A design optimization workflow for tall buildings using parametric Algorithm

Mahsa Nicknam¹, Mahjoub M. Elnimeiri²

Ph.D. Candidate, College of Architecture, Illinois Institute of Technology, Chicago, USA,
Email address: mnicknam@iit.edu ¹

Professor, College of Architecture, Illinois Institute of Technology, Chicago, USA,
Email address: elnimeiri@iit.edu ²

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Mahjoub M. Elnimeiri

Biography

Dr. Mahjoub M. Elnimeiri holds a B. Sc. In Civil Engineering (with Honors) from the University of Khartoum; a D.I.C. and M. Sc. in Structural Engineering from the Imperial College, University of London, London, England and a Ph.D. in Structural Engineering and Structural Mechanics from Northwestern University, Evanston, Illinois, USA.

Since his educational completion in 1974, he has been involved in the practice of structural and architectural work of buildings in Chicago, USA and overseas. His expertise is in the areas of structural analysis, design and construction of buildings, and in particular tall buildings, and in the application of computer technology. He is very active and well known in the professional and academic communities. He has been speaker in many conferences and conventions. His publications are directly related to his areas of study, and he is a recipient of the “State of The Art Award” of the American Society of Civil Engineers for the year 1989.

Dr Elnimeiri is Chairman of CECI+ Engineers International, Chicago, Illinois, USA. CECI+ is a progressive engineering firm using cutting edge of technology for service provision to its clients. The practice includes structural analysis, design and overseeing construction of very special buildings, primarily tall buildings, at different places in US and overseas. Few of these buildings are located in highly seismic areas. Before beginning his own practice, Dr Elnimeiri worked with Skidmore Owings & Merrill, Chicago from 1979-1990. During his experience at SOM, he worked closely with Architectural Partners in the design development of many outstanding projects. Dr Elnimeiri left SOM as an Associate Partner and Senior Structural Engineer.

Dr Elnimeiri is also a full professor, Founder & Director of the PhD Program, at the College of Architecture at Illinois Institute of Technology, Chicago, Illinois, USA.
Abstract

This research paper is intended to incorporate structural performance and energy efficiency strategies of tall buildings through an architectural form generation process. The main objective is to propose a basis for a generative design methodology in order to develop architectural forms of tall buildings that are optimized both in terms of the structural performance and energy conservation in architecture. To achieve this goal, the research paper proposes a digitally-based workflow to aid direct interaction among energy efficiency, structural performance and formal design considerations within the schematic design phase. By employing the parametric modeling platforms, the structural and energy efficiency implications of changing architectural forms of tall buildings would be understood by the architect. Some architects may use the outputs as general concept for their designs and others may choose to use them to understand how a sensitive tall building form responds to certain performance metrics. The core of this research will be to define design driven criteria to focus on the optimization process.

Keywords:
Multi objective Optimization, Environmental design, Generative system, Performance-based design, Parametric design, Energy efficiency, Tall buildings, Genetic algorithms, Structural Performance

Introduction

The depleting energy resources on earth and the rising cost of energy are the most real problems in today’s world. In such a context, energy efficient design is becoming important as we think more about energy conservation and the environment. Meanwhile, structure has to assume its place and directly contribute to the building’s overall energy conservation strategy (Elimeiri and Almusharaf, 2010). The interest in efficient structure within a tall building highlighted by the fact that the structural costs constitute up to 30% of the total construction cost of the building, (Figure 1) (Elimeiri and Almusharaf, 2010).

![Figure 1. Structural cost in relation to the total building construction cost (source: Elimeiri and Almusharaf, 2010)](image-url)
Today architectural design is driven by the search for exotic forms that more that often lead to costly construction. In the current tall building design practice, issues pertaining to structure and energy conservation are typically left to be dealt with after the architectural form is well articulated. Hence as a result, such an approach may enable a building to stand upright, and may also reduce the energy consumption in the building. It will not yield solutions that will perform well with reference to structure and energy efficiency, (Figure 2).

Moreover, sometimes in the traditional engineering analysis and design process, the geometry is imported manually into Analysis Tools and the pre-processing is performed by an engineer via the graphical user interface. This approach takes a lot of time when multiple options are proposed by the architect. In such approach, the engineer will often finish a preliminary analysis and begin to communicate the new scheme to the architect, only to find out that the design has been radically changed, (Chok and Donofrio, 2010)(Figure 3).

![Figure 2. Tall building design process](image)

The process shows the results are not necessarily efficient neither structurally nor energy wise

![Figure 3. Traditional Architectural design workflow which maybe yields a different architectural form](image)

It is evident that during the modern era of architectural design of tall buildings, in Chicago, between 1960 and
1975, there was a meaningful collaboration between the architect and the structural engineer. A good example for that is John Hancock Building in Chicago, 1996, (Figure 4). However energy efficiency strategies were never considered in this building.

Figure 4. John Hancock Center, Chicago, USA. (Courtesy of Skidmore Owings and Merrill)

As mentioned above, the development of tall buildings had been traditionally a product of a close collaboration between the architect and the engineer. Since in the design process, the most important design decisions, those which have the most significant cost impacts, are made at the concept stage of a project, the collaboration between different disciplines within the design team in this stage become very important. Barriers to this collaboration often have resulted in that small and large architectural firms either left the sophisticated modeling of environmental metrics until too late in the design process, or they neglect it altogether (Galasiu and Reinhart, 2007), so as a result they would come up with inefficient architectural form. To address such disconnect, this research paper propose a digitally-based workflow to aid direct interaction among energy efficiency, structural performance and formal design considerations to assist early design activities.

Parametric Design

Within the last years digital tools have extensively progressed so as to allow the architects to increasingly become involved in an integrative collaborative architectural building design approaches. In these years, digital media is not used as a representational tool for visualization but as a generative tool for the derivation of form and its transformation.

Figure 5. Tall Building Generation Process by Parametric Design (Courtesy of Park, 2005)
In the last few decades computer simulations have proven to be a powerful digital tool for studying the environmental performance of buildings. By using simulation and analysis tools, it is possible to engage in an architectural design practice that is significantly enhanced by iterative process that depends on feedback from the evaluation of the environmental impact into the architectural design decision making. (shown in Figure 6).

Among various digital design approaches, parametric design has become a strong trend in contemporary architectural design practice and education (Day, 2010). The term refers to a practice of digitally modeling a series of design variants whose relationships to each other are defined through one or several mathematical relationships (parameters), then form a parametric space that may comprise of tens or hundreds of related but distinct forms. By relying on parametric values, it becomes possible to associate variables, relations, and dependencies to geometry and structure in the design process (Dominik, Jiwu, Mike & Mark, 2004). This facilitates rapid editing, re-adaptability, and enables useful libraries of scripts and reusable parts for future use. Hence these parametric modeling systems help the architect to rapidly generate and test a large number of design options and variation in the early stage of design by linking the generative tools to structural, energy efficiency analysis and evaluation tools. This approach minimizes performance-based study time and aids the project team in making better informed decisions earlier in the design process.

Extending the potential of parametric/associative models to respond to both structural and energy efficiency inputs and performance criteria is the main focus of this research.

**Proposed Workflow**

In this work, we emphasize mainly on a general trend to architectural form design approaches defining mostly the basics of performance strategies of tall buildings. The advantage of parametric design in research application is to plan and synthesize the overall requirements and relationships of many design elements into one form. The convergence of generative tools, analytical solutions and moving away from traditional form-driven approaches are the main achievements. Various parametric modeling platforms have been employed to simply evaluate how changes in architectural forms of a tall building would affect its structural performance as well as its energy efficiency.
This research paper demonstrates how a fixable 3D model can be parametrically altered towards targeted solutions with the help of a near real time feedback generated by structural/energy analysis and optimization. The main focus in this work is defining the architectural model in a way to be parametrically reconfigurable while at the same time remains dynamically responsive to performance-based engineering input. The architectural model will be kept in a fluid state allowing for intuitive variations according to the feedback from performance-based data. All different solutions can be analyzed and evaluated according to ones objective and preference.

Energy performance analysis, in parallel with structural analysis, is performed on the parametric models through an optimization framework leading to a considerably faster performance-based study. It is shown that, the proposed workflow gives the architect the opportunity to select among different design options based on ones objectives. Using this workflow to simulate environmental and structural performance provides a visualization of results with color mapping, enabling performance to be easily understood by all members of the design team.
**Multi-objective optimization**

This research paper will focus on Multi-objective optimization techniques in lieu single optimization approach. Since Multi-objective optimization allows direct communication between multi-disciplinary simulation software, it is becoming a key factor in the design process. The proposed workflow, (Figure 8), allows integrating the Structural and Energy Simulation softwares into one design environment. The proposed automated process, as shown in Figure 9, will allow the achievement of a final architectural form satisfying the specified optimization objectives.

![Figure 9. Conceptual Framework for the Proposed Process](image)

The optimization part of the proposed workflow will encounter more than one objective including structural efficiency and Energy efficiency objectives. So in some cases we might have conflicting objectives. One of the major advantages of using Genetic Algorithm (GAs) is that they allow true multi-objective optimization. Multi-objective optimization techniques keep the objectives separate during the optimization process rather than being collapsed into a single, weighted objective function from the beginning. So in cases with conflicting objectives there will be no single optimum result.¹

![Figure 10. Tall building form generation using Genetic Algorithm](image)

¹ [http://www.esteco.com](http://www.esteco.com)
optimal trade-offs among multiple criteria can be found. In this process the output is not a single solution but a Pareto Frontier (or trade-off curve) of high-performance solutions, which will allow the architect to pick the point at which he would like to operate or he can choose to consider a new criteria (Caldas and Norford, 2001) (Figure 11).

Figure 11. Example of a Pareto frontier. The boxed points represent feasible choices, and smaller values are preferred to larger ones. Point C is not on the Pareto Frontier because it is dominated by both point A and point B. Points A and B are not strictly dominated by any other, and hence do lie on the frontier. (Courtesy of Wikipedia)

Conclusions
This research paper introduced a workflow that encompasses a loop of four main phases of the procedure, namely form generation, structural performance evaluation, energy performance evaluation, and optimization that are to be conducted under predefined criteria. Parametrically architectural form generation proved to be flexible enough that allows architect to manipulate certain architectural design intentions to improve the performance of the tall building with respect to structure and energy efficiency strategies. The workflow developed in this research paper is intended to help the architect to incorporate structure and energy efficiency considerations into the architectural form generation process. This will help the architect to achieve a well-rounded performance-based architectural design of tall buildings.

In such case of Multi-objective optimization, structure and energy considerations might have conflicting objectives; hence extermination of one goal can only be achieved at the expense of another. In this process it is better to keep all objectives separate. The optimization process will then lead to a Pareto frontier of solutions. Therefore, Genetic Algorithm was chosen as an optimization technique in the proposed workflow that manipulates in parallel a population of high-performance solutions.

References


