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Optimal building envelope design based on simulated performance: History, current status and new potentials

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Abstract: Green building design is among the hottest research topic at present world. Maintaining a comfortable indoor environment with minimum energy consumption is a challenging subject that attracts attention all around the world. With the progress of the building performance simulation tools, it is now possible to predict and assess building performance at the design stage. Simulation-based optimization on building design is potential application that connects building performance simulation and optimization algorithms. In this paper, literatures about the optimization on building envelope design were focused and reviewed. Popular optimization algorithms were compared and discussed. Targeted objectives were collected and summarized. Based on the statistic result, the limitation in this research area was proposed while some potential breakthroughs were also suggested.

Keywords: design optimization, building performance simulation, building envelope, optimization algorithms, optimization objectives

1. Introduction

Since the "Energy Crisis" in the 1970s, saving energy has become the common sense for people all around the world. Buildings, together with industry and transportation, are the major destinations for energy consumption. Buildings have already been responsible for more than 30% of the total energy consumption of human kind, and the figure is expected to be growing [1]. Compared with other aspects, saving energy in building sector is the simplest and most efficient. Based on the above considerations, energy-efficient and sustainable building designs as well as retrofitting are believed to be a necessary path for the future of human society. Besides, building is the most important element in everyday life. Normally a person will spend over 70% of his lifetime inside buildings. A comfortable indoor environment can not only improve the working efficiency but also preserve the occupant's health. To achieve a comfortable indoor environment within an energy-efficient

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building is the spotlight which draws the attentions of professionals from architecture, civil, mechanic and electric.

As the increasing of the computer's calculation capacity, a large number of building performance simulation tools emerged since later last century. With their user-friendly interfaces and sophisticated calculation engines, these simulation tools can easily display instantaneous building thermal, visual and acoustic performance. The reliability of these simulation tools have been tested and proved by various studies [2 – 7]. With the assistance of these simulation tools, the researchers could investigate the impact of different design parameters on the building performance as well as the sensitivity of building performance on different parameters so as to serve as a reference for actual building design activities. This simulation-based building design process has become a common practice in construction industry nowadays. However, the number of parameters which could affect the building performance is rather huge, and there often exist parameters with conflict influences. To achieve an optimal design solution simply using building performance simulation tools often requires the running of a large amount of simulation cases. This process is expensive and time-consuming. Conducting systematic and effective optimization process for building design solutions is becoming a hot topic for researchers in building performance simulation area.

There were several previous literature review papers discussing the optimization studies in building design area. Stevanović made a summary of previous literatures on the optimization of the passive solar design in buildings. He focused on the statistics of the existing studies, trying to figure out the most popular building performance simulation tool, the most popular optimization objective and the most popular search engine during optimization [8]. Evins selected 74 studies, trying to give a brief introduction on the computer-assisted optimization method on sustainable building design, including the optimization researches towards building envelope, HVAC system and the renewable energy supply [9]. Nguyen et al. made a summary and introduction on the details within the optimization process during building performance analysis. They discussed the main activities during major phases of optimization process, the difficulties and challenges for different optimization problems [10]. Machairas et al. and Negendahl studied the common used Algorithms and building performance models and their integration for building design optimization [11, 12]. Carlucci bet al. focused on a specific optimization objective, the visual comfort issue. They discussed the description and assessment of visual comfort and presented the conventional process of the optimization toward visual comfort [13]. Attia et al. interviewed 28 optimization experts and made a summary on their opinions, so as to receive a general picture of the research progress on building performance optimization aspect, including algorithms, simulation tools as well as the expected future development [14].

Clearly, all of the previous reviews summarized the research progress in building performance optimization problems as a whole. Actually there are two main objects in building design aspect, HVAC system design and building envelope design. Compared to HVAC system design, the building envelope design involved a much larger number of parameters. The relationship between different design parameters and the impacts of different design parameters on the performance of the building envelope are more complicated. Besides, there exist more evaluation systems toward the performance of the building envelope. In a word, the optimization design on building envelope is a more complex problem compared with HVAC system design.

In this review paper, simulation-based optimization toward building envelope design was considered specifically as the topic. The paper was divided into 5 parts. Part 1 was the introduction part, giving the brief information on the topic of the paper. Part 2 discussed the major algorithms used for building envelope optimization. Part 3 introduced the main optimization objectives of the simulation-based optimization toward building envelope design. Part 4 presented the popular optimization software tools applied in previous studies. Part 5 made a summary on the paper and discussed the possible future work in this research area.

2. Algorithms applied in simulation-based building envelope optimization

2.1. History and early development of simulation-based building envelope design optimization

As early as 1983, Gero et al. discussed a simple multi-criteria building model for the purpose of energy performance-based optimization. In the optimization, the method they applied was quite similar to the multi-criteria Pareto optimization [15]. In 1990, Bouchlaghem and Letherman reported an attempt on the optimization of the building envelope's thermal performance towards a comfortable indoor temperature. They applied a hybrid simplex and non-random complex algorithm in their study, and selected the indoor environment as the optimization objective [16]. In the year 1992, Sullivan et al. raised the concept of optimization of building envelope based on simulation. They applied a regression analysis as the optimization algorithm. With a series of DOE-2 based simulation, they received a data base for the energy performance of various building envelopes as well as lighting systems. Then they defined two variables, respectively the solar aperture (which is a function of shading coefficient and window-to-wall ratio) and the effective daylighting aperture (which is a function of visible transmittance and window-to-wall ratio). With the energy performance data base, they conducted a regression analysis between the electric energy consumption and the two predefined variables [17]. Though these approaches were rather rough with many limitations, they were still the first attempt to search for optimal solution in building design area with the assistance of numerical simulation, and thus still enlightenment.

Al-Homoud reported his work on the optimal thermal design for office buildings under several different cities in the U. S. and Saudi Arab. He considered 14 design variables in the optimization. First he defined an initial value as well as upper and lower boundaries for each variable. With a selected value difference, he conducted over 700 simulation runs to list the thermal performance of every possible combination of variables [18]. In the year 2001, Depecker et al. reported a very simple study on the optimal building shape design under different climates. They defined the shape coefficient which was the surface area of the building envelope divided by the building's volume, and utilized the shape coefficient to describe the shape of the buildings. From the result they concluded that only in extreme cold climate would the shape affect the energy performance of the buildings [19]. Ghisi and Tinker also presented their study on the optimal design of window-to-wall ratio in single office rooms. They selected the total building energy consumption as the optimization objective and conducted 17600 DOE-2-based simulation cases. From all those simulation cases, they were able to choose the solutions with the best energy performance and summarized several design principles as a reference for building envelope design in England and Brazil [20].

During studies of this period, researchers started to realize that though optimization process could achieve a reduction in energy consumption, it was way too time-consuming. They raised the importance of a solution searching engine in the process. During the 2000s, the development of mathematical and algorithmic methodologies gave a possibility of solving optimal building envelope problems more quickly and accurately. Among all the methodologies, direct search and stochastic population-based search (evolutionary algorithm) were the most popular.

2.2. Direct search

Direct search methodology relies completely on the value of the objective function. The basic principle of direct search is the searching around the current solution point. During a direct search, a current point is first defined with the value of the objective function. A series of points are then searched and their objective function values are recorded and compared. If an objective function value closer to the optimization target is achieved, the corresponding point would be defined as the latest current point. The process will be repeated until an optimal point is found [21]. Direct search methodologies can be generally divided into two types, gradient-deterministic and gradient-free.

2.2.1. Gradient-deterministic search

Gradient-deterministic search can be considered as the straightforward optimization methodology. In a gradient-deterministic problem, there usually exists an objective function that can be analyzed with Taylor's series expansion. In this condition, the optimal solution can be easily obtained by going in the direction with a reducing gradient. Since the 2000s, optimization studies on various design variables utilizing gradient-deterministic search keep coming out.

In the year 2003, Marsh presented a methodology on the optimization for the geometric design of shading shape. He considered the shading shape as the design variable and applied a ray-tracing technology to display the shadow area required and a cut-off scheme to form the shading shape, trying to form a function to connect the shading shape with the solar heat gain [22]. In the year 2004, Al-Homoud made a brief summary on the optimization problem in architecture area, and described an optimization approach based on direct search technique. He claimed that an effective result search method would significantly improve the speed of optimization process. Later, with the assistance of his optimization approach, he conducted a series of researches on the optimization design of mosques, which had a special occupied schedule with 5 peak values each day [23, 24]. Wang et al. made an optimization on the façade design parameters. They considered the U-value of the wall material and the window-to-wall ratio, trying to find an optimal thermal comfort indoor environment [25]. Adamski applied the ratio of the area of the southern part of the building S_1 to the area of the building S as the design variable and the payback period as the optimization objective in his research. He developed a mathematical model to describe the relationship between the building's shape and the life cycle cost. With the assistance of computer-based simulation, he was able to select the optimal case directly [26]. Ucar and Balo introduced a simple optimization case about the thickness selection of the insulation materials. They considered the payback period as the optimization objective and deduced the functional relationship between the heat loss and the insulation material thickness. With the function, they were able to make a simple and fast selection of the optimal solution [27]. Later, they reported a similar case study involving the application of their previously proposed method [28]. Similar methodology could be referred in the study of Lollini et al. [29]. Bambrook et al. reported a case study on the optimization of the envelope of an individual residential house in Sydney. They conducted 210 simulation cases to test the performance of popular designs of the wall, window and shading device, trying to reach a minimum life cycle cost [30]. Albatici and Passerini presented a simplified approach to search for the best solution of building shape in order to minimize the heating requirement within a residential building in Italy. They defined a new index named south exposure coefficient, and did a regression analysis on the south exposure coefficient and the shape coefficient. They claimed that both the shape coefficient and the south exposure coefficient were almost linear related to the heating energy consumption, and those two indexes could guide the building design regardless of the building's volume [31]. Jiang et al. described a research on the optimization of building internal envelope's specific heat, for the purpose of phase change material application. They constructed a simplified room temperature model, and did an analytical optimization toward room temperature, trying to build up a function connecting building internal envelope's specific heat and indoor space temperature [32]. Later, Cheng et al. reported a similar study on the optimization of building external envelope's transient performance [33].

From the above literatures it is clear that the application of gradient-deterministic search methodology continued until very recently, which indicated that compared to more complex algorithm the performance of gradient-deterministic search methodology was satisfactory. Actually in the year 2014, Asadi et al. proposed a multi-linear regression method to estimate the building energy consumption. They conducted over 10000 simulation cases and selected 17 building design variables for the multi-linear regression. A coefficient of determination R2 of around .94 to 0.95 was achieved, indicating that 94% to 95% of the building's energy consumption could be determined by those 17 variables. Their research showed that regression analysis based on gradient-deterministic search methodology was still an acceptable approach in the optimization of building energy design [34]. It should also be noted that the majority of existing gradient-deterministic search studies were focused on the optimization toward building energy consumption (only one research is about thermal comfort optimization [26]), which indicated that the performance of gradient-deterministic search methodology in other optimization problems was not good.

2.2.2. Gradient-free search

A gradient-free search methodology does not require any information about the gradient of the objective function. As mentioned above, it constantly replaces current point with different searching rules, trying to approach the optimal solution. Based on different methods of searching for neighboring points, the gradient-free search methodology can be further divided into pattern search method, simplex method and adaptive search directions set method. All the present gradient-free search methodologies, such as the Hooke-Jeeves algorithm, Tabu search and the orthogonal method, were just modifications of these three basic methods [35].

In the year 1990, Bouchlaghem and Letherman tried to apply simplex method in the optimization of indoor thermal comfort [16]. Hasan et al. applied a hybrid GPS Hooke Jeeves/PSO algorithm in their optimization of a Finnish house for minimum life-cycle cost [36]. Futrell et al. reported a study on the optimization for a classroom’s thermal and visual performance. In the study, they also selected the hybrid GPS Hooke Jeeves/PSO algorithm to get the optimal design solution for the window’s size, location as well as optical properties. Both energy consumption and visual comfort were chosen as the objectives. They discovered that for the south orientation, the thermal performance and the visual performance did not conflict much, while for the north orientation, the conflict was the worst [37]. Stazi et al. conducted a life cycle assessment on the optimization design of solar wall systems. In their assessment they proposed a “factorial plan technique” for the selection of the optimal design. They determined n parameters as the design variables, and assigned these variables with a 2-level value definition. Then, they conducted 2^n simulation runs to search for the optimal result. They claimed that their method was fast, simple and intuitive, however it could only be applied on simple systems and the result was not quite accurate [38]. Gong et al. presented their research on the optimal passive design of residential building envelope in 25 different Chinese cities with orthogonal method. They selected 7 control parameters and defined the parameters into 4 levels. In addition, they also considered 15 possible interactions between parameters. With the help of a $L_{32}(2^{31})$ matrix, they were able to select the optimal design solution for different cities. They claimed that unlike other algorithms, an orthogonal method did not require a deep knowledge of computer programming, and thus suitable for architects [39]. Ruiza et al. reported a case study on Spanish residential building optimization design based on Tabu Search Algorithm. In their case study, they considered the energy efficiency and the life cycle cost as the objective [40].

2.3. Stochastic population-based search

An evolutionary algorithm is a stochastic population-based search that inspired by biological evolution. The core of evolutionary algorithm is the selection of high-performance individuals and the reproduction of new individuals based on existing performance data. A typical evolutionary algorithm process includes selection, crossover and mutation. First, a series of points are generated randomly as the initial population. An evaluation was then conducted to assess the fitness of each individual. The individuals that fit the optimal solution best were chosen as the parents. The parents were applied for the reproduction of children, which form the next generation through crossover and mutation. Then the new population went through a new round of selection. This process would be repeated until the termination of the algorithm [41]. Compared with direct search methodology, evolutionary algorithm has a higher calculation speed, accuracy and a stronger adaptability. Based on different implementation details, evolutionary algorithm was divided into genetic algorithm, neuroevolution, Particle swarm optimization, etc.

2.3.1. Genetic algorithm

Genetic algorithm is no doubt the most popular method applied in simulation-based building envelope optimization design. Of all the literatures selected in this paper, over 60% were conducted via genetic algorithm. In genetic algorithm, many individuals are considered simultaneously so that the possibility of ending up at a local minimum is reduced [42]. Genetic algorithm and its modifications are considered to be the best choice for building design optimization problem.

As early as the year 2002, Coley and Schukat made an attempt of introducing in Genetic Algorithms to the design of buildings. They first built a very simple thermal model in which only five variables were considered. Then they applied the Genetic Algorithms for the search of the best solutions with minimum annual energy consumption. Their result was satisfactory: a large number of optimal solutions were identified [43]. In the year 2003, Wang et al. presented a case study in which Genetic Algorithm was applied to minimize the life cycle exergy. In the year 2005, Wang et al. further presented a Genetic Algorithm for the optimization for a rectangular shape building with a fixed floor area. They considered the life cycle exergy as the objective, tried to find the optimal solution for the building's orientation and the building materials [44, 45]. Later, Wang et al. summarized the previous optimization studies, and claimed that though all those studies applied Genetic Algorithm, the methodologies applied in the studies lacked versatility. The optimization approach would fail when applied to another design case. Wang et al. raised a development of object-oriented framework so that the GA method could be adopted easily with numerical simulation within a much more user-friendly interface, which would significantly improve the efficiency of the optimization process [46]. With their developed approach, they further conducted a systematic study considering façade design variables including shape, structure, material type and shading device [47]. Wright and Mourshed designed an interesting study to test the stochastic behavior and the reliability of the Genetic Algorithm in the optimization of window-to-wall ratio of building envelope. They divided the building façade into small rectangular cells, and each cell could be equipped with solid wall material or glazing. They run the Genetic Algorithm-based optimization for several times and found that though for each optimal solution the distribution of glazing cells was different, the number of glazing cells stayed constant [48]. Tuhus-Dubrow and Krarti conducted an optimization on shape of the U. S. residential building envelope. They chose the whole-building energy consumption as the objective. From their result it was discovered that though there did exist some difference among the energy consumptions of different building shapes, the deviations were within 0.5%. They claimed that other variables such as orientation, construction materials could affect the building's energy performance more significantly, thus should be paid more attentions [49]. Sahu et al. conducted a Genetic Algorithm-based design optimization on the shape, orientation as well as the materials of the building envelope. They selected the energy consumption as the optimization objective and did a detailed validation with the TRSYS simulation tool. They discovered that the climate would affect the accuracy of the optimization. If the space load situation was complex, including multiple combination of heating, cooling and humid, the error would be larger [50]. Ioannou and Itard conducted a Monte Carlo sensitivity analysis against the design variables on their impact towards the building energy consumption. They claimed that under heating condition, the window thermal properties were the most critical parameters among all the variables, because heat loss through window took the majority in the total heating load. The similar conclusion could be applied in other climate situation: the sensitivity of a specific design variable depends on its impact on the optimization objective [51].

Besides the optimization on the energy performance of building envelope, genetic algorithm was also applied in optimization problems involving visual comfort assessment. Torres and Sakamoto conducted an optimization on the daylighting performance. They considered 21 different variables during the design of window and shading systems, trying to minimize the visual discomfort. They proposed a modification on the existing daylight glare probability index (DGP) and applied the dynamic daylighting simulation software Radiance to calculate the values of DGP on several viewpoints inside the building. Considering the modified DGP as the optimization objective, they selected Genetic Algorithm to search for the optimal solution. They discovered that Genetic Algorithm was especially effective for the optimization of daylighting performance because a fast convergence was obtained. They also claimed that hybrid fitness may be helpful for the accuracy of the optimization [52]. Later, Kampf et al. reported a similar research involving the coupling of Radiance and Genetic Algorithm search engine on the optimization of building shape with consistent building volume. They also announced a further implement of an urban scale optimization with the same methodology [53]. Gagne and Andersen proposed a simulation approach for the optimization of façade design based on the daylighting objectives (illumination level and glare). In their approach, a simple building data model was first defined based on the design case from the designers, while a series of new 3d building models were automatically generated during the optimizations. Micro-Genetic Algorithms were applied for both single-objective and multi-objective optimization. During their research they discovered a notable limitation: The micro-GA based optimization required much more computing time and a relatively large population size [54]. Rakha and Nassar developed a

Genetic Algorithm-based searching method of the optimization for the geometry form of the ceiling area. They claimed that though the approach was time-consuming, it could reach the optimal solution precisely and thus useful for optimization towards daylighting issue [55]. Yi and Kim also reported several case studies involving the optimal design of sunlight exposure time on tall residential buildings based on Genetic Algorithm [56].

For Genetic Algorithm-based building envelope optimization considering thermal comfort issue, relating literatures were limited. In the majority cases, thermal comfort issue was considered as a subsidiary factor of energy consumption. Hamdy et al. carried out an optimization research, aiming at integrating thermal comfort issue with energy performance as the optimization objectives. They adopt the Genetic Algorithm optimization tool of Matlab with an IDA-ICE 4.0 building performance simulation. They claimed that in an optimal solution considering both thermal comfort and energy saving, an extra 10kWh/ (m2a) would be expected compared with optimal solution that considered only energy saving [57]. Stavrakakis et al. also reported their study on the optimal window-opening design for thermal comfort status based on meta-model construction [58]. Yu et al. conducted a multi-objective optimization, trying to improve the energy performance and indoor thermal comfort at the same time. During their optimization process, they applied the Genetic Algorithm into the back propagation neural network, so as to speed up the simulation while keeping the result more accurate. They discovered that under the same energy consumption rate, the indoor thermal comfort status did not change a lot. If a specific energy consumption value was fixed, the difference of thermal comfort hours among different cases was insignificant [59].

2.3.2. Improvement of genetic algorithm

As the development of computer technologies and mechanism, many professionals started to notice the limitations of genetic algorithm: the searching speed is still beyond acceptable. The search result is highly affected by the definition of selection, crossover and mutation. Many efforts were taken to improve the performance of the genetic algorithm in building envelope optimization design. For the reducing of computing time, generally speaking there are two ways. The first way is application of simplified models instead of complex simulation tools. The second way is reducing the size of the population and the number of generations. For the improvement of the result's accuracy, a common thinking is conduction of a dominating relationship-based selection before generation, in other word increasing the survival probability of better individuals [60]. Table 1 summarized different modification approaches applied for the improvement of the genetic algorithm's performance.

Table 1 different modification approaches applied for the improvement of the genetic algorithm's performance

Name of researchers	Modification approach	Major finding	Reference
Znouda et al.	Applying elitism selection instead of traditional wheel selection. Introducing in an immigration procedure into the mutation process.	The speed and accuracy of the Genetic Algorithm searching engine were largely improved.	[61]
Palonen et al.	Applying Omni-optimizer, simulated binary crossover operator (SBX) and polynomial mutation in crossover and mutation operations.	The stopping criterion definition is very important for reduction of the computing time.	[62]
Kämpf and Robinson Ramallo-González and Coley	Application of hybrid Covariance Matrix Adaptation Evolutionary Strategy and HDE algorithms	The Covariance Matrix is used for decorrelation of design variables. Though the calculation of Covariance Matrix was time-consuming, compared with computing time used for annual building simulation, it was way acceptable.	[63] [64]
Eisenhower et al. Stavrakakis et al. Geyer and Schlüter	Applying multiple algorithms for building envelope optimization. Applying a meta-model approach to avoid the repeating simulation cases. Introducing in Design Space Exploration into the traditional Response Surface Method to further improve the accuracy.	The proposed approach could save around 80% of the computing time while the error was negligible. The error could be reduced by more than 70% when Design Space Exploration was utilizaed.	[65] [66] [67]
Bucking et al.	Considering Mutual Information (dependency between variables) during the evolution of the design cases.	With the consideration of Mutual Information, the data mining within Genetic Algorithm optimization would save 40% computing time and improve the accuracy by 25%	[68]
Junghans and Darde	Combination of Genetic Algorithm and simulated annealing algorithm.	In 1/3 of the optimization runs, the accuracy was improved by at least 5% while the computing time did not change significantly.	[69]
Yu et al.	Applying the Genetic Algorithm into the back propagation neural network.	A quite small relative error on the prediction (1.7% for energy consumption and 2.1% for indoor thermal comfort hour)was reported.	[59]

2.3.3. Harmony search algorithm

Harmony search algorithm is also a population-based optimization method. It was inspired by the improvement activities of musicians to find a best harmony [70]. It was considered as a special case of evolution strategies [71]. Fesanghary et al. presented a multi-optimization model based on Harmony Search Algorithm. They selected the life cycle cost as well as the CO_2 emission as the optimization objectives. They applied their approach in an optimization of a residential house in the U. S. and claimed that though the method required a relatively long computing hour, its result was stable and trustable [72].

2.3.4. Evolutionary artificial neural networks

Artificial neural networks are a series of learning models which were inspired by biological neural networks. It can be described as a system of neurons connect and send messages with each other, which enables the network to learn from present observations and improve the performance during the task. The core of evolutionary artificial neural network application is the training of the neural network.

Magnier and Haghighat proposed an optimization methodology in which artificial neural network and Genetic Algorithm were coupled. An artificial neural network was first applied to mimic the behavior of the building simulation model. Then, the output of the artificial neural network was used as the population. The key factor of the methodology was the training of the artificial neural network. As long as the artificial neural network could output accurate building performance, the optimization result could be received fast and reliably [73]. Zemella et al. also proposed their evolutionary artificial neural networks, which was a combination of evolutionary algorithms and artificial neural networks. They divided the total population into two parts. 80% of the population was used for training of a three-layer neural network, while the rest 20% population was used for root predictive error testing. During the training of the neural network, the evolutionary algorithm was applied for adjustment of the structure parameters. They claimed that the proposed approach was more accurate and less time-consuming, due to the application of artificial neural network [74]. Later, Gossard et al. reported a similar study involving a cooperation of Genetic Algorithm and artificial neural network [75].

2.4. Summary

From above literatures it can be concluded that, in building envelope optimization area, for direct search method, gradient-deterministic direct search methodology was more popular than gradient-free direct search methodology, even though the latter one was more advanced. The reason lies in the limitation of direct search. For gradient-deterministic direct search methodology, it is only applicable for relatively simple optimization problems. For gradient-free direct search methodology, it is time-consuming. Besides, the accuracy of direct search is not satisfactory. When encountered with simple optimization problems, researchers tend to use gradient-deterministic direct search. When encountered with complex optimization problems, researchers tend to use algorithms which cost less time and perform more precisely (such as evolutionary algorithms). For evolutionary algorithms, genetic algorithm and its modifications are the best choices applied due to their vast applicability, high accuracy and less time-consuming.

It should also be noticed that within all the studies reviewed, the majority were on the optimization toward energy related performance, researches on visual comfort and thermal comfort optimal design were quite limited. Also, most studies were single-objective optimization. Limited multi-objective optimization reports were all on thermal comfort and energy efficiency.

3. Optimization objectives

3.1. Classification of objectives

Building envelope is the most important element in a building. Building envelope separates the building indoor environment from the outside world, supplying the occupant with a stable and comfortable living space. As mentioned above, the target of sustainable building envelope design is maintaining a comfortable indoor environment with minimum energy consumption. Thus naturally, the indexes which describe the performance of building envelope are the focused objectives for building envelope design optimization problems:

(1) Energy performance index, including space cooling load, space heating load, HVAC system energy consumption and building total energy consumption.

(2) Life cycle cost index, including life cycle CO2 emission, life cycle primary energy consumption and life cycle financial investment.

(2) Thermal comfort index, including mean PMV level, mean PPD level, thermally comfortable hour, space temperature and operative temperature.

(3) Visual comfort index, including illumination level, illumination uniformity, Daylight Factor, Daylight Autonomy, Useful Daylight Illuminance and Daylight Glare Probability.

A statistic was conducted to see the attentions on every possible objective. The result was presented in Figure 1. It should be noticed that life cycle cost index has a direct connection with energy performance index. With some simple extra information, it is easy to transfer energy consumption into life cycle cost [76]. Thus in Figure 1, literatures focusing life cycle cost optimization were considered a part of the literatures on energy consumption optimization.

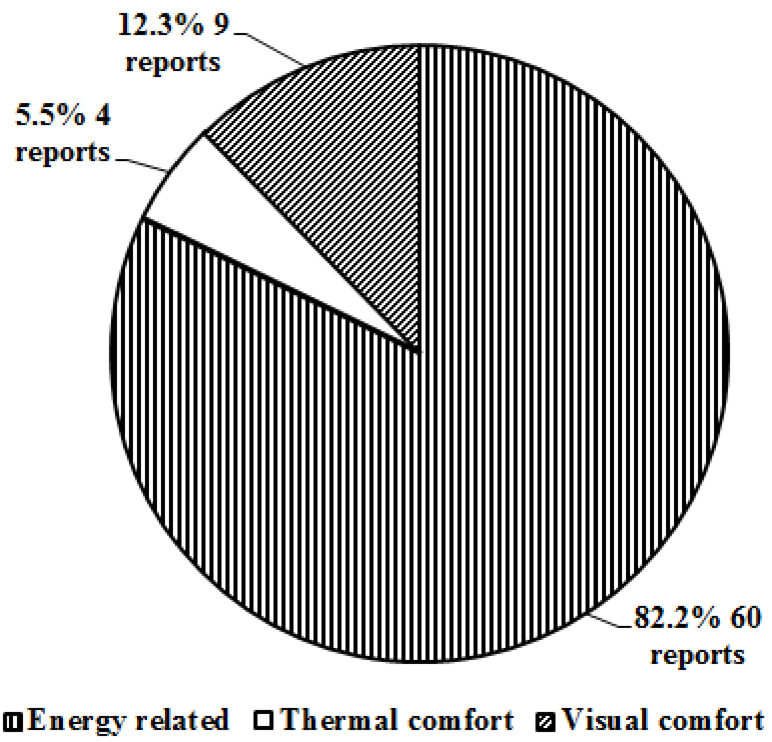

Figure 1 Statistic result for optimization cases focused on different objectives

From Figure 1 it is clear that energy drew the majority attentions. Of the over 70 optimization cases collected in the paper, over 80% aimed at the minimizing of the energy consumption or life cycle cost. The optimization cases on comfort issue were quite limited.

At present, the factors that affect the occupant's thermal comfort have been investigated deeply. The indexes describing the thermal comfort status have been widely accepted. However, most studies on thermal comfort were focused on the design and control of HVAC systems. Not many researchers analyzed the impact of building envelope on the indoor thermal comfort in detail. With respect to visual comfort, right now the academe still lacks accurate and effective measures to assess the visual environment. Existing visual environment optimization cases were mainly based on a very simple assumption that sufficient daylight and acceptable illumination distribution can achieve a comfortable visual comfort. Improvement and adoption of the assessment system of occupant's comfort is a possible direction for simulation-based building envelope optimization design.

Besides, the impact of occupant behavior cannot be ignored. At present, occupant behavior was only introduced in building simulation as fixed schedules. However, occupant is not just a composition of the building system that accepts the controlled environment passively. Occupant will adjust the surrounding environment initiatively by HVAC system and shading device. The activity the occupant taken will in turn affect energy consumption, indoor comfort status and even the occupant's future activities. How to consider the occupant behavior more precisely in building simulation is a challenging topic for academy.

3.2. Multi-objective optimization

Since the genetic algorithm simultaneously calculates a set of points, it is able to reach multiple Pareto optimal solutions within one calculation run, which makes it a perfect choice for multi-objective optimization problems. Caldas and Norford proposed a computing method for design optimization of the placing and sizing of window openings in office buildings. They used DOE-2 to simulate the annual air-conditioning and lighting energy consumption, serving as the objective. Genetic Algorithms were applied to search for the design solutions. They reached several conclusions which were widely accepted by the later professionals: They claimed that the climate, the orientation, the type of the building all can significantly affect the result of the optimization. They also observed that in many cases similar minimum annual energy consumption could be achieved with several different configurations, which illustrates that a multi-objective optimization is possible [77]. Manzan and Pinto presented a case study on the optimization of the position and size of the external shading equipment. They prepared a simplified office model and conducted the energy and daylighting simulations to form the data base. They claimed that with the optimization process, the energy consumption difference between the best and the worst solution could be as large as 17% [78]. Hamdy et al. constructed a multi-objective optimization method to guide the residential building design in Finland. In their method the Genetic Algorithm was utilized while primary energy consumption and life cycle cost were considered as the objective. Based on their method, they proposed a series of reference data for residential house design in Finland [79]. Later, Ferrara et al. also reported a similar study on the optimal design of residential house in France [80]. Karmellos et al. thought that a multi-objective optimization should consist two parts: an optimization process and a decision making process. They provided a decision maker (DM) software tool to assist the multi-objective optimization process [81].

From the existing reports it can be easily observed that most of the so-called "multi-objective optimization studies" in building envelope design area considered energy consumption and life cycle cost as two objectives. However, actually life cycle cost and annual energy consumption have a direct relationship. With some extra information, it is not difficult to calculate life cycle cost (no matter financial cost, primary energy or CO_2 emission) from annual energy consumption data. Strictly speaking, these studies cannot be treated as "multi-objective optimization". There were only very limited literatures on the optimization considering comfort issue and energy consumption.

3.3. Summary

From the statistic and analysis of the targeted optimization objectives in the collected literatures, several obvious conclusions can be drawn. Of all the previous studies on simulation-based building envelope optimization, over 90% focused on the optimal solution for single objective. Of all the single-objective optimization cases, over 80% were targeted the minimization of energy consumption. Of the few multi-objective optimization studies, energy consumption was still included.

Right now, energy efficiency is still the top concern for the scientists and engineers, during the design stage of buildings, energy consumption is the first issue that is considered and analyzed. Besides, the present limitation in the definition of occupant comfort status and lacking of precise occupant behavior description also pull back the development of comfort related quantitative evaluation system, which may be a potential research direction in the future.

4. Common optimization tools

4.1. Matlab

Matlab is a world famous multi-paradigm numerical computing tool, which allows algorithm development, data visualization, numerical calculation and interaction with programs written in other computer language. Matlab has a toolbox specifically designed for optimization. The Matlab Optimization Toolbox includes a large amount of choices of algorithms. Its ability of cooperating with other program makes it a perfect numerical environment for optimization problem based on third-party simulation program. Before the appearance of software developed specifically for optimization, Matlab was the first choice of researchers aiming at simulation-assisted building design optimization. Even now, Matlab is still a popular choice because if using Matlab in the optimization process, the researchers could use all the other Matlab functions which provide significant improvement in data presentation and analysis. Lu et al. conducted a series of optimization process on the passive solar and renewable energy design on a reference building envelope in Hong Kong. They applied the Genetic Algorithm for single-objective optimization process and the Non-dominated Sorting Genetic Algorithm (NSGA- II) for multi-objective optimization process in Matlab environment. With the assistance of Matlab software, they were able to utilize both algorithms easily, regardless of the ten times of generations and computing-time difference between those two algorithms [82]. McKinstray et al. also applied the NSGA- II in

Matlab Optimization Toolbox in his research of the optimal BIPV installation on a single-store building [83], while shea et al. applied ant colony optimization from Matlab Optimization Toolbox in their research [84].

4.2. GenOpt

GenOpt is a generic program which was developed by the famous simulation research group of the Lawrence Berkeley National Laboratory. GenOpt can be used with any building simulation tools with text-based input and output, and the users could also add self-defined optimization algorithms into GenOpt's library, which makes GenOpt a practical and flexible optimization tool. However, GenOpt cannot carry out multi-objective optimization. Its postprocesssing ability is also limited [85, 86].

Holst reported an optimization case study involving the cooperation of the thermal performance simulation tool EnergyPlus and the decision making software GenOpt. He considered the annual primary energy consumption as the optimization objective, trying to find the optimal solution for 14 design variables in building envelope design. He also discussed the thermal comfort status in the optimal solution and found an improvement in thermal comfort as well [87]. Hasan et al. also reported an optimization case involved the cooperation of DOE-2 and GenOpt [88].

4.3. modeFRONTIER

modeFRONTER is a platform developed by ESTECO corporate. Its advantage mainly lies in the workflow interface, variable choices of algorithms and the easy combination of other simulation tools [89]. Shi integrated modeFRONTIER with the popular building performance simulation tool EnergyPlus and conducted an optimization on the installation of insulation material on an office building envelope [90].

4.4. ParaGen

Turrin et al. described a Genetic Algorithm-based optimization tool named ParaGen for the application of both single- and multi-objective optimization in the area of architecture design. They presented several practical projects involving ParaGen to show the practicability of the tool [91].

4.5. MultiOpt

Chantrelle et al. developed a multi-criteria optimization tool named MultiOpt. The software was built in a TRNSYS-based simulation environment. Genetic Algorithm was referred as the search engine. They presented several case studies to prove that MultiOpt was able to manage the optimization of energy consumption, life cycle cost as well as thermal comfort issue [92].

4.6. GENE_ARCH

Caldas made a detailed introduction on the capacity of GENE_ARCH. With the assistance of the genetic algorithm, GENE_ARCH could cooperate with the building energy simulation software DOE-2 to solve optimization problem in architecture design area, from an individual house to an urban scale. Caldas also pointed out that when it came to complex 3D design problems, GENE_ARCH's performance was still not satisfactory because it required very precise information on the building model [93].

5. Conclusion and future work

In this paper, simulation-based optimization on building envelope design was focused. Literatures of this subject in the past 30 years were collected, summarized and discussed. The history and development were introduced. Popular algorithms were presented and compared. Statistic of objectives was conducted and analyzed. Some interesting conclusions were presented as follow:

(1) Genetic Algorithm and its modifications are the most popular optimization algorithms in the building envelope optimization study. The applicability, speed and accuracy were considered highly.

(2) For relatively simple optimization problems, professionals tent to use gradient-deterministic search, while for complex problems, genetic algorithms were their first choice.

(3) In the area of simulation-based building envelope design, single-objective optimization is still dominant.

(4) Energy consumption was the top concern for researchers and designers at present.

(5) Though there have been many software tools developed specially for building optimization design, Matlab is still the most popular tool used for optimal solution search.

Based on the above conclusions, some potential future working directions were proposed.

(1) The comprehensive design for building envelope requires the assessment of energy performance, thermal comfort performance and visual comfort performance. To achieve the goal of sustainable building, multi-objective building envelope optimizations involving all three indexes are of great importance and use. Since there have been many user-friendly multi-objective optimization tools, efforts can be made on the multi-objective optimization towards a sustainable building envelope design considering both comfort issue and energy efficiency.

(2) The attention paid on the impact of building envelope on indoor thermal and visual comfort is not enough. The description and evaluation system for occupant comfort feeling still has some limitations. In the future, professionals can improve the optimal building envelope design with more accurate and practical comfort functions.

(3) The importance of occupant behavior has not been noticed enough. The reaction of occupant behavior on the energy performance and indoor environment is often ignored. In the future, a more precise and complete occupant behavior model should be added into the building simulation. Occupant behavior should not be considered as just fixed schedules, but initiative interference that changes as the simulation processes.

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