Molina, Window design in architecture: Analysis of energy savings for lighting and visual comfort in residential spaces, Applied Energy, 168 (2016) 493-506.

[193] F. Goia, Search for the optimal window-to-wall ratio in office buildings in different European climates and the implications on total energy saving potential, Solar Energy, 132 (2016) 467-492.

[194] A. Zani, M. Andaloro, L. Deblasio, P. Ruttico, A.G. Mainini, Computational design and parametric optimization approach with genetic algorithms of an innovative concrete shading device system, Procedia engineering, 180 (2017) 1473-1483.

[195] C. Lavin, F. Fiorito, Optimization of an external perforated screen for improved daylighting and thermal performance of an office space, Procedia engineering, 180 (2017) 571-581.

[196] A. Aldawoud, Windows design for maximum cross-ventilation in buildings, Advances in building energy research, 11 (1) (2017) 67-86.

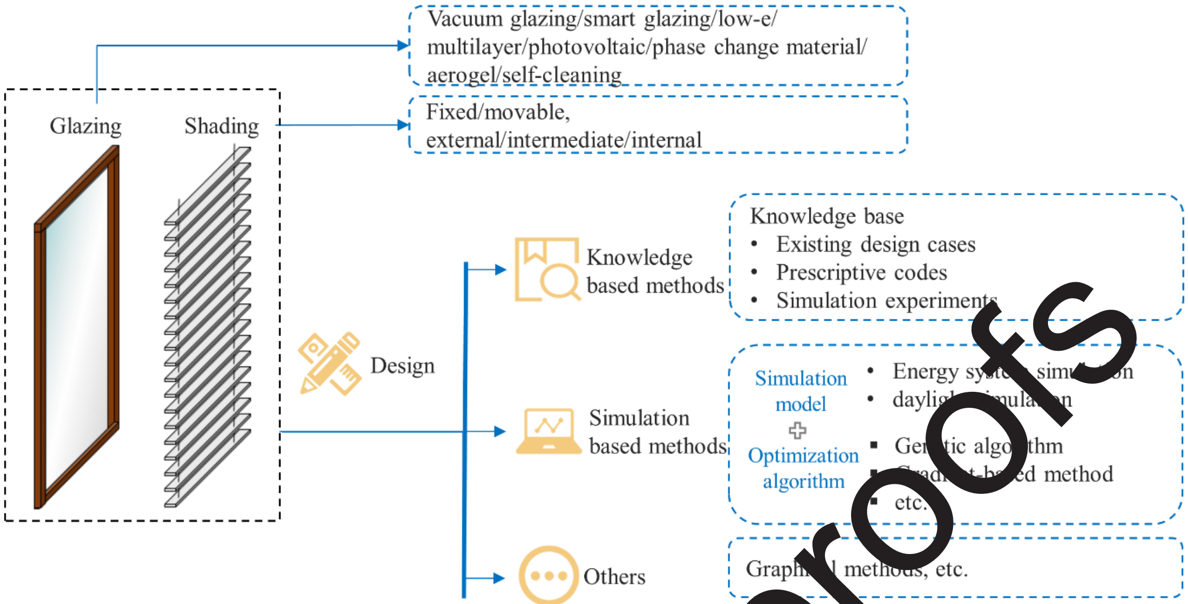
[197] S. Marzban, L. Ding, F. Fiorito, An evolutionary approach to single-sided ventilated façade design, Procedia engineering, 180 (2017) 582-590.

[198] Y. Lin, S. Zhou, W. Yang, C.-Q. Li, Design optimization considering variable thermal mass, insulation, absorptance of solar radiation, and glazing ratio using a prediction model and genetic algorithm, Sustainability, 10 (2) (2018) 336.

[199] Y. Zhai, Y. Wang, Y. Huang, X. Meng, A multi-objective optimization methodology for window design considering energy consumption, thermal environment and visual performance, Renewable energy, 134 (2019) 1190-1199.

[200] V. Charpentier, F. Meggers, S. Adriaenssens, O. Baverel, Occupant-centered optimization framework to evaluate and design new dynamic shading typologies, PloS one, 15 (4) (2020) e0231554.

Journal Pre-proofs



Journal Pre-proofs