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RESEARCH ARTICLE

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Performance-based and performance-driven architectural design and optimization

Abstract As the architecture, engineering, and construction (AEC) industry is marching into the sustainable and low-carbon era, the performance of architecture has drawn more attention than ever. Simulation technology has made quantified analysis of architectural performance possible and, therefore, directly enables architects and engineers to incorporate performance analysis into the design work flow. It is argued that performance-based and performance-driven architectural designs differ in that the latter involves computer-aided optimization technique so that the performance can be used as the criteria to truly “drive” the design. The paper starts with a brief introduction of performance issues in architectural design, followed by a review of the evolution of performance-based architectural design. The concept of performance-driven architectural design is presented, and some design projects and research work are reviewed. The driving engine, i.e., optimization technique, and its application in architectural design is discussed. Challenges to making performance-driven design a common practice are explained, and a schematic of integrated performance-based/driven architectural design software is proposed.

Keywords performance, optimization, architectural design, simulation, sustainability

1 Introduction

The purpose of designing and building architecture is multifaceted. Architecture can be designed to represent, to symbolize, to indicate, to worship, to commemorate, and to like. However, first and foremost, architecture is designed and built to perform. Therefore, performance-based architectural design is a natural design philosophy and should and must be emphasized. It can be considered as a philosophy, a methodology, a doctrine, a technique, or an approach. No matter how we understand performance-based architectural design, it needs to be studied and practiced to fulfill its potential value.

2 Concept of performance

In Merriam-Webster’s Collegiate Dictionary [1], the word performance has multiple meanings. It can be explained as the execution of an action, something accomplished, or the manner in which a mechanism performs. It can also be simply understood as the ability to perform. In this sense, performance is the synonym of efficiency. In architectural design, performance is often used as a generic tem to describe many design considerations of a building. Almost any term can be put in front of performance and form a phrase that makes sense to architects, e.g., thermal performance, structural performance, fire-resistant performance, etc. A more effective way to understand what performance really means to architectural design is to study what performance issues we need to consider in designing a building.

3 Categories of performance issues in architectural design

There are certainly different ways to categorize the performance issues encountered in architectural design. The following categorization is proposed not because it is the most accurate one, rather because it is straightforward and quite useful in furthering our discussion later in the paper.

1) Structural performance. Structural performance is arguably the most critical performance issue that needs to be carefully studied and designed in architectural design. One of the primary functions of a building is to provide a

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safe shelter. Structural performance is directly linked to the safety of occupants and properties under the shelter of the building. Therefore, almost every country has stringent structural codes and standards to ensure that the structural performance of a building satisfies what is required and that the occupant safety is not in danger.

2) Performance of physical environment. This category of performance includes solar, thermal, moisture, acoustics, lighting, wind and air, energy, and many others that have an impact on the quality of built environment, both indoor and outdoor. These performances issues have one thing in common, i.e., they can all be quantified to different degrees. In a world of green, sustainable, and low-carbon design, these performance issues are becoming the new focuses for architects to design responsibly. Different kinds of green building standards reflect his mindset and contribute to making the performance of physical environment a more important design consideration. For instance, the well-known green building standard LEED (Leadership in Energy and Environmental Design) was issued by USGBC (Unite States Green Building Council) in 1998 and has many credits that are associated with the performance of physical environment [2]. The MOHURD of China (Ministry of Housing and Urban Development, previously known as the MOC, Ministry of Construction) issued the first Chinese green building standard in 2006, and it also has many regulations on the physical performance of the building [3].

3) Aesthetic and cultural performance. These performance issues have long been the focal point in architectural design. The form, organization of space, material selection, color, shape, and details all play a role in determining the aesthetic and cultural performances of a building. These performances, contrary to the performance of physical environment, are often difficult to quantify. Therefore, assessment is dependent on many factors, and sometimes, it becomes a matter of personal preference or taste.

The performance this paper's discussion is mainly limited to the first and second categories since they can be quantified and simulated and, therefore, can be used to establish an effective and objective technique to achieve performance-based or performance-driven design. It by no means indicates that aesthetic and cultural performance cannot be the base of architectural design or drive the design. In contrast, many master works in architectural history are exactly designed based on aesthetic and cultural performance considerations.

4 Evolution of performance-based architectural design

The concept of performance-based architectural design can be dated back to the 1970s. The "Architectural Machine" proposed by Negroponte was the first example that reflected the idea of performance-based architectural design [4]. The essence of the Architectural Machine was three notable capabilities:

1) Generation. This is an environment for rapid design manipulation.

2) Evaluation. This is knowledge on various aspects of architectural design.

3) Adaption. This is a learning mechanism.

In these three capabilities, evaluation is the critical link between generation and adaption. What the Architectural Machine evaluates is essentially the performance of the architecture. Evaluation enables the Machine to adapt, i.e., to optimize the design to achieve the best performance.

Limited by the technology available, especially the computerization and visualization technology, the Architectural Machine was just a vision and could not be turned into reality in the era of Negroponte. On one hand, the CAD technology was still in its infancy and could not provide a convenient yet powerful digital platform that is necessary to support generation and adaption of the Machine. On the other hand, performance simulation programs were not available to evaluate various aspects of the design. Calculating and analyzing performances of the building by hands is simply too daunting a task to become practically valuable for architects. Despite all these, the grand vision of Negroponte encouraged a series of efforts and research work to develop methodology and tools for performance-based architectural design.

Following Negroponte's Architectural Machine, a lot of research work was conducted following the same line of thoughts and trying to develop an integrated design system to facilitate performance-based architectural design. A notable trend was that these efforts, to different degrees, all focused on specific types of buildings, possibly because this approach could avoid the challenge of developing a general-purpose system that is applicable to all types of buildings. For instance, Bijl and Shawcross developed a housing design system called SSHA [5]. Hoskins and Meager worked on OXSYS and Harness, respectively [6,7]. Both were for hospital design. More of these works were reviewed by Ìlal [8].

Performance-based architectural design started becoming the mainstream toward the end of the 20th century because of the rise of sustainable design in the AEC industry. The other driving engine is the maturation of simulation tools, which contributes significantly to making performance-based architectural design possible. Sustainable and green design is the response of the AEC industry to face environmental challenges, such as resources depletion, shortage of energy, etc. The previously mentioned green building standards, such as LEED in the US [2] and BREEAM in the UK [9] both emphasize on many performance issues including natural lighting, energy consumption, visibility, etc. Encouraged by these green building standards and sometimes required by clients, architects, and engineers have focused more on studying, optimizing, and fine-tuning the performance of buildings.

Performance-based architectural design requires a fast and accurate analysis of performance issues. Without this analysis, design can only be based on concept and estimation, and performance-based design is not possible. Today, there are many simulation programs being used in architectural design. However, many of these programs were originally developed only for research, and therefore, they were not very user friendly and typically required a deep understanding of a special field, which was not commonly found among architects. As these simulation programs became more powerful and convenient to use, practicing architects and engineers realized their value and used them more and more in design. Incorporating simulation programs into the design workflow enables architects and engineers to analyze performances rapidly and accurately, making performance-based architectural design possible.

The commonly used simulation programs by architects and engineers include energy simulation programs, such as EnergyPlus [10,11]; Computational Fluid Dynamics programs (CFD), such as Fluent [12], Flovent [13], Star CCM +, etc.; and integrated building environment simulation programs, such as IES [14] and Ecotect [15].

Examples of using simulation programs to achieve performance-based architectural design are plenty; many of which are high-profile projects designed by world renowned firms and architects. Buro Happold developed an in-house simulation program based on the nonlinear finite element method to analyze the performance of tensile structures [16]. The program was successfully used in the Stuttgard 21 project to design a series of compressive shell surfaces that form the roof of a new major train station in Stuttgard, Germany (Figs. 1 and 2).

Arup assisted SOM in the New York's Penn Station project to use a simulation program to study the performance of daylighting and its effect on the visual clarity of electronic displays [17]. The performance-based approach helped the architect to study the quality of the design in the early stage and proceed with a greater level of confidence (Figs. 3 and 4). Norman Foster collaborated

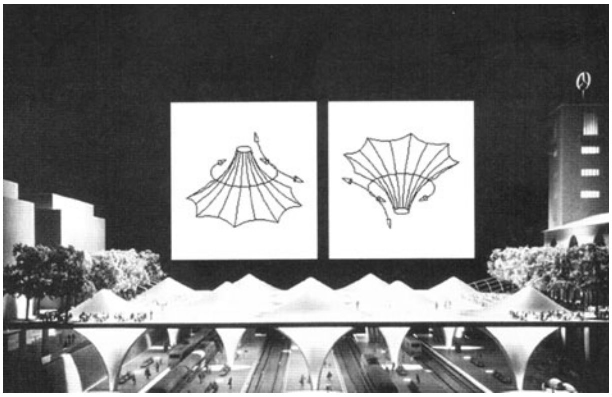

Fig. 1 Stuttgard 21 project, new railway station roof made of concrete shells formed with tensile membranes [16]

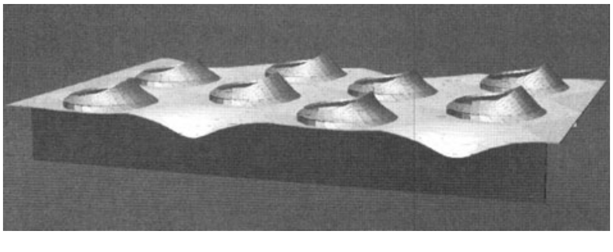

Fig. 2 Stuttgard 21, computer rendering showing staggered individual shell units [16]

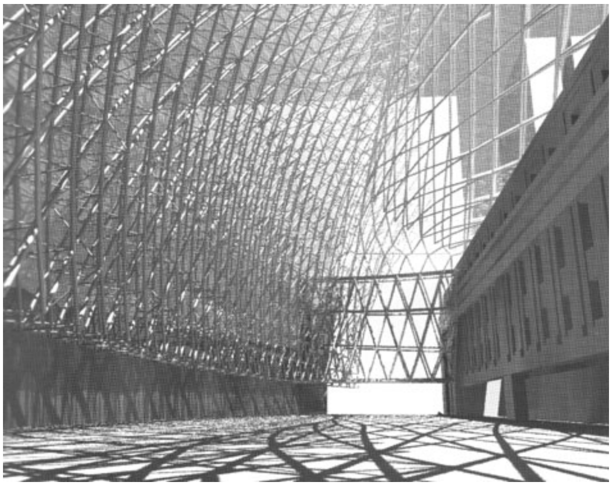

Fig. 3 Lighting simulation of Penn Station project in New York [17]

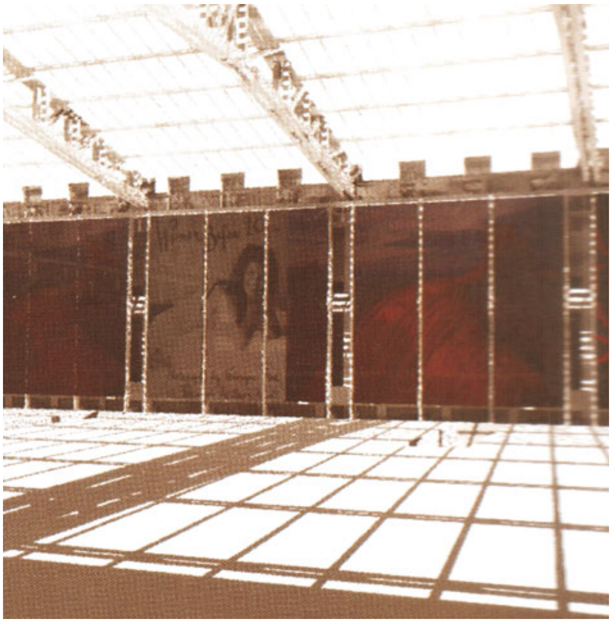

Fig. 4 Lighting simulation designed to investigate the visual clarity of electronic displays in the Penn Station project [17]

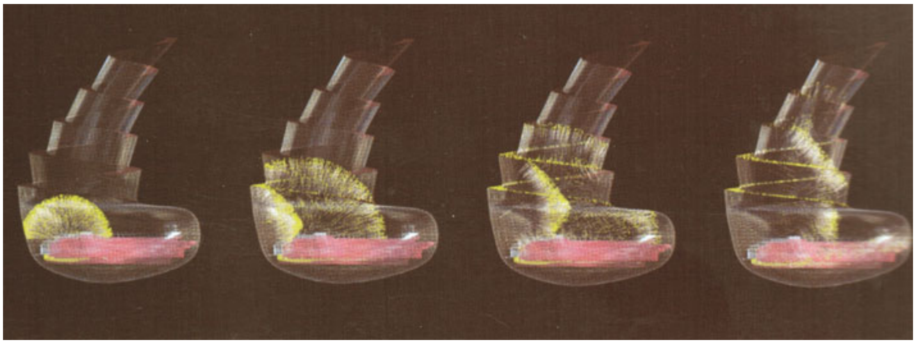

Fig. 5 Acoustic progression of the Greater London Assembly [17]

with Arup in the design of Greater London Assembly Building [17]. The acoustical performance of the assembly was simulated and visualized to assist the architect in determining a form that was both architecturally and acoustically sound (Fig. 5).

Project ZED was a high-rise building integrated with renewable energy including photovoltaic cells and wind turbines. The design purpose was for the building to be self-sufficient in energy supply. Future Systems, a design firmed based in London, conducted a CFD analysis to study the aerodynamic performance of the building and used the results to optimize the design [18] (Fig. 6). CFD technique was also used in the conceptual design phase of the PennDesign Building to study the ventilation and thermal performance [19] (Fig. 7). Large residential areas planning and designing can also benefit from incorporating CFD simulation to analyze the thermal performance and wind environment. Figure 8 shows a CFD analysis of the temperature field at 1.5 m above the ground in a large residential area in Nanjing, China.

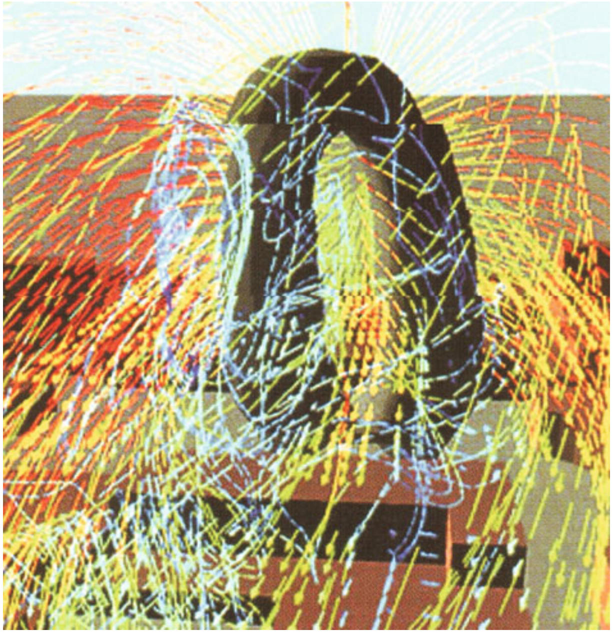

Fig. 6 CFD simulation to optimize the aerodynamics performance of the ZED project [18]

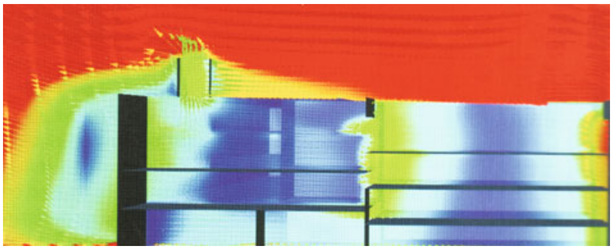

Fig. 7 CFD analysis to study the ventilation and thermal performances in the PennDesign project [19]

5 From performance-based to performance-driven

Performance-based architectural design can refer to a principle or methodology in which the designer emphasizes performances of the building. In this sense, it is a general term that describes a broad range of design practices. The design process, incorporating the performance simulation, can be illustrated using Fig. 9. In Fig. 9, the conceptual design is carried out using conventional approaches. Once the model is set up, the simulation program is called upon to analyze one or several performances that the designer is interested in. The simulation results are then analyzed and assessed. The architect modifies the design based on the assessment, trying to improve the performance of the building. The process, in essence, should be iterative because one round of modification can seldom achieve the best result because of the complexity of the design problem. However, the iteration is often not conducted fully in practice because of the tight project schedule and the amount of time and manpower required. According to a survey [20], the average number of iteration is only 2.7, which is far less than what is needed to find the optimal design.

Fig. 8 Thermal performance analysis of a large residential area using CFD

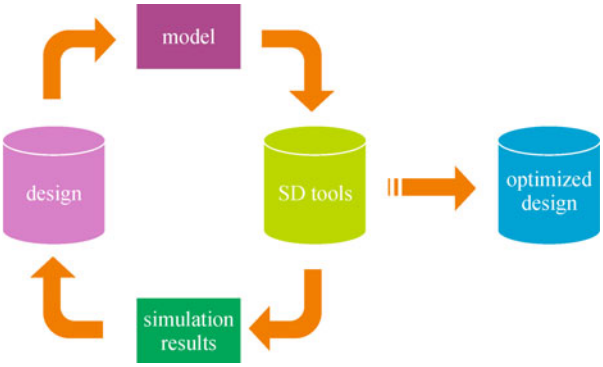

Fig. 9 The iterative process to conduct performance-base design

What lacks here is an effective methodology that can automate the iterative design process and quickly find the optimal design based on one of multiple performance criteria. This is where the optimization technique comes into play. Performance-based architectural design, assisted by an effective optimization technique, becomes automatic and more efficient. It is upgraded from being performance based to being performance driven. The driving engine is the optimization algorithm.

Incorporating rigorous optimization techniques is a key step toward performance-driven architectural design. Some researchers and practicing architects are quite active in this field and have produced encouraging results. Wang et al. presented a methodology to optimize building shapes in plan using the genetic algorithm [21]. The building footprint was modeled using a multisided polygon. An optimization model was set up with shape-related and envelope-related variables considered. The optimization objectives were life-cycle cost and life-cycle environmental performances. The study obtained interesting results with practical values. Flager et al. studied the structural and energy performances of a classroom building using Process Integration and Design Optimization (PIDO) method [22]. The authors briefly reviewed several design optimization programs used in the AEC industry, namely, BEopt, OptEPlus, GENE_ARCH, and GenOpt. The optimization and performance simulation were integrated using a commercial optimization program called ModelCenter. Geyer argued that Multidisciplinary Design Optimization (MDO) requires a special setup of the optimization model that considers the uniqueness of buildings and allows the designer to interact with the optimization in order to assess various performances of the building [23]. To solve the problem, Geyer proposed a component-oriented decomposition methodology, which follows the Industry Foundation Classes (IFC) as a common Building Information Model (BIM) standard in order to allow a seamless integration into an interactive CAD working process. A case study of a framed hall was presented to further explain the methodology.

Kämpt and Robinson studied how to use the solar energy performance and the evolutionary algorithm to drive the form generation [24]. The context of the study was the urban environment, and one of the examples presented was to find the optimal city shape to maximize the total solar energy potential of all buildings in the cluster. Marks presented a study on determining the optimal dimensions of the shape of a building of volume and height considering two performance issues: 1) building costs and 2) yearly heating costs [25]. A stringent mathematical model was established to describe the arbitrary shape of the building and to quantify the two performance indices. The solution obtained was composed of a circular segment bounding the northern part of the building and a curve described in parametric form describing its southern part. Jedrzejuk and Marks followed similar approaches to establish a theory and obtain solutions and presented an example for the optimization of shape and functional structure of buildings, as well as heat source utilization [26–28].

In addition to being used in research, optimization techniques have been applied on real projects to achieve performance-driven architectural design. Luebkeman and Shea presented the so-called Computational Design + Optimization (CDO) in building practice [29]. Several high-profile architectural projects presented in Ref. [29] include the Aquatics Center of the 2008 Beijing Olympics, the Bishopsgate Tower in London, and a media center in Paris.

6 Conclusions

Today, performance-based architectural design is gaining momentum in the context of sustainability because it provides a paradigm shift from focusing on form and aesthetics to emphasizing the balance between traditional concerns of architectural design and the building's quantifiable and physical performances. The end result is a better design in all aspects, especially in structural and environmental performances. However, moving from the traditional design approach to the performance-based and even performance-driven design methodology requires not only a paradigm shift but also a set of special techniques as well. These techniques include, but are not limited to a good knowledge base about the different kinds of performance issues, such as daylighting, solar, acoustics, energy, structural, air, thermal and moisture, etc., the following:

1) a capability of correctly using simulation programs and interpreting the results;

2) optimization algorithms and integrated software, and in some cases; and

3) computer programming.

Not every architect is familiar with all of the above knowledge and techniques. Therefore, performance-based/driven architectural design is still a fairly new approach and mainly conducted in research and some high-profile projects. We argue that developing a more powerful and integrated design software that is capable of modeling, simulating, evaluating, optimizing, and generating can contribute significantly to making performance-based/driven design more practical and appealing. Figure 10 shows a schematic of the components of such software. While most available programs in the field focus on either modeling or simulating, what is lacking is evaluating, optimizing, and generating. An integrated design platform that is capable of doing what that in Fig. 10 describes can upgrade computer-aided-drafting or computer-aided calculating to computer-aided design. With such software installed, the computer is not just the extension of architect's hands any more. It becomes the extension of architect's mind and infinitely close to Negroponte's Architectural Machine.

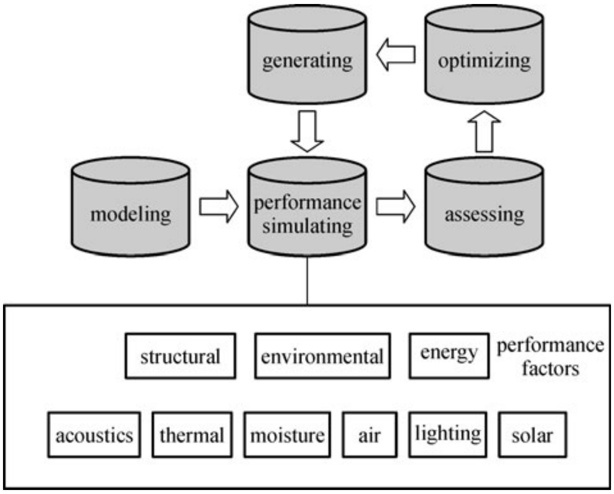

Fig. 10 Schematic of an integrated performance-based/driven architectural design platform

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