

A Framework for Performance-Based Facade Design: Approach for Multi-Objective and Automated Simulation and Optimization

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Abstract

Buildings have a considerable impact on the environment, and it is crucial to consider environmental and energy performance in building design. In this regard, decision-makers are required to establish an optimal solution, considering multi-objective problems that are usually competitive and nonlinear, such as energy consumption, financial costs, environmental performance, occupant comfort, etc. Sustainable building design requires considerations of a large number of design variables and multiple, often conflicting objectives, such as the initial construction cost, energy cost, energy consumption and occupant satisfaction. One approach to address these issues is the use of building performance simulations and optimization methods.

This paper presents a novel method for improving building facade performance, taking into consideration occupant comfort, energy consumption and energy costs. The paper discusses development of a framework, which is based on multi-objective optimization and uses the genetic algorithm in combination with building performance simulations. The framework utilizes EnergyPlus simulation engine and Python programming to implement optimization algorithm analysis and decision support. The framework enhances the process of performance-based facade design, couples simulation and optimization packages, and provides flexible and fast supplement in facade design process by rapid generation of design alternatives.

Introduction

Buildings account for about 40% of the global energy consumption and contribute over 30% of the global carbon emissions [14]. Energy used in building sector for heating, cooling and lighting comprises up to 40% of the carbon emissions of developed countries [14]. A large proportion of this energy is used for meeting occupants' thermal comfort in buildings, followed by lighting. The building facade forms a barrier between the exterior and interior environments, and has a crucial role in improving energy efficiency and building performance. Therefore, this research focuses on performance-based facade design, appropriate simulation and optimization tools and methods for design analysis and support.

Building performance simulation (BPS) provides relevant design information by indicating potential (quantifiable) directions for design solutions. BPS tools and applications facilitate the process of design decision-making by providing quantifiable data about building performance. BPS tools are an integral part of the design process for energy efficient and high-performance buildings, since they help in investigating design options and assess the environmental and energy impacts of design decisions [1]. The important aspect is that simulation does not generate design solutions, instead, it supports designers by providing feedback on performance results of design scenarios.

Optimization is a method for finding a best scenario with highest achievable performance under certain constraints and variables. There are different methods for

optimization, requiring use of computational simulation to achieve optimal solution, or sometimes requiring analysis or experimental methods to optimize building performance without performing mathematical optimization. But in BPS context, the term optimization generally indicates an automated process that is entirely based on numerical simulation and mathematical optimization [13]. Integrating BPS and optimization methods can form a process for selecting optimal solutions from a set of available alternatives for a given design problem, according to a set of performance criteria.

This paper first focuses on identifying the role of BPS and design optimization methods, and outlines potential challenges and obstacles in performance-based facade design. This part is primarily based on literature reviews. Then, a new framework for performance-based facade design is presented. This framework takes into account occupant comfort and energy cost optimality, and implements BPS and relevant optimization methods to achieve a proper process for performance-based facade design. The components and development of the framework are discussed in detail. The last part of the paper offers conclusions and presents steps for testing and validating this framework.

Literature Review

There are many existing studies that provide literature reviews about whole building performance simulations and optimization methods. In this research, building facade was selected because of its influence on energy consumption, thermal and visual comfort of occupants. The literature review focuses on the role of BPS, optimization and tools, applications and methods in facade design.

High performance buildings require an efficient performance-based design process that integrates optimization methods into building performance simulations. Coupling simulation tools and optimization

algorithms are aimed at removing the existing barriers between optimization and building simulations. Efforts to implement some optimization algorithms into EnergyPlus simulation program have been conducted [17]. Another effort aimed to develop ArDOT program to automate the coupling of existing simulation engine (EnergyPlus) with formal optimization method through neutral data standards [13]. An effort to develop a zero energy building design tool that facilitates the use of building performance simulation in early design stage in hot climate has also been conducted [1].

Role of Building Performance Simulations in Different Stages of Facade Design

The role of simulations in design process has evolved, and simulation models are used in different design phases to predict energy consumption and comfort levels of buildings. These methods are used at the conceptual, schematic and design development phases to optimize building performance, during the occupancy phase to monitor and control the performance and during the retrofit to decide about the benefits of different alternatives and interventions. Therefore, understanding the effects of design decisions and outlining a framework in which the simulation models should be used is crucial to achieve high levels of performance.

Simulation is an integral part of measuring and quantifying performance criteria. Defining the interface between physical building element and performance criteria plays an important role. For instance, the existing building or the reference building (i.e., in case of new construction) can be defined in BPS software programs, including thermal envelope and the HVAC systems, operation, schedules, material properties, etc. Then, the parameters that most affect the energy performance can be identified as design variables, such as different materials, efficiencies of HVAC system, characteristics of thermal envelope, etc.

The biggest challenge of simulation in performance-based design is to provide a variety of normative calculations when an advanced simulation cannot provide a more accurate answer, either because of the presence of uncertainties, the lack of available information, or the context of decision that demands it [9].

Computational building performance modeling and simulation is multidisciplinary, problem oriented and wide in scope. Simulation is one of the most powerful analysis tools for a variety of problems, but it does not provide solutions or answers, instead it supports user understanding of complex systems by providing (relatively) rapid feedback on the performance implications of design scenarios [2].

Role of Optimization in Facade Design Process

There are several methods that can be used to improve building performance, and to achieve an optimal solution to a problem. For example, computer building models can be created by repetitive method, constructing infinite sequences of progressively better approximations to a solution. These methods are known as “numerical optimization” or simulation-based optimization [8]. For example, one study focused on optimizing building engineering systems, where the direct search method in optimizing HVAC systems was used [10].

In conventional optimization study, this process is usually automated by the coupling between a building simulation program and an optimization engine, which may consist of one or more optimization algorithms or strategies [1]. Genetic Algorithms (GA) are well suited to solve multi-objective optimization problems. GA-based multi-objective optimization methods that are frequently used in building research include Multi-Objective Genetic Algorithm (MOGA) and Niche Pareto Genetic Algorithm (NPGA). These methods aim to produce subset of the optimal set, from which decision-makers can select the most appropriate solution to the problem at hand.

One of the earliest studies used multi-objective optimization in building design and performed a Pareto optimization using dynamic programming [7]. Objective functions included thermal load, daylighting, usable area and cost, and the variables covered massing, orientation and construction. The authors provide an important concept of Pareto optimality applied to building design by calculating process and optimization method. It is shown that computational feasibility depends on the ordering of stages in the formulation to minimize the dimension of Pareto sets [7]. Other study shows that fenestration and its design have a significant impact on the energy use associated with the artificial lighting, heating and cooling of a building [15]. This study described an approach in which a building facade is divided into a number of cells, each cell having one of two possible states, a solid wall construction, or a window. GA search method was used to optimize the state of each cell, selecting a desirable number or aspect ratio of the windows while minimizing building energy use [15]. In other study, a GA was combined with human judgment to minimize energy use. It presented both optimal and near optimal design in visual manner, and enabled users to choose based on their preference [5].

Another study used a GA to minimize energy use; where authors varied thermal conductance and thermal capacity for each zone in model [3]. Presentation of both optimal and near optimal designs in a visual manner enabled the user to choose, based on preference that need not be formalized as constraints or objectives [11]. The study brought “virtual enclosure” concept that describes the building skin based on thermal and visual properties. In this approach, multiple actual realizations were used to map a single virtual enclosure and allow optimization algorithm to solve only the core underlying problem, without conflicting information relating to its realization.

Tools, Applications and Methods

Providing an overview of BPS tools and the methods to

quantify the objectives (performance criteria) in design process is important, since designers need to choose appropriate and efficient methods among several number of available approaches. The core tools in the building energy field are the whole-building energy simulation programs, which provide users with key building performance indicators, such as energy [4].

A large number of BPS tools currently exist, and these tools can evaluate many aspects of building performance, such as capital and operating costs; energy performance and demand; human comfort, health and productivity; illumination; electrical flows; water and waste; acoustic design; renewable energy; and atmospheric emissions [4]. Because the number of simulation tools are large, this research focuses only on human factors, energy performance and energy cost.

BPS tools have essential role in the process of building design to achieve energy performance, environmental impacts, cost and etc. Number of simulation engines exist and are often used in different stages of building design process, but out of 406 BPS tools, less than 19 tools are for building performance optimization [13]. According to existing surveys and interviews with professionals, users and participants, findings reveal that Matlab toolbox and GenOpt are effective optimization tools, and the most used simulation tools are EnergyPlus and IDA ICE, followed by TRNSYS and Esp-r [1].

Optimization tools for building design can be divided into three categories: custom programmed algorithms, general optimization packages and special optimization tools for building design. First category requires advanced programming skills and the main benefit is flexibility. Second category often includes a graphical user interface, and consists of many effective optimization algorithms and capabilities. In this category, a commonly used optimization tool is GenOpt, which is a generic optimization program. In order to automate simulations and comparison of several design building

variables, a number of researchers have coupled energy simulation tools with optimization techniques through self-produced tools, commonly based on MATLAB [12], or other dedicated software [16].

Current Gaps in Research and Literature in Performance-Based Design of Facades

A limited number of studies have focused on the performance-based design process for building facades which integrate simulations and optimization methods. There is lack of workable framework that implements both simulation analysis and optimization methods for facade design, taking into account performance criteria specific to this building system. Discussions are no longer about software and tools' features, but about the integration and increased use of simulations in design process. The future performance-based design approaches and simulation tools for facades should increase effectiveness, speed, quality, assurance and users' productivity.

Energy modeling and simulations in design process are usually limited to analysis of few different scenarios. It is not possible to simulate and analyze all possible design scenarios because of time constraints. Therefore, this research focused on developing a framework that couples simulation and optimization processes, and allows multiple design scenarios to be tested rapidly. The framework was implemented by coupling Python scripting with EnergyPlus simulation engine, enabling users to consider more variables during the design process.

Benefits of the Developed Data-Driven Framework

The basic characteristics that differentiate the developed framework and improve decision-making process can be summarized as:

- **Automation and Speed:** The framework enables users to automatically send the design scenarios to simulator and gather the outputs, and then screen out and sort these outputs to find optimized results. The

advantages of this automate process are efficient testing methodology, consistency, reliability and increase in the number of possible design scenarios. Also, by implementing this framework, simulation time will be decreased for thousands of design scenarios.

- Variety of variables (multi-objective variables): This framework enables users to test multiple variables at the same time during the design process.
- Modularity: The framework is designed in multiple modules, which work independently. The key benefits of modularity in this framework are distinct functionality and manageability. Each module provides a distinct function and can be combined to provide entirely new collective function. The separate modules make it easier to test and implement this framework in design process or detect the errors.

Methodology: Framework Development for Performance-Based Facade Design

The new framework for performance-based design approach, aiming to minimize building energy

consumption and energy cost with considering occupant comfort level, was developed as part of this research. This is a modular framework, consisting of independent scripts that represent modules, steps and function of application under test. The modules are used in a hierarchical fashion to apply the framework, consisting of four steps:

- 1) Defining goals, performance criteria, facade variables, and their properties, acceptable range in strategies for high-performance facade design
- 2) Generating the database that includes all possible design scenarios based on the variables with permutation in Python and selected outputs after simulation in EnergyPlus. This is module 1.
- 3) Coupling Python script with simulation engine (EnergyPlus) to automatically perform simulations for scenarios from database (measurements methods) to quantify variables and generate the needed outputs. This is module 2.
- 4) Filtering and narrowing down the results by implementing Python script, GA and reinforcement

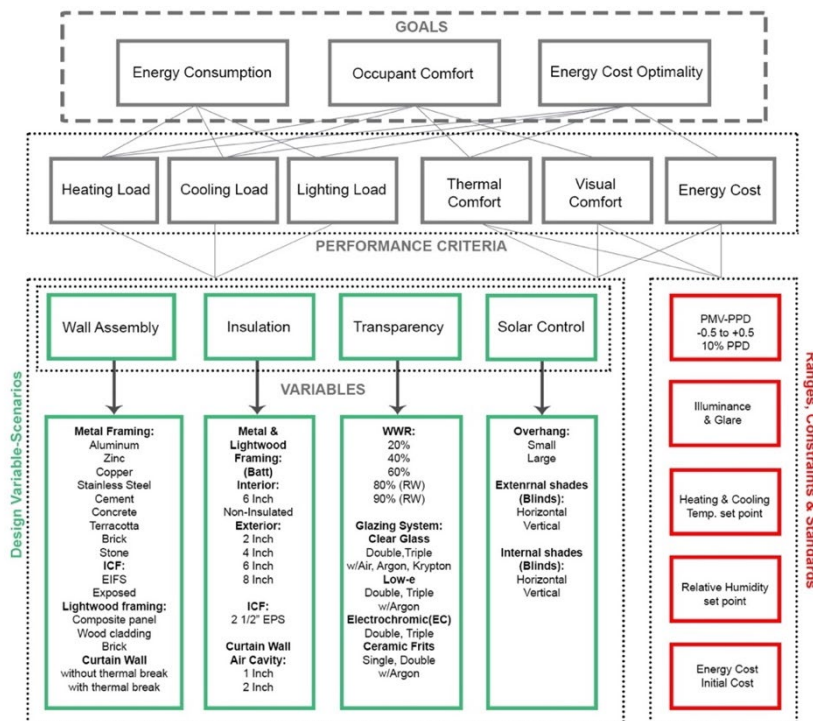


Fig. 1. Conceptual diagram, showing components of the framework.

learning to evaluate outputs and find the optimal scenarios. This is module 3.

The next sections discuss the components of the framework and its implementation in detail.

Step 1: Defining Goals, Performance Criteria, Facade Variables

Figure 1 shows the components of the framework. Performance-based facade design requires a holistic approach, considering performance indicators, such as energy performance and human comfort. These performance requirements (variables) must be quantified. The goals for this framework are to aid the design decision making process, where energy consumption and cost are minimized, and occupant comfort (thermal and visual) is maximized. The energy requirements for heating, cooling, and lighting of buildings are strongly driven by the performance of the facade, especially glazing parts. The objectives for reducing energy consumption are to reduce heating, cooling and lighting loads. Performance requirements (variables) to meet this objective are window to wall ratio (WWR), wall assembly, insulation, solar control, and glazing system. Performance-based facade design objectives that are related to human factors and contribute to occupant comfort and satisfaction in buildings include thermal comfort and visual comfort. The variables that relate to facade design include: air temperature, mean radiant temperature, air movement, relative humidity, clothing levels and activity levels. The predictive mean vote (PMV) suggested by Fanger [6] predicts the effects of these six factors on thermal comfort. Predicted Percentage of Dissatisfied (PPD) persons predicts the percentage of people who would feel discomfort with certain thermal conditions.

Step 2: Creating the Database

After setting all variables and parameters for facade design, all possible scenarios are generated using Python programming. With permutation in Python script,

design scenarios are generated and added to database with specific scenario ID. In this study, we have 38,400 scenarios to investigate for the test cell, described in the next section. After running simulation in EnergyPlus, all outputs in step 3 are populated in this database with identical scenario ID. EnergyPlus provides wide range of outputs, but for this purpose, the following results are obtained: cooling, heating and lighting loads, Energy Use Intensity (EUI) for electricity and gas, PMV and PPD, and total energy costs for electricity and gas. Module 1 is responsible for generating all scenarios with defined variable and populating these scenarios in database. Module 2 is responsible for sending automatically these scenarios to simulation engine and for populating the selected outputs in the database. Data Flow Diagram (DFD) in Figure 2 shows the overview of the framework system that represent the flow of data through this process.

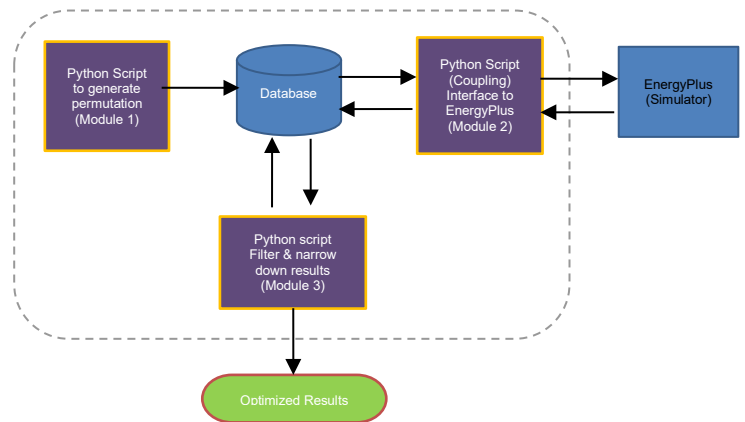


Fig. 2. Data Flow Diagram for the framework.

Step 3: Coupling Python Script with Simulation Engine (EnergyPlus)

EnergyPlus 8.5 is used in this research as an energy modeling engine. EnergyPlus has been chosen as BPS tool for two main reasons: (a) this program allows reliable modeling of both building and HVAC systems, and, (b) it works with text-based inputs and outputs, and these facilitate the interaction with Python scripts. EnergyPlus can investigate discussed variables as inputs and

simulate envelope related outputs in the study. Thermal comfort is calculated based on PMV and PPD. The formulas for both PMV and PPD are built into EnergyPlus and their values can be obtained directly from the simulation output file.

Initial simulation test cell considered a single office space (40'x40'x10'), located in Atlanta, Georgia. The south-facing facade was used to develop different design scenarios, varying WWR, materials, glazing system and shading control. Defining related parameters as inputs and setting data needed for outputs are the primary method for connecting design scenarios in the database with the simulation engine. Python script works as an interface to call scenarios from database and to send them to simulator. Each parameter must identify a well-defined relation with discussed variables, which reveals facade behavior in relation to performance aspects being analyzed.

Step 4: Filtering and Narrowing Down the Results by Implementing Python Script, GA and Reinforcement Learning

This optimization method in this study is a combination of GA and Reinforcement Learning. The GA in combination with flood fill algorithm and path planning create a new technique to find a relation between the outputs, to assign weights and dynamically adjust the target position. For this framework, three indices are defined for consumption, comfort and cost as indicators. Indicators are combined values that are used to measure performance, achievement or the impact of changes.

The flood field algorithm takes three parameters: start node, target and replacement, and determines the area connected to our target. This algorithm facilitates the optimization by sorting the highest indicators and decides which scenarios have to be simulated, based on the specific scenario ID. Using this algorithm decreases the process time, because it is not necessary to simulate all

scenarios—rather, only scenarios that are closer to the target. The comparison is based on the assigned indicator value. In dynamic system, it is necessary to scale indicators to represent the impact of the indicators, so as to configure following tasks, and converge the results to the goal based on these scores. Figure 4 shows a sample for scoring total EUI electricity indicator.

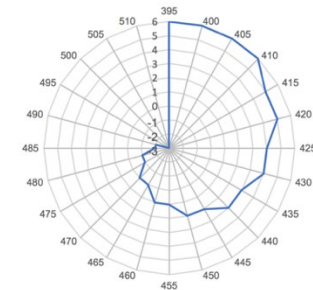


Fig. 4. Total EUI-Electricity (MJ/m^2) and indicator scores.

The initial population is generated randomly, based on the range of possible design scenarios. It is sent to the simulator to run the initial calculations, and then results are returned to the database to compare with the goals and standards. Then, design scenarios that have results closer to the goals are kept, and others are removed. In this framework, goal is summation of three indicators, for energy consumption, comfort and cost. The indicators are dynamically updated based on the range of results. Figure 4 shows an example, where indicators from 6 to -3 are used for the initial test cell energy consumption results. Occasionally, the solutions may be "seeded" in areas where optimal solutions are likely to be found. Individual solutions are selected through a fitness-based process, where fitter solutions (as measured by a fitness function) are typically more likely to be selected. This method accelerates the simulation process and the results give us clusters of optimized scenarios for analysis in next phase of optimization. Figures 5 and 6 show how optimization algorithm selects and sorts the fitted results for this framework.

Figure 5 shows the results before applying optimization for 2,061 scenarios and Figure 6 shows the result of 18,103 scenarios with assigning the first step of optimization. In this case, we have 1,627 scenarios that scored 20 and more than 20 (1,591 scenarios at 20 and 36 more than 20). Next step of optimization will analyze and evaluate these selected results.

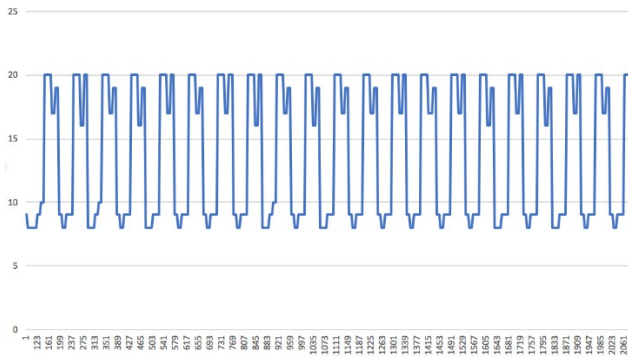


Fig. 5. Total Indicators vs. Scenario IDs (for 2,061 scenarios).

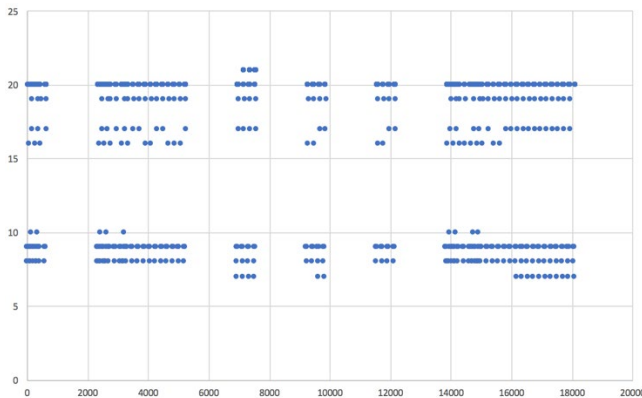


Fig. 6. Total Indicators vs. Scenario IDs (for 18,103 scenarios).

Conclusion and Future Work

This paper discussed the role of simulations and optimization in design decision-making process.. Then, a novel performance-based facade design framework was described, where different performance criteria and variables have been defined for achieving energy efficiency, occupant comfort and cost optimality. The framework has been implemented by coupling

EnergyPlus as a simulation engine, and custom scripts using Python programming language. The paper describes the components and functionality of this framework in detail. Future research will focus on testing and evaluating efficiency of this framework, as well as its application for facade design.

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