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Simulation-Based Building Envelope Design Optimization Methodologies for Indoor Thermal Comfort – A Review

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Abstract: *Thermal comfort is defined as 'that condition of mind which expresses satisfaction with the thermal environment'. One of the basic requisite of building is to provide comfortable indoor conditions to maintain good health and improved productivity by using least possible energy. This is achieved by optimizing thermal performance of building envelope at the design stage. As in case of building-envelope thermal design optimization problem, there is no direct relationship exists between design variables and the objective function. In most cases it is difficult to optimize such problems by modelling the objective function in terms of design variables. Hence, it is solve by using Simulation-based optimization techniques. This paper reviews available whole Simulation-based optimization methodologies implied on building envelope thermal design. This technique is very useful for early decision making so as to provide building with comfortable and sustainable built environment with little or no cost. The scope of future research work was identified and clearly specified in conclusion.*

Key words: *Building envelope, thermal comfort, simulation, optimization, EnergyPlus, DesignBuilder, TRNSYS, GenOpt.*

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I. Introduction

1.1 Backdrop

The fundamental purpose of building is to protect the human beings from extremes of the environment. In these days of industrialization, man passes maximum time indoor either at home or at the workplace [1]. Hence, one of the basic requisite of building should be to provide comfortable indoor conditions to maintain good health and improved productivity. Thermal comfort is defined as 'that condition of mind which expresses satisfaction with the thermal environment' [2]. Normally this means that the person does not know whether he would prefer a warmer or a cooler environment. People are not alike, thermally or otherwise. If a group of people is exposed to the same room climate it will therefore normally not be possible, due to biological variance, to satisfy everyone at the same time. Hence, the designer should intend to provide such optimal thermal comfort conditions that thermally satisfy the highest percentage of the occupants [3]. Buildings consume 40% of energy produced. Major part of this energy is used to cool or heat the indoor spaces so as to provide indoor thermal comfort [4]. Hence, it is a big challenge to the construction communities to provide such comfort by utilizing as minimum energy as possible. This is achieved by optimizing sustainable passive building envelope design features.

As, in case of the building-envelope design optimization problem, there is no direct relationship exists between design variables and the objective function, it is difficult to solve by modelling the objective function in terms of design variables. Hence, it is solve by using Simulation-based optimization techniques [5]. The simulation based optimization technique is also known as numerical optimization techniques [6].

1.2 Previous reviews and scope of this review paper

Very comprehensive review studies were conducted by the previous researchers on various aspects of thermal comfort studies such as human thermal comfort in the built environment [7], indices for evaluation of general indoor thermal comfort conditions [8], thermal comfort models and indicators [9], computational optimization for thermal comfort [6], [10], [11] and algorithms for optimization of building design [12].

This paper reviews available simulation based optimization methodologies for thermal comfort employed on building envelope design. For the present review, Science Direct database of Elsevier and Google Scholar has searched by using keywords viz. building envelop, thermal comfort, simulation, optimization, EnergyPlus, DesignBuilder, TRNSYS and GenOpt. It is observed that, by using these words in the literature survey, literatures related to the building energy optimization are also came up which are also mentioned here as energy optimization is directly related to the building envelop design optimization.

II. Simulation-Based Optimization Methodologies

Traditionally, thermal design optimization of building envelop was dealt by testing a number of design alternatives through computation of thermal performance of each one. One design variable is tested at a time while keeping the others fixed. In this way final design alternatives are generated. This approach was very laborious and time consuming, rather the generated design values may be far away from the practical values and the best design alternative had been missed. The best way of approaching this type of problem is to incorporate the thermal design by an optimization method and a thermal analysis technique that would determine the optimum solution for thermal design by consistently searching the whole of the solution space. Ultimately, this will provide the best optimum solution for the thermal design of building components [13].

Nguyen et al., [6] have stated that according to the simulation-based optimization community the term 'optimization' indicates an automated process which is entirely based on numerical simulation and mathematical optimization. Conventionally, in building design optimization problems, a simulation program is coupled with an optimization tool which consists of distinct optimization algorithms or strategies. The most typical strategy of the simulation-based optimization is summarized and presented in Fig.1.

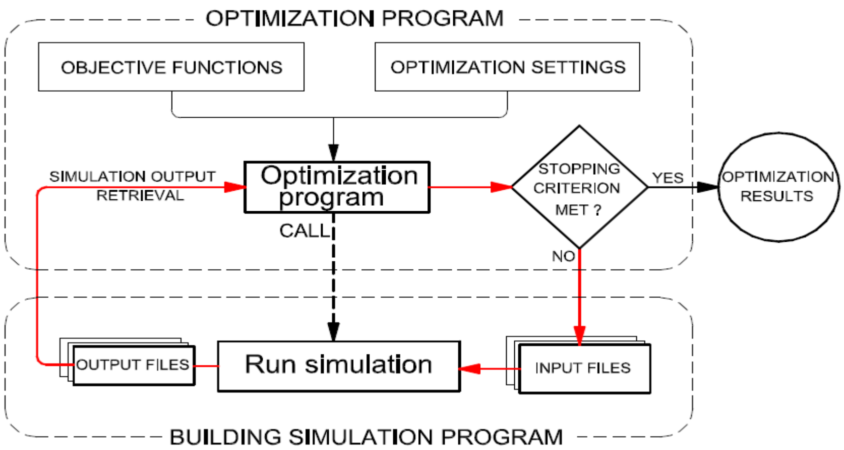

Figure 1: The coupling loop applied to the simulation-based optimization in building performance studies [6]

Østergård et al. [14] have reported that optimization refers to the automated use of mathematical optimization in combination with building performance simulations. A building optimization analysis typically consists of the following steps that may be repeated in an iterative design process:

1. Identification of design variables and constraints.
2. Selection of simulation tool and creation of a base line model.
3. Selection of objective function(s).
4. Selection of optimization algorithm.
5. Running simulations until optimization convergence is achieved.
6. Interpretation and presentation of data.

The traditional method of handling building envelop thermal design problem is to investigate a number of design alternatives by thermal performance of each building envelop component. The design options are achieved by varying one variable by keeping other variables constant. This method is time consuming and it is not present the effect produced by varying two or more variables simultaneously. And there may be possibilities of the optimization results are not practical. Therefore, in simulation based optimization technique, first the thermal performance of building envelop is simulated by using a simulation engine and then these simulation results are integrated with the optimization tools as illustrated in the figure 2 [15].

For unconditioned building, Al-Homoud (2005) considers the discomfort degree hours, as a function of operative temperature and comfort band, as objective funtion which is expressed as follows:

$$\min \mathrm{DDHS} = \sum_{i=1}^{n} [(T_{oi} - T_{cu})^{+} + (T_{cl} - T_{oi})^{+}]$$

where n is the number of simulation hours of the year; T_{oi} is the calculated comfort operative temperature at the ith hour; T_{cu} is the comfort operative temperature upper limit; T_{cl} is the comfort operative temperature lower limit; DDHS is the discomfort degree hours; and the '+' sign indicates that only positive values are summed. In the simulation phase, 15 variables were considered with their constraints and then the building thermal design optimization model, termed ENEROPT (ENERgy OPTimization), was established to incorporate the optimization technique of Nelder and Mead with the hourly energy simulation program. The four operations of reflection, expansion, contraction, and reduction are used until the best optimum value of the objective function is reached, and only the minimum value of the objective function and the corresponding variables are stored at each stage of the search.

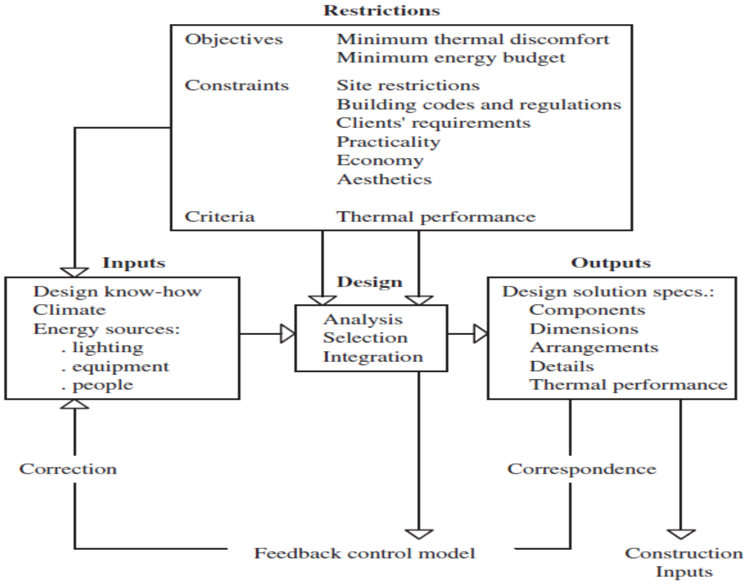

Figure 2: Structure of building thermal design optimization process [15]

Kalua [16] had performed optimization of envelope thermal design of free-running urban residential buildings in Malawi. The objectives of the study were to enhance the urban residential buildings' thermal comfort and recommend optimal envelope thermal design features for the buildings under consideration. Energyplus simulation tools was used to simulate the building performance along with Openstudio plug-in with Google Sketchup. Here, it is interesting to state that in Energyplus simulation tools, weather files of the three Malawian cities Mzuzu, Lilongwe and Blantyre was not available. Hence Amos Kalua had compared the climatic conditions of the these cities with Harare city of Zimbabwe. Then it is found that the climatic conditions of Harare is simillar to Mzuzu and Lilongwe rejecting the city of Blantyre. The simulation results are then used as input to the orthogonal array optimization technique.

Chowdhury et al. [17] had performed a study on thermal performance of readymade garment factory (RMG) in Bangladesh. In this study, a 3D model has been developed to analyze thermal simulation of a typical RMG factory. EnergyPlus with OpenStudio plug-in with Google SketchUp was used to perform the simulation.

Then field measurements are taken to validate the simulation results. Two types of variables "thickness of exterior wall" and "type of local construction materials" were considered. The thermal properties of these local construction materials were tested in the laboratory. Then various values of these variables were adjusted within the available discrete values so as to reduce the thermal discomfort with the RMG factory.

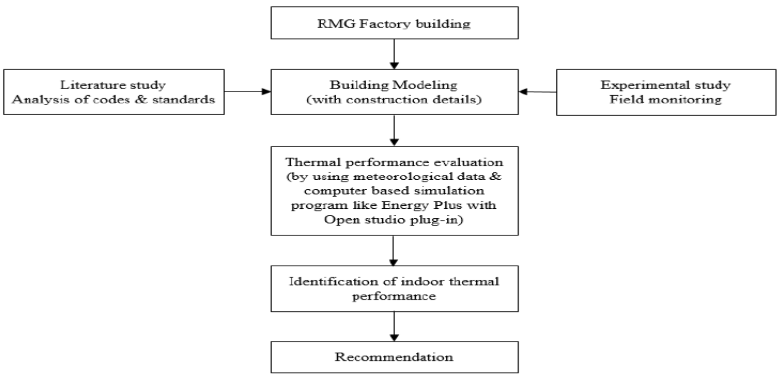

Figure 3: Building performance simulation methodology adopted by Chowdhury et al.[17]

Magnier and Haghighat [18] have presented the GAINN approach in which first a simulation-based Artificial Neural Network (ANN) technique has used to characterize building behaviour, and then combines this ANN with a multi-objective Genetic Algorithm (NSGA-II) for optimization. The methodology has used for the optimization of thermal comfort and energy consumption in a residential house.

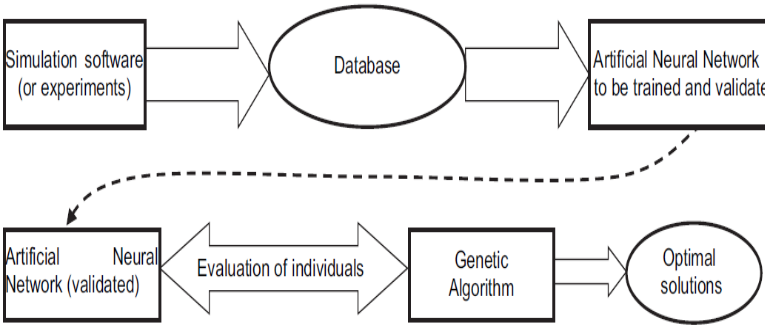

Figure 4: Building performance optimization presented by Magnier and Haghighat [18]

Lapinskiene and Martinaitis [19] have investigated the performances of building design tools and suggested a framework of an optimization model for building envelope, without compromising on energy efficiency, comfort, cost, and environment. They coupled building performance simulation tool DesignBuilder, the most widely used life cycle analysis (LCA) software SimaPro and method of multiple criteria complex proportional assessment (COPRAS) for the decisions making. By using the suggested optimization framework, more energy efficient, cost effective and environment friendly building design can be achieve.

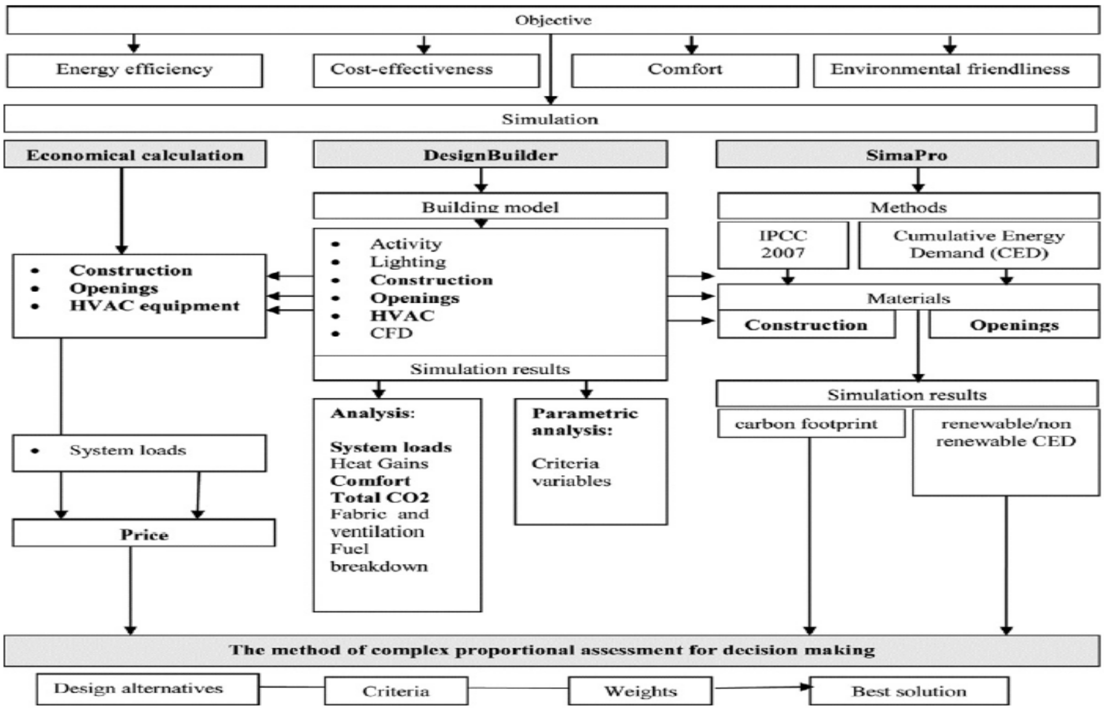

Figure 5: A framework of a model for building envelope optimization [19]

Gou et al. [20] have applied a simulation based optimization technique to optimize the passive design of newly-built residential buildings in hot summer and cold winter climate of Shanghai City of China for improving indoor thermal comfort without compromising energy demand. The optimization methodology comprises of three steps i.e. developing baseline model for multi-objective optimization, reduction of input variables through sensitivity analysis and multi-objective optimization by using the Non-dominated Sorting Genetic Algorithm II (NSGA-II) coupled with the Artificial Neural Network (ANN). They introduced a new thermal comfort index viz. Comfort Time Ratio (CTR).

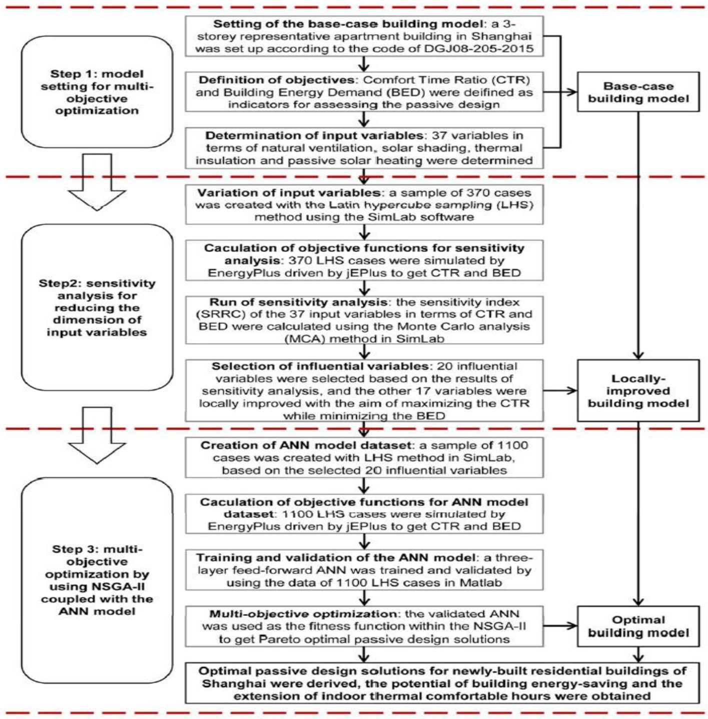

Figure 6: A framework for multi-objective building envelope optimization [20]

Shi and Yang [21] have presented an optimization framework for architectural envelop design of buildings as illustrated in figure 7. They have integrated Rhinoceros/Grasshopper rendering tool with Ecotect simulation tool. Ecotect simulate building envelope features and generate the results as exporter file as an import to the optimization engine. It is user's choice to choose the particular algorithm for optimization and to set specific objective(s) functions.

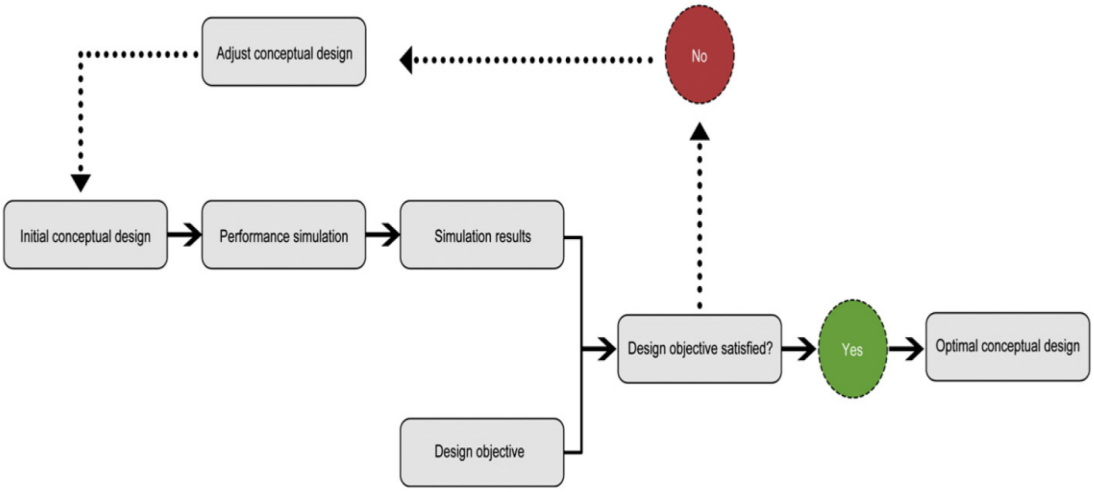

Figure 7: The workflow of performance driven conceptual design optimization methodology [21]

Mourshed et al. [22] have developed ArDOT, an Architectural Design Optimization Tool at IRUSE, National University of Ireland, Cork. ArDOT couple EnergyPlus building performance simulation tool for performing simulations. During problem definition stage, input files are called from the international standard Industry Foundation Classes (IFC) server. Each simulation result is send back to IFC server. ArDOT facilitates the use of both gradient and non-gradient based algorithms through C API (Application Programming Interface) available in VisualDOC; a generic optimization software. The component of ArDOT are presented as shown in figure 8.

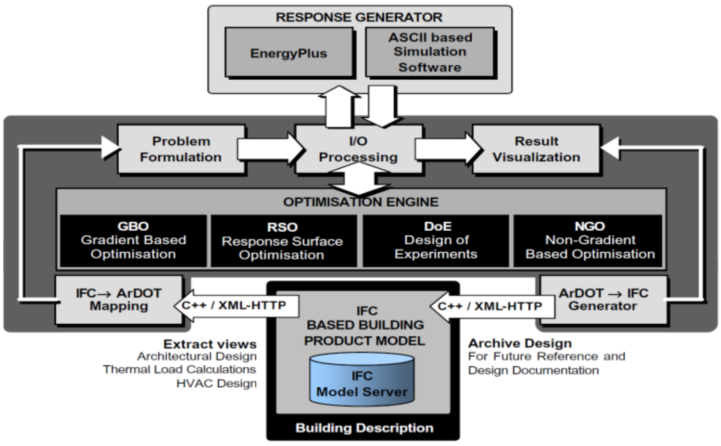

Figure 8: Component of ArDOT [22]

Futrell et al. [23] have performed bi-objective simulation based optimization of a class room. The objective functions are lighting and thermal comfort as Pareto fronts without scarifying energy use. EnergyPlus is used as simulation tool and optimization is performed by using GenOpt.

III. Concluding Remark

By using the above mentioned key words, literatures related to the performance, analysis and optimization of building envelope design were come up. In this review only the methodologies applied to optimization of building envelop design, by considering thermal comfort as objective function, are confined to discuss here. The generalized frame work of simulation based optimization technique is divided into three phase viz. modelling, simulation and optimization. In the first phase i.e. modelling phase, the building model is drawn in a graphical interface. Generally Google SketchUp is used for this purpose. Then, in the simulation phase, this model is imported into a simulation tool like EnergyPlus, DesignBuilder and OpenStudio. DesignBuilder is whole building simulation and optimization tool with its own modelling interface. EnergyPlus and OpenStudio have special plug-ins with Google SktechUp. In the optimization phase, a optimization tool like GenOpt is used or non-traditional algorithms like Particle Swarm Optimization, Genetic Algorithm or MatLab optimization tools are used by considering proper convergence criteria. The convergence criteria may be iteration time or it may be specifications and size of the building envelop component. Finally, it is concluded that simulation based optimization technique is very useful for early decision making so as to provide building with comfortable and sustainable built environment with little or no cost.

From the future point of research studies, one can model an objective function to be optimized by choosing thermal comfort as cost function and directly defining the cost function in terms of building envelope design variables.

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