A REVIEW OF PERFORMANCE-BASED FACADE DESIGN: APPROACH FOR MULTI-OBJECTIVE SIMULATION-BASED OPTIMIZATION

Abstract

This paper presents a comprehensive literature review of research relating to performance-based facade design, considering energy consumption, cost minimization, and improvement of occupants' comfort. Applying building performance simulations and optimization methods supports designers in design process and decision-making by providing relevant design information. Building performance optimization, within which optimization is coupled to building performance simulation tools, is a process that aims at the selection of the optimal solutions from a set of available alternatives for a given design or control problem, according to a set of performance criteria. This paper reviews tools and methods for performance-based facade design, considering energy efficiency and occupant comfort. This paper focuses on fundamental concepts of understanding building performance simulation and optimization methods, as well as tools for performance-based facade design. Based on this review, a new framework for facade design is presented, which considers energy, cost and occupant comfort optimization.

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Keywords

Performance-based facade design, building performance simulation, simulation-based optimization, energy efficiency, occupant comfort

Introduction

The energy use of buildings and the release of carbon greenhouse gases associated with buildings are one of the largest contributors to climate change. Buildings account for about 40% of the global energy consumption and contribute over 30% of the CO_2 emissions (Lombard, 2008). Energy used in building sector for heating, cooling, and lighting comprises up to 40% of the carbon emissions of developed countries (Lombard, 2008). 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; therefore, it has a crucial role in improving energy efficiency and building performance. 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. Building performance simulations are an integral part of the design process for energy-efficient and high-performance buildings, because they help in investigating design options and assess the environmental and energy impacts of design decisions (Attia, 2013). 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 an alternative or a scenario with the highest achievable performance under certain constraints and variables. There are different methods for optimization, each 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 (Nguyen, 2014). BPS and optimization methods can form a process that aims at the selection of the optimal solutions from a set of available alternatives for a given design or control problem, according to a set of performance criteria.

This paper addresses the following questions:

- How do BPS methods support performance-based facade design through different stages of a design process?
- What are the appropriate BPS tools and optimization engines for building facade design?
- What are the building optimization processes for building facades? What are the current issues associated with using optimization methods? How can BPS and optimization methods be coupled to form a framework for performance-based facade design?
- How does the proposed framework work? What are the performance criteria associated with facade design to reduce energy consumption and cost, and meet occupant thermal and visual comfort levels? How can energy cost and occupant comfort objectives be detected in this framework?

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 last part of the paper offers conclusions and presents steps for testing and validating this framework.

Literature Review

Designers often use simulation programs to improve the overall building performance and analyze thermal, acoustical and energy behavior of a building, and to achieve specific performance criteria. These criteria can include multiple objectives, such as reducing energy consumption and costs, environmental impacts or improving indoor environment.

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 first part of the literature review focuses on the role of BPS in facade design. The second part presents and discusses the role of optimization in the process of design, as well as tools and methods.

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 an EnergyPlus™ simulation program have been conducted (Zhou, 2003). Another effort aimed to develop an ArDOT program that is able to automate the coupling of an existing simulation engine (EnergyPlus) with a formal optimization method through neutral data standards (Nguyen, 2014). An effort to develop a zero-energy building design tool that facilitates the use of building performance simulation in an early design stage in a hot climate has also been conducted (Attia, 2013).

ROLE OF BUILDING PERFORMANCE SIMULATION 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 conceptual role. It helps to show how simulation is performed to quantify a particular performance criteria (variables). 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 system, 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 (Hensen, 2012).

Sometimes simulation is not appropriate. For example, this can occur when the problem can be solved using common sense, when it is easier to change or perform direct experiment on actual systems, when there are not enough resources or data available for the project, or when a model cannot be verified or system behavior is too complex (Banks, 1996).

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 (Clarke, 2015).

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 (Gosavi, 2003). The methods for optimizing building engineering systems, where the direct search method in optimizing HVAC system was used (Huang, 2016).

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 (Attia, 2013). 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 Niched Pareto Genetic Algorithm (NPGA). These methods aim to produce a 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. Objectives included thermal load, daylighting, usable area, and cost, and the variables covered massing, orientation and construction. They 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 (Gero, 1983). Another 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 (Wright, 2009). 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. A Genetic Algorithm search method was used to optimize the state of each cell, selecting a desirable number or aspect ratio of the windows were desirable while minimizing building energy use (Wright, 2009). In another study, a genetic algorithm was combined with human judgments to minimize energy use. It presented both optimal and near optimal design in visual manner, and enabled users to choose based on their preference (Evins, 2012).

Another study used a genetic algorithm to minimize energy use; where authors varied thermal conductance and thermal capacity for each zone in the model (Coley, 2002). The novelty of this work was the combination of GA with human judgements. 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 (Mahdavi, 2003). The study brought a "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 the optimization algorithm to solve only the core underlying problem, without conflicting information relating to its realization.

TOOLS, APPLICATIONS, AND METHODS

Providing an overview of building performance simulation tools and the methods to quantify the objectives (performance criteria) in design process is important, because designers need to choose appropriate and efficient methods among several 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 (Crawley, 2008).

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 (Crawly, 2008). Because the number of simulation tools are large, this research focuses only on human factors, energy performance, and cost.

BPS tools have an essential role in the process of building design to achieve energy performance, environmental impacts, cost, etc. A 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 (Nguyen, 2014). Simulation and optimization tools are dramatically increased over time.

According to existing surveys and interviews with professionals, potential 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. (Attia, 2013). Figures 1–5 show results of studies (Adapted from Attia, 2013): Simulation and optimization tools ordered by use, then participants' choice of variables, and objective functions and constraints they've used in their studies and works.

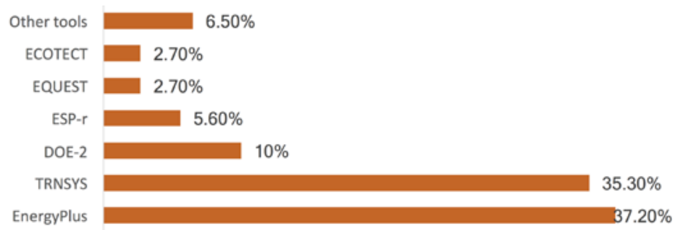

Figure 1: Major simulation programs in building optimization research.

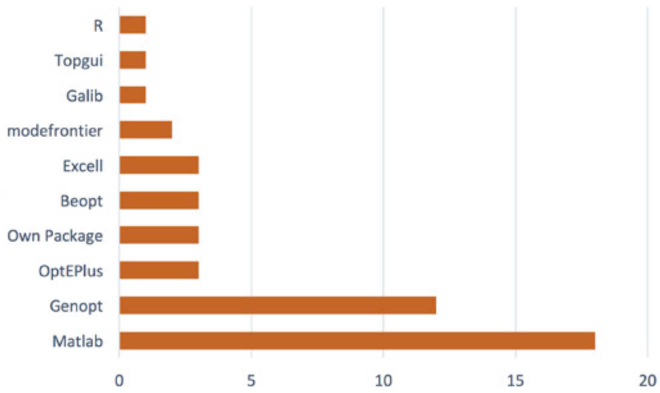

Figure 2: Optimization tools ordered by use.

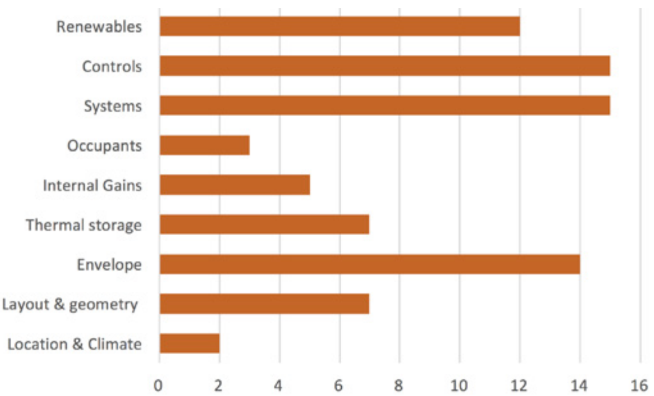

Figure 3: Participants' choice of optimization variables.

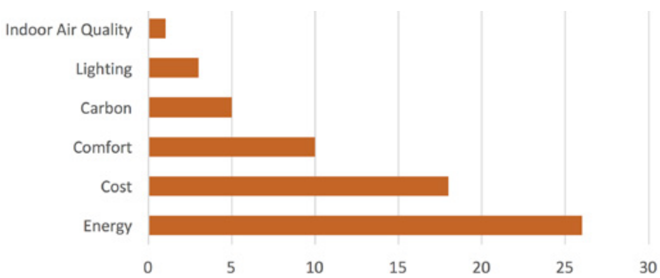

Figure 4: Participants' choice of objective functions.

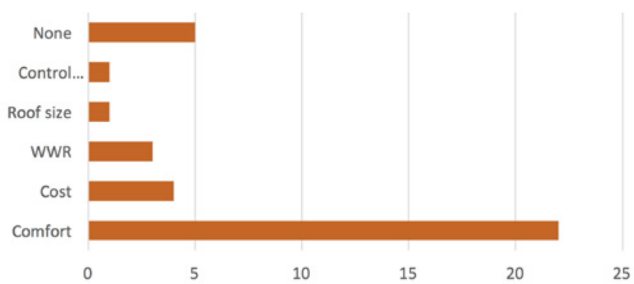

Figure 5: Participants' choice of constraints.

In 1996, a US federal agency (Department of Energy) began developing a new building energy simulation tool, EnergyPlus, building on development experience with two existing programs: DOE-2 and BLAST. EnergyPlus includes a number of innovative simulation features, such as variable time steps, user-configurable modular systems that are integrated with a heat and mass balance-based zone simulation, and input and output data structures tailored to facilitate third-party module and interface development (Crawly, 2001). According to Nguyen (2014), EnergyPlus is probably the most widely used "whole building energy simulation program" (Tian, 2013) for the research focusing on building optimization.

Optimization tools for building design can be divided into three categories: custom programmed algorithms, general optimization packages, and special optimization tools for building design. The first category requires advanced programming skills, and the main benefit is flexibility. The 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 (The Matlab works, 2012), or other dedicated software (Zhang, 2009).

CURRENT GAPS IN PERFORMANCE-BASED DESIGN FOR FACADES

A limited number of studies have been focused to develop a design process for building facades that couple simulations and optimization and considering different performance criteria like energy, thermal, and visual comfort. There is a lack of workable framework that implements both simulation analysis and optimization methods during the process of facade design based on performance criteria that are related to this domain of building.

Discussions are no longer about software and tools' features but on the integration and use of simulation in building process so the discipline to the next level should increase effectiveness, speed, quality assurance, and user's productivity, which is the goal of this study.

Energy modeling and simulation in design process are usually limited to analysis of a few different scenarios. It's not possible to have simulation and analysis of all possible scenarios because of time constraint. This framework with implementing Python scripting and coupling directly to an EnergyPlus simulator, enable us to consider more variables in the design process and generate all possible scenarios and automatically send them to a simulator and facilitate to modify the output result based on acceptable performance more precise and prompter.

Methodology: Framework Development for Performance-Based Facade Design

The framework for a performance-based design approach, aiming to minimize building energy consumption and energy cost with considering occupant comfort level, will be developed. It will be applied to a test cell to simulate, analyze, and evaluate the performance of facades. Four main steps will be conducted to develop and test the framework:

— Defining goals, performance criteria, facade variables and their properties, and acceptable range in strategies for high-performance facade design
— Generating all possible scenarios based on the variables with permutation in Python to create a database
— Coupling Python script with simulation engine (EnergyPlus) to automatically perform simulations for scenarios from a database (measurements methods) to quantify variables and generate the needed outputs
— Filtering and narrowing down the results by implementing Python script, genetic algorithm, and reinforcement learning to evaluate outputs and find the optimal scenarios.

STEP 1: DEFINING GOALS, PERFORMANCE CRITERIA, FACADE VARIABLES

Figure 6 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 that will be addressed in this research are window to wall ratio (WWR), wall assembly, insulation, solar control, and glazing system.

Facades have different properties, such as U-values, R-values, solar heat gain coefficients, and visual transmittance. These variables can have different impacts on heating, cooling, and lighting. For instance, a deeper exterior shading system reduces daylight and solar heat gain, which can lead to minimized illuminance and cooling loads. At the same time, it causes higher heating and lighting loads. The larger window to wall ratio could lead to a higher solar heat gain and daylight, therefore, a higher cooling load, lower heating load, and lighting load. These variables have antagonistic effects on the objective functions. Therefore, simulations of facade scenarios that are defined based on related variables and analysis of results help to support the design decision.

Occupant comfort has different kinds of objectives and according to these objectives, different performance requirements (variables) are defined. 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 (Fanger, 1970) 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. Adaptive approach derived from field studies focuses on the real acceptability of thermal environment, which depends on the context, the behavior of occupants and their expectation. Proposed Adaptive Comfort Standard (ACS) for ASHRAE Std. 55 is applicable for naturally ventilated buildings. The adaptive comfort zone will change depending on prevailing mean outdoor temperature. For visual comfort, illuminance and glare are variables that are included in the framework.

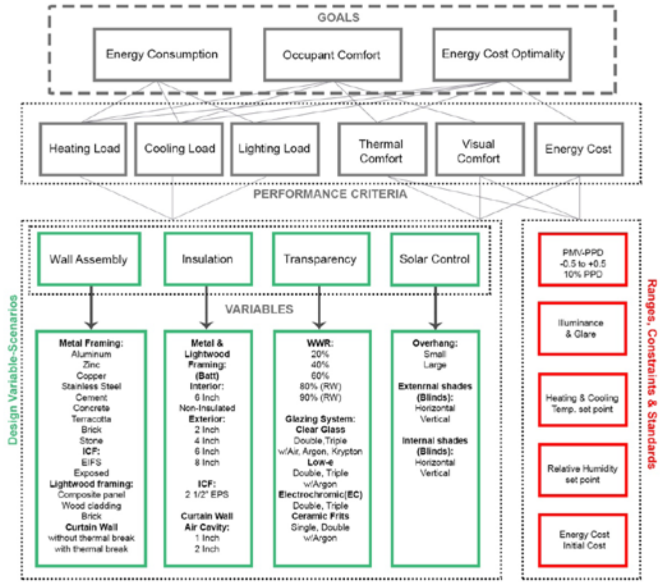

Figure 6: Conceptual diagram showing components of the framework.

STEP 2: PERMUTATION IN PYTHON TO CREATE A DATABASE

After setting all variables and parameters for facade design, all possible scenarios will be generating using Python programming. Python scripting language will facilitate the formulation of optimization problems and provide a flexible environment to model optimization problems. Data Flow Diagram (DFD) in Figure 7 shows the overview of the framework system that represent the flow of data through this process. Each step is hyperlinked to scripts and related data to shape this framework.

STEP 3: COUPLING PYTHON SCRIPT WITH SIMULATION ENGINE (ENERGYPLUS)

EneryPlus 8.5 as an energy modeling engine software and simulator used in this study. EnergyPlus has been chosen as the 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, which 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.

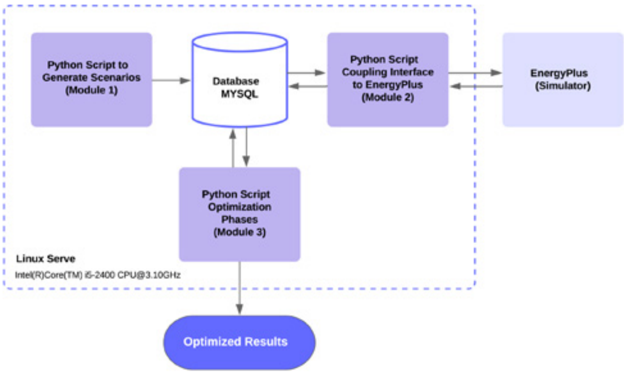

Figure 7: Data Flow Diagram for this framework.

Initial simulation test cell will be conducted for an office space (40'Lx40'Wx10'H) in Atlanta, Georgia (Climate Zone 3A). The south-facing facade under different scenarios will be modeled in EnergyPlus 8.5. Impact of different facade types, opening ratio, glazing system, and shading control will be investigated in a simulation study. So, all related parameters for these variables should be specified in IDF editor in EnergyPlus so Python script can call these variables and send it to the EnergyPlus engine to simulate automatically all these scenarios in the database. Then the determined output can be stored in the database for the filtering step.

Verification and finding related parameters as inputs and setting data needed as outputs are the keys to the connection of the scenario in the database with the simulation engine. Python script works as an interface to call scenarios from the database and send them to the 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: FILTER AND NARROW DOWN THE RESULTS BY IMPLEMENTING PYTHON SCRIPT, GENETIC ALGORITHM, AND REINFORCEMENT LEARNING

To support this framework, the methods need to generate integrated scenarios which are discussed earlier in generating scenarios and shortening the analysis evaluation cycle as described. This optimization method in this study is a combination of genetic algorithm and reinforcement learning which is a unique and new way in facade design process.

The initial population is generated randomly, between the range of possible scenarios. It is sent to the simulator to get the result and sent to the database to compare with our goals and standards. Then it keeps the ones that are closer to the goals and removes the ones that are far off the goals. 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. The final goal of this multi-objective programming is the achievement of optimized solutions for decision-making in performance-based design process.

Conclusion and Future Work

The largest proportion of energy consumption in the building sector relates to heating, cooling, and lighting. Building facade has an important role in controlling heating, cooling, and lighting loads, because it creates barriers between inside and outside and provides occupant comfort both thermally and visually. Therefore, a performance-based design needs to consider energy consumption, costs, as well as occupants' comfort.

This paper discussed the role of simulation and optimization in the design decision process and explained how coupling these can support design decision-making. Then a performance-based facade design framework was discussed, where different performance criteria and variables have been defined for achieving energy efficiency, occupant comfort, and cost optimality. Based on characteristics of variables, simulation or optimization methods will be used to support the decision-making for facade design. Future research will design experiments and scenarios, and apply to multiple case studies in order to simulate, analyze, and evaluate the performance of facades. These experiments will be tested to validate the framework.

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