International Journal of Design & Nature and Ecodynamics
Vol. 17, No. 2, April, 2022, pp. 239-248
Journal homepage: http://iieta.org/journals/ijdne

Constraint-Based Design Formation - A Case Study of Wind Effects on High-Rise Building Designs

Dhuha A. Al-Kazzaz

Department of Architecture Engineering, College of Engineering, University of Mosul, Mosul 41002, Iraq

Corresponding Author Email: dhuha.kazzaz@uomosul.edu.iq

https://doi.org/10.18280/ijdne.170210

Received: 25 January 2022
Accepted: 12 April 2022

Keywords:
architectural design processes, design constraints, digital design, tower designs, wind constraint

ABSTRACT

The use of constraint-based knowledge assists designers in making well-informed decisions at different stages of digital design process. A constraint is conceived as a direct control on design formation, or as a filter which does not impose a control over a formation process. The paper aims to gain insights into the ways the designers manipulate constraints in the digital design process. It investigated whether the same type of buildings, designed by the same or different architects, presents different approaches to deal with the same constraint. Scenarios of handling a constraint using shaping and validation processes were identified before initial modelling, through modelling, and after modelling. Constraints can effectively participate in design formation by proposing a new shape or a typical shape at pre-modelling. They are refining or developing the initial design through modelling, and optimizing or enhancing the design after modelling. Furthermore, constraints play significant roles in the feasibility study of design solutions. This is done by evaluating the initial forms and selecting the fittest through modelling, in addition to testing and filtering the solution space after modelling, and approving the final design. The paper examined the impact of wind on the morphology of twelve contemporary tower designs. The findings support the opinion that constraints may not restrict the designer's free will, inspiration, and creativity. They revealed that different scenarios of wind-driven processes had implemented at different design stages even by the same designer. The wind constraint had a substantial impact on the derivation of new morphologies. Through modelling, it had an active role in the refinement of the initial architectural and structural design. Constraint-based design was handled in iterative processes of evaluating and developing or refining the initial forms through modelling; and optimizing or enhancing, testing, and approving the final forms after modelling.

1. INTRODUCTION

In the last decades, constraint processing techniques and tools have been widely applied to validate the features in a variety of architectural design domains, especially environmental and structural design. In architectural design practice, constraints can be defined as conditions or limitations result largely from required or preferred relationships between various elements of a design [1]. They are mostly considered as limiting factors in spite of the fact that constraints can drive and trigger innovative designs in a solution space [2].

Engineering design problem is considered as constraint satisfaction process in which the design must satisfy conditions imposed by a set of constraints. On the contrary, the architectural design problem is almost ill-defined making it difficult to deal with a conception of constraints. Therefore, two approaches of constraint based design formation can be inferred from previous studies. The deterministic constraint-based design process proposes that constraints should be met and play an important role in the design formation process. On the other hand, other opinion considered that constraints control the design output in a non-deterministic way. In this case, constraints do not suggest a specific solution but they represent a set of design conditions such as: cultural, aesthetic, programmatic, functional, etc., that guide the selection of successful design solutions. This paper investigated the different roles the constraint can play in the derivation of formal properties of a design.

Lawson referred to both deterministic and non-deterministic roles of constraint in the design process. He classified design problems as internal and external constraints. The internal constraints are the basis of the design problem and comprise the majority of the design brief. The external constraints are ranging from "standards and codes of practice to guidelines and recommendations". In some cases, the external constraints such as "the site, location, or the specific context" are factors that virtually influence the whole form of design by emphasizing its individuality [1].

Row identified two types of constraints within the procedural approach of design thinking. They are "problem-oriented constraints" and "autonomous constraints". The former is deterministic and primarily derived from a previously defined problem. It results from "means-ends analysis" in which the means are outlined in terms of particular ends. The latter, on the other hand, is non-deterministic and independently provided by a designer to reformulate and organize a problem space in a different light [3]. Oxman presents similar opinion. She classified constraints into "external given constraints" and "internal derived constraints". The former is explicitly defined in the problem statement such as the environmental constraints. The latter is implicit, based on domain knowledge, "usually propagated by other constraints which emerge during the process", to maintain the design consistency [4].

In addition, non-deterministic constraint can be subject to refinement and adaptation. Oxman considered that to satisfy all constraints, the adaptation process of design allows both design constraints and design components to be modified in a cyclic process [4]. Gross defined a design problem as a collection of constraints on attributes of the product to be designed. He considered a design requires describing and identifying constraints and specifying an object to satisfy them. In this case, the design is a process of successive refinement, proceeding in two integrated phases, the exploration of alternative sets of constraints, and the examination of alternative design solutions within each set of constraints. The designer selects building elements and positions them to meet design constraints. He adds to the constraints and changes them to explore alternatives by setting the values of design variables or fixing them [5].

In recent years, the influence of constraints on the derivation of design is growing steadily with the progress in software technology. The rapid development in CAD tools has facilitated the handling and processing of design constraints. Many constraint-based simulation tools have been developed to support the architectural designer in formulating and satisfying large sets of environmental, structural and functional constraints. The linking of design tools to simulation and analysis tools has produced designs that respond to performance criteria. Digital generative design systems have incorporated constraints in the form of parameters, mathematic formulas or algorithms to generate a solution space within specific design goals. Niemeijer et al. classified two methods of implementing constraints in the digital design process: constraint solving and constraint checking. In the first, constraints are inputs to generate all valid alternative design solutions that satisfy them. In the second, the role of constraint method is checking. After generating a design, it is examined to verify its compliance with constraints, and to adjust it if required [6]. Wang et al. considered that the use of a simple generative model with few constraints results in a large search space of design solutions. Therefore, different constraint handling strategies are required based on explicit or implicit rules to control and reduce the size of the search space by eliminating the infeasible solutions. In this case, embedding more constraints in the generative model improves the rationality of the generated solutions and avoid impractical designs from being generated [7].

Many previous studies adopted digital constraint-based design approach to solve specific optimization problems. For examples, a constraint-based model was implemented for the optimization of building evacuation time including space constraints and design constraints to find the optimal positions of door to minimize the distance of evacuation [8]. Also, natural lighting optimization was conducted to find the courtyard design that maximizes the floor area of indoor daylight and minimizes the courtyard floor area [9].

In addition, constraints played a significant role as determinants of formal design solutions. Many design tools can assist the generation of a constraint-based geometry and restrict the geometrical transformations to assist the application of some design decisions. Bollmann & Bonfiglio applied design constraint systems (DCS) as an experimentation tool with complex form. This tool included the generative description of existing architectural types and styles, in addition to the experimentation with new ones. It consisted of two components: a constraint system defining the essential rules of the architectural style and a formal language for describing and generating 2D or 3D shapes. In addition, DCS incorporated a search strategy of design spaces for good solutions [10].

Based on the mentioned studies, constraint-based design is the use of influence to guide the derivation process of design. Constraints can be deterministic or non-deterministic, adapted or non-adapted. In a digital design process, they are handled in both the generation and search processes of design solutions. The designer conducts formal experiments and exploration to satisfy a constraint. This paper seeks to identify when, where, and how a constraint can be applied as a design driver in the design process to guide the digital formation of a design solution. The contribution of this paper is twofold. Firstly, it presents a comprehensive framework for possible roles deterministic and non-deterministic constraints can play in the architectural design process. Secondly, it provides insight into how architects manipulate constraint during design formation of real projects. Built on previous literature, the study concluded different scenarios of constraint role in a design process. These scenarios were investigated in the design practice of twelve tall building projects to identify the effects of wind on their morphologies. The results showed that designers considered wind constraint at different stages of design using different processes of shaping and validation, which have contributed to formal and aesthetic diversity in tall buildings.

2. RESEARCH PROBLEM AND METHOD

This paper aims to investigate the impact of design constraints on the morphology of contemporary architecture. It questions whether the same type of buildings is subject to different methods of dealing with the same design constraint. Also, does a designer apply different processes to meet the same constraint for the same type of buildings? To answer the research questions, the paper presented a framework for different scenarios of dealing with a design constraint as a form driver in different stages of a digital design process. Then, the scenarios of handling a constraint as a design driver were investigated in the practice of contemporary tower designs.

3. SCENARIOS OF HANDLING CONSTRAINTS IN DESIGN FORMATION

The architect must comprehend the constraints that influence design to be able to make valid decisions in responding to them. Constraints on the architectural design are imposed by a variety of sources such as designers, clients, users, or legislators. It can be dictated by functional, formal, environmental, structural, safety requirements, project resources such as site restrictions, available budget and time, etc. [1].

This paper basically aims to conceptualize the notion of constraint based design formation. It seeks to gain insight into the roles of constraint in the design process while evolving from concept initiation to design completion. Various scenarios of design formation based on constraints are identified from architectural theory and practice. These scenarios can be classified into constraint-based shaping processes of design and constraint-based validation processes of design.

3.1 Constraint-based shaping processes of design

Constraints play a significant role in directing the generation process of design solutions. Constraints can be managed during design initiation and development until completing and finalizing the design. During the generation process, a designer would take the same constraint into consideration once or more than once in different stages of a design process. Three scenarios of constraint-based design modelling can be distinguished depending on the timing of constraint application. They are:

- The initial handling of constraints (before modelling).
- The early handling of constraints (through modelling).
- The late handling of constraints (after modelling).

In the first scenario (before modelling), handling the constraints imposed by the definition of design problem is regarded as a first step to finding possible solutions. Here, constraints are specified and predefined in the description of problem statement to drive the solving process. In the early stage of design process, some of the geometrical decisions are decided in response to design constraints known at the outset. Constraint schemata are inputs that precede formal decisions and guide the initial design concepts. Designers depend on prior knowledge, experience and design expectations to usual and standard solutions within the design community. The constraints concern the investigation of possible configurations built on the designer's knowledge and experience. They exist in the design brief to participate in the initial form generation such as architects dealing with the primary function of design by drawing bubble diagrams and flow charts to represent the required decisions [1, 4].

The shaping strategies responding to constraints at the outset can be intuitive decision-making that draws on designers' past experience with related problems which suggest either new formal characteristics to the object being designed or typical formal characteristics.

In the second scenario (through modelling), at the early stage of the design process, the design emerges through a series of form explorations and experiments. Morphological analysis aims to identify the design parameters affecting the constraint and to find the possible range for each parameter. In this case, the designer can examine different configurations to study the effects of different properties on constraint. In addition, subsequent constraints can be recognized or readdressed throughout the design process. New constraints may be added at any time along the initial modelling to drive the design process. These constraints follow formal decisions to improve design performance. They may introduce new decisions to narrow or widen the range of possible design alternatives. For example, the variables of rigid constraints, such as gravity, have particular values to control the generation of design solutions; while flexible constraints are generative mechanisms having unspecified values and can be changed such as stylistic conventions [5]. Therefore, flexible constraints could support the emergence of a variety of design solutions and may trigger novel solutions [2, 11].

Constraints, at this stage, may restrict geometric and dimensional features and may establish new ones. Constraint-based manipulation of initial design schema through sequences of re-representations can result in unexpected designs wherein the new shape can emerge from the parametric variations of existing one [4]. The designer examines the design variables of each constraint to suggest additions or changes to the initial design model. Each iteration of successive modifications generates new design variables. Then, the cyclic process is repeated until an acceptable alternative is met. According to that, in this scenario, the designers' actions to satisfy constraints are either the development of design by undergoing major changes in the formal characteristics of the initial model, or the refinement of design by making minor changes in the formal characteristics of the initial model.

In the third scenario (after modelling), constraints can be handled in the later stages of design process. They are added, readdressed, or even prompted in response to subsequent developments to increase the design efficiency. Control mechanisms such as parametric modelling or custom programmed scripts are developed to drive the geometrical model in response to design constraints. Parametric modelling is a strategy to analyze a design into parts using constraints to define the associative relations among these parts, and to generate design alternatives to be explored. Thus, the use of an appropriate parametric modelling is critical for the process of design optimization [9]. These mechanisms allow dramatic shifts through the exploration of the design solution space. The designer receives feedback via dynamic reporting including analysis, evaluation and generating comparative options. The shaping strategies responding to constraints in the third scenario are rational decision-making associated with performance simulation. Their actions are either optimizing the design model by making changes to maximize its efficiency to meet the constraints or only enhancing the model by making changes to improve its efficiency to meet the constraints.

3.2 Constraint-based validation processes of design

Constraints play a significant role in the process of exploring varied design space. The role of constraint here is to reduce the solution space dramatically. The validation processes aim to decide which of the possible designs can be implemented. The design evolves starting with open-ended exploration and progressing towards a definition of a specific geometry. There are two scenarios of validation driven by constraints depending on when the designers would take constraints into consideration. They are:

- The early exploration based on constraints (through modelling).
- The late exploration based on constraints (after modelling).

In the early stage of design modelling, a constraint-based search process starts with an empty design space and adds solutions to it based on matching constraint criteria. The size of the generated constrained solution space varies according to the degree of flexibility of constraints. Rigid constraints (deterministic) can help to focus the design exploration while flexible constraints (non-deterministic) facilitate the exploration of a significant search space [11]. The flexible constraints "gives the designer the ability to provide personal inputs at each step of the exploration process and to redirect the process any time and to any desired direction" [12]. Therefore, criteria based on constraints are used to narrow the range of possible alternatives. Evaluation of the design solution space is the process of making judgments based on criteria and evidence including analysis and making comparative assessments.

According to that, adopting constraints in the exploration of design solutions (through modelling) seeks to guide the search of a solution space as the evaluation criteria of alternative designs, and the selection criteria of a design solution.

Exploration based on constraints following the generation of initial models (after modelling) seeks to test the design space, to filter it, and to approve the final model. In this stage, testing a design model measures the level of constraint satisfaction that has been reached. Filtering takes the results of testing a design solution space (full space of initial models) and eliminates the designs based on constraint criteria that don't match. The filter of potential alternatives includes ranking each design based on a set of scoring criteria of target constraints that the design tries to satisfy. For example, scoring criteria for optimizing indoor day lighting in a courtyard space of low-rise building are both the amount of natural lighting penetrated to the lower floors and the areas of shading on the courtyard facades [9].

The different scenarios of dealing with constraints during the design process are clarified in Table 1.

Table 1. Scenarios of Handling Constraints During the Design Process

	Before modelling	Through modelling	After modelling
Shaping processes	Proposing a new shape Proposing a typical shape	Developing the initial model Refining the initial model	Optimizing the model Enhancing the model
Validation Processes		Evaluating the initial model Selecting the initial model	Testing the model(s) Filtering the models Approving the model

3.3 Constraint-based design process

Depending on the type of constraint, its effect on design formation can be limited to one stage of design only (before modelling, through modelling or after modelling) or continue to more than one stage. There is a cyclical process of design adaptation and change to satisfy a constraint. The constraint identifies design properties that should be modified and guide the transformation process. Through modelling, after the evaluation of initial model(s) and selecting the best solution, this initial solution can be subject to further development or refinement to improve its performance. In addition, other cyclic process can be found after testing or filtering the models. The design model may be subject to iterative processes of optimization or enhancement, testing and filtering until it is approved. Figure 1 shows the workflow of design process based on constraint.

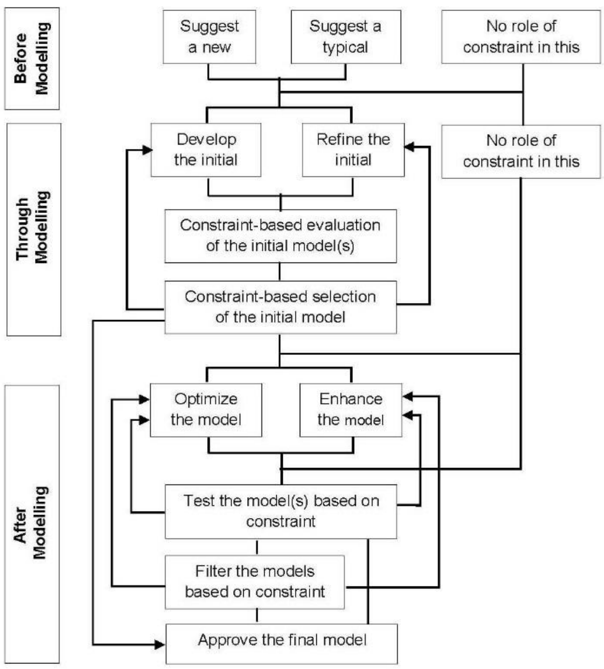

Figure 1. Workflow of digital design process based on constraint handling

4. CONSTRAINT-BASED PRACTICE OF TOWER DESIGNS

The paper seeks to investigate how architectural designers managed a constrain during a design process and to answer the following research questions:

- Does the same type of buildings present the same or different scenarios of handling a constraint? and,
- Does a designer implement the same constraint handling scenarios for the same type of buildings?

The effects of wind constraint, as a design driver, on the configuration of high rise building were examined in case studies of contemporary tower designs. The reason for choosing tower designs as case studies is that the iconic forms of tall buildings are driven by the interaction of constraints related to aesthetics, structural engineering, and environmental performance. The recent projects of tower designs have incorporated digital simulation techniques to assess how variations in the geometry of tall buildings would affect its environmental and structural performance such as “twisted, rotated, tilted, irregular, ambiguous, dynamic or plastic forms". These forms are not driven by accidental and subjective forces, but rather they are “rational parameterized controls based on environmental data” [13].

In addition, wind is the greatest challenge in the design of tall buildings. The aerodynamic design the building shape is a strategy to tackle the problem of vibrating structure. It results from vortex shedding (wind force against the tower) by preventing the concentrated vortices from forming or at least weakening them. Examples of shaping strategies are softened corners, tapering and setbacks, varying cross-section shape, spoilers, and porosity or openings (Figure 2) [14]. The designers rely on the simulation of physical wind tunnel using quantitative environmental factors. They control building morphology by enabling “continuous and real-time physical changes”. This technique converts the environmental performance data into geometric parameters that control the generation of building morphology based on optimized environmental performance [13].

Based on the above, an investigation of twelve contemporary iconic tower designs (Figure 3) was conducted to track formal design decisions guided by wind constraint and to determine the scenarios of controlling a wind in the formation of these buildings. The criteria for choosing case studies were:

- They are contemporary projects.
- Most of the descriptions of design processes are authored by the design teams.
- The wind was a factor in the design process.

There are three projects designed by Adrian Smith + Gordon Gill Architecture and five projects designed by Skidmore, Owings & Merrill LLP (SOM) to realize if the design team uses the same scenarios of handling a wind in these projects or not.

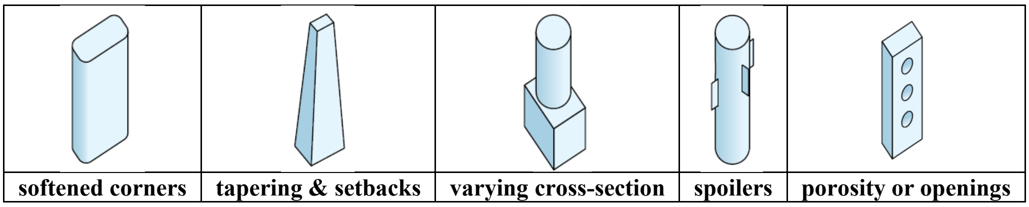

Figure 2. Typical shaping strategies for reducing the effect of wind [14]

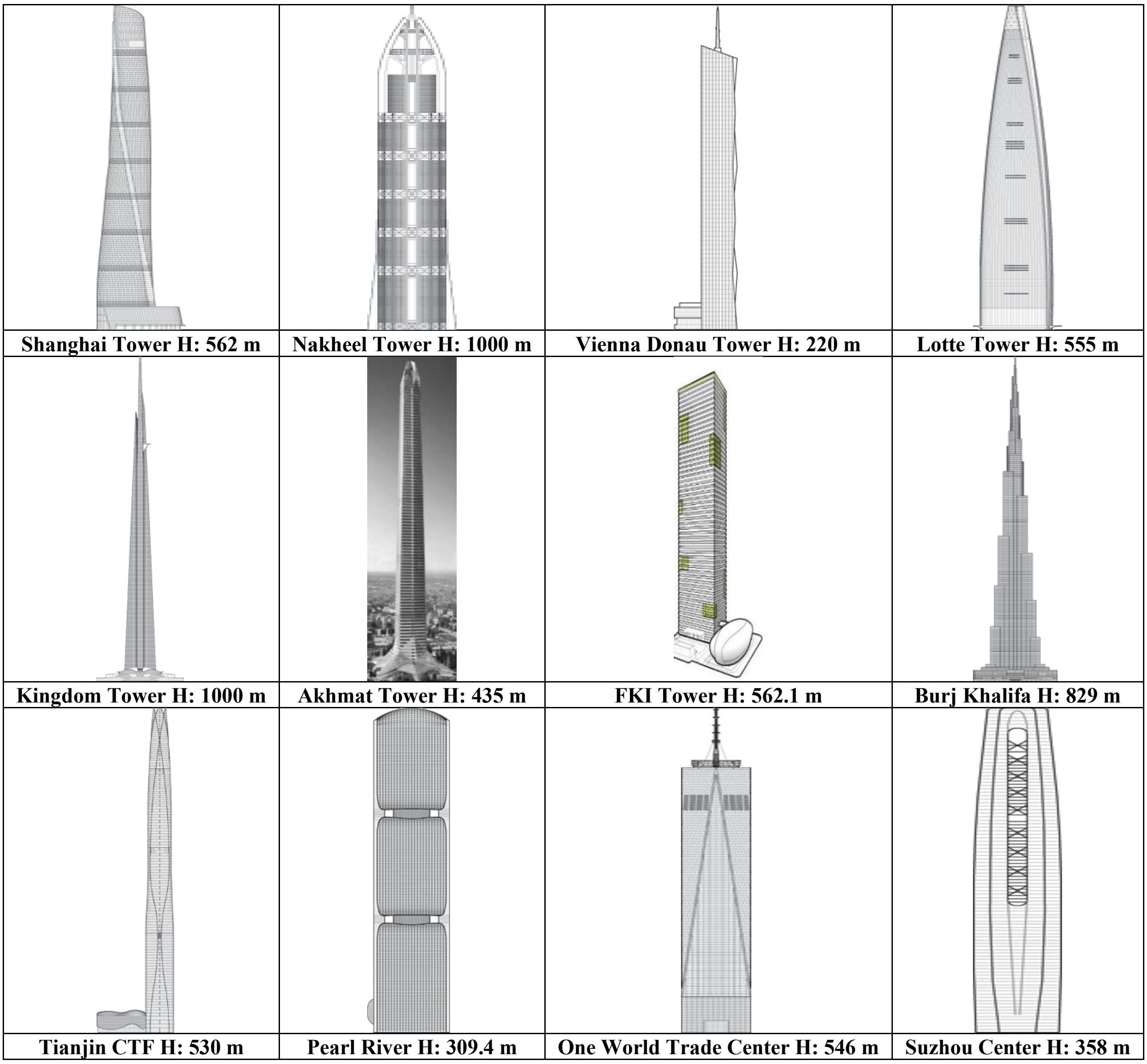

Figure 3. Case studies (from: https://www.skyscrapercenter.com/)

5. SCENARIOS OF HANDLING THE CONSTRAINT OF WIND IN TOWER DESIGNS

The investigation of twelve case studies was summarized in the following paragraphs.

5.1 Scenarios of handling the wind constraint in the formation of Shanghai Tower

Shanghai Tower in China, designed by Gensler, is a triangular column that tapers and twists as it rises. The scenarios of handling wind can be identified as follows:

Before modelling: Both new and typical design principles were implemented to reduce wind loads common to shanghai. The new concept is the asymmetry of the tower's facade resulted from "a unique spiraling exterior facade", while the typical principles are "its tapering shape and consistently rounded corners" [15].

After modelling: The initial models were explored by Wind Tunnel Test to find out the best alternative design to withstand typhoon wind loads common to Shanghai. The percentage of tapering, the angle of twisting and the curved corners of the triangle plan were optimized to minimize wind loads such as the angle (A) [16], the percentage of tapering, and the angle of a twisting [17] (Figure 4).

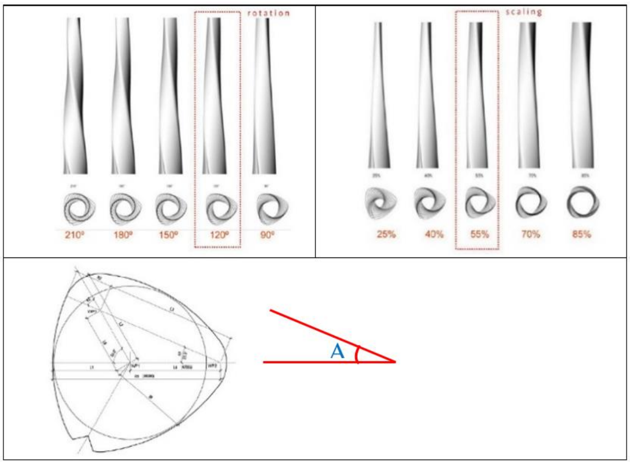

Figure 4. A study to determine the optimum shape of Shanghai tower [18]

The results showed that the best geometry is tapered 55% and twisted 120° that reduces 24% in wind loads on the structure in comparison to a tapered rectangular tower with the same height. In addition, efficient structure and material were defined to reduce the wind load of the asymmetrical tapered tower [16, 17].

5.2 Scenarios of handling the wind constraint in the formation of Nakheel Tower

Nakheel Tower in Dubai (UAE), designed by Woods Bagot, is a symmetric cylindrical form with a central void creating large vertical slots through the tower. The Wind effects on the morphology of tower can be summarized as follows:

Before modelling: The design team implemented new design principles driven by wind. Contrary to typical tall buildings, Nakheel Tower does not taper as it gets taller. The constant cylindrical form of the tower was subject to vortex shedding, therefore the design team allowed the wind to pass throughout the center of the tower, rather than around it. This is achieved by incorporating two vertical slots through the height of the tower which effectively creates four separate quadrants (Figure 5) linked together by three sky bridges [19, 20].

Through modelling: In this stage, initial indicators to the building's response to wind such as computational fluid dynamic (CFD) and dozens of high frequency force balance (HFFB) experiments were applied to study many small variations in the geometry of tower [19, 20].

After modelling: The design team confirmed that slight changes in the geometry of slot or the internal void had an impact on the aerodynamic behavior. Many tests were conducted such as "Aeroelastic model testing, high frequency pressure integration studies, and large-scale tests at high Reynolds Number (Re)" to optimize the model of the tower [19, 20].

Figure 5. Two vertical slots of Nakheel Tower [19]

5.3 Scenarios of handling the wind constraint in the formation of Vienna Donau City Tower

The Vienna Donau City Tower, in Vienna, Austria, designed by the architect Dominique Perrault, is a unique shape with slenderness and folded facade. The influences of wind on the final design are summarized as follows:

Through modelling: During the schematic phase of design, wind tunnel experiments were conducted to identify the best lateral and structural systems performance against wind forces. Alternative structural systems were investigated such as: "a core wall system, an outrigger-based system with the core wall, a megastructure truss system at both short facades, additional shear walls, and combination of each variation". The feasibility study found that the high efficient structural design is the outrigger system [21].

After modelling: Further studies were conducted to reduce the tower vibration along the longitudinal axis [22]. "A Tuned Mass Damper" was applied to offer the safety and comfort by reducing wind loads [21].

5.4 Scenarios of handling the wind constraint in the formation of Lotte World Tower

The Lotte World Tower, Seoul, South Korea, designed by Kohn Pedersen Fox Associates, is an elegant, tapered shape transforming gradually from a square at the bottom to a circle at the top [23]. The building was designed to resist strong winds. The effects of wind on the tower's morphology can be summarized as follows:

Before modelling: Lotte Tower's tapered geometry enhances its stability against instantaneous wind force. The design draft of the tower was a tapered column, "with square cross section, whose edges are rounded" to prevent the wind vortex shedding [24].

Through modelling: The CFD simulation was conducted to analyze how the building shape was affected accurately by wind conditions [24]. In addition, wind tunnel experiments were performed to ensure that the tower structure and cladding could resist wind loads [25].

After modelling: The effect of wind noise and disturbance was investigated by the engineering team. They examined different features such as the fins on the facade, the canopy, and the crown [25].

5.5 Scenarios of handling the wind constraint in the formation of Kingdom Tower

Kingdom Tower, in Jeddah, Saudi Arabia, designed by Adrian Smith + Gordon Gill Architecture is an asymmetrical, Y-shaped plan with the sloping exterior. The wind effects on the formation of the tower can be summarized as follows:

Before modelling: The wind constraint informed and guided the design concept that shaped the Tower. The choice of typical aerodynamic morphology such as the triangular shape and the sloping exterior was aimed to reduce the wind load. In addition, a new concept of three asymmetrical converging petals was implemented to make the tower stable against winds [26, 27].

Through modelling: During preliminary design analysis, the model of the tower was examined in a wind tunnel. The tower cross-sectional sizes and orientation was refined and adjusted to mitigate the wind (as a rigid constraint) in the critical locations at the pedestrian level [26].

After modelling: The effect of wind on the stability of the structure was studied to calculate the structural wind-loads and to predict the wind caused motions on the building and their effect on the occupants' level of comfort. These analyses of wind helped to minimize the wind loading and motion, and to specify the exterior cladding type suitable for wind conditions [27].

5.6 Scenarios of handling the wind constraint in the formation of Akhmat Tower

Akhmat Tower in Grozny, Chechen Republic, Russia, designed by Adrian Smith + Gordon Gill Architecture, is a crystalline-shaped tower with four-sided pyramidal geometry. Its design was inspired by the Nakh tower, a traditional watchtower type. The influences of wind on the final design can be summarized as follows:

Through modelling: "An initial force-balance test" of the initial model revealed that "a square-shaped plan with a flat top and sharp, square corners is not an ideal wind performance profile for a supertall tower", therefore design refinements were conducted to improve the wind performance. In addition, the shaping strategies of the top of the tower and the bottom of the building were influenced by wind tunnel data [28, 29].

After modelling: Three techniques of wind tunnel testing were applied to assess the tower responses to wind loads. They are "High Frequency Force Balance, High Frequency Pressure Integration, and an Aeroelastic test" [28]. The final design optimization included chamfered corners, sculpted and crystalline top, and shaping the flared base and canopies of the building. Also, the optimization made the structural members more efficient, reducing wind loads on the building [29].

5.7 Scenarios of handling the wind constraint in the formation of FKI Tower

FKI Tower, Seoul, South Korea, designed by Adrian Smith + Gordon Gill Architecture, is a rectangular-shaped tower. The exterior wall is innovative, high-performance photovoltaic panels designed for onsite energy generation. The influences of wind on the design derivation can be summarized as follows:

Through modelling: The tower vibration that the occupants may experience was studied. To resist the wind force, the design team considered that both weight and stiffness are required, therefore " a reinforced concrete core" was chosen. Also, the ratio of the slenderness core (the height to width is 20:1) was decided to reduce the wind draft [30].

5.8 Scenarios of handling the wind constraint in the formation of Burj Khalifa Tower

Burj Khalifa, in Dubai, UAE, designed by Skidmore, Owings & Merrill LLP (SOM), is a spiraling pattern using setbacks. The effects of wind on the configuration of tower can be summarized as follows:

Before modelling: The effects of wind on the morphology of tower was considered earlier in the design concept such as: the use of "Y' shape plan to minimize the influence of wind on the tower, tapering and stepping the mass to "confuse the wind" over the tower height, and varying the building shape at each tier to prevent the formation of wind vortices [31].

Through modelling: The geometry of the tower was evolved through several rounds of wind tunnel simulation. In each round, the tower was reshaped to reduce the wind effects such as: the number of setbacks and their spacing, and the shape of wings [31].

After modelling: Wind tunnel tests were applied later to optimize both architectural and structural design such as " rigid-model force balance tests, a full multi degree of freedom aeroelastic model studies, measurement of localized pressure, pedestrian wind environment studies and wind climatic studies". The parametric studies on the detailed shape were carried out to investigate the influence of wind on varying mass distribution and stiffness. The data of wind tunnel test were linked to the dynamic properties of design to compute the dynamic response of tower and the distribution of wind force over the building [31].

5.9 Scenarios of handling the wind constraint in the formation of Tianjin CTF Finance Centre Tower

Tianjin CTF Finance Centre Tower, in Tianjin, China, designed by Skidmore, Owings & Merrill LLP (SOM), is square in plan with rounded corners and tapered vertical profile. The strategies that informed the design of the tower can be summarized as follows:

Before modelling: The design concept did not start with iconic shapes. Instead, controlling the wind forces in this design was targeted using typical shaping strategies. For example, tapering the vertical outline of the tower reduced the area of exposed surface to wind, and softening the sharp corners in plans using rounded corners reduced wind loads at the corners (Figure 6). In addition, "the stepped, core-in-core system" allowed the floor plan to be as small as possible, which diminished the wind sail area [32].

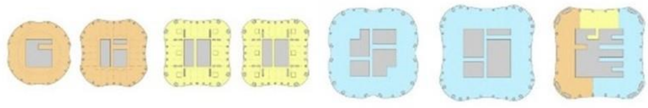

Figure 6. Rounded corners of stepped plans of Tianjin CTF tower [32]

After modelling: The design team developed many variations of the tower tapered massing and the convex and concave forms using an early wind tunnel testing. In addition, wind testing guided to further enhancements to the tower such as: “a scalloped building surface", a crown configuration, and a porous design of the tower’s apex which dramatically reduced wind acceleration. Also, the optimization of structural shape included enhancing the rate of slope change of the tower perimeter [32].

5.10 Scenarios of handling the wind constraint in the formation of Pearl River Tower

The Pearl River tower, in Guangzhou, China, designed by Skidmore, Owings & Merrill LLP (SOM), is a sleek, aerodynamic form. It was designed through a careful understanding of wind patterns around the site [33], as follows:

Before modelling: The most innovative feature of the tower is the integration of generating wind energy into the building design. The design team developed not only a detailed understanding of the wind action on the tower but also they had improved the aerodynamics of tower form “to maximize the energy-production capacity of the building-integrated wind turbines” (RWDI). Contrary to the rectangular based towers in which the narrowest facade faces the prevailing winds, the Pearl river tower is a rectangular based tower with a curved front facade and four openings that allow wind to pass through the core of the building. The openings called wind tunnels where turbines generate energy for the building were located [33-35].

Through modelling: To maximize the velocity of wind through the turbines, the design team applied “both wind tunnel testing and computational fluid dynamics (CFD) to test different sizes and locations for the openings, and to refine the building’s shape to direct and accelerate the wind through the openings [36].

After modelling: The tower’s curvilinear form was sculpted to optimize the pressure difference between the windward and leeward side of the building [37], and to enhances turbine performance by directing the wind through the openings [34].

5.11 Scenarios of handling the wind constraint in the formation of One World Trade Center Tower

The One World Trade Center, New York City, USA, designed by Skidmore, Owings & Merrill LLP (SOM), has a cubic base, chamfered edges forming eight isosceles triangles facades, and octagonal plan at the mid of the tower. The geometry of the building enhanced the tower performance against wind loading, as follows:

Before modelling: The tapering and rotating of form and structure aimed to deviate wind forces and reduce wind loads exposure [38].

Through modelling: Wind tunnel experiments were performed to measure the tower's response to wind with respect to human comfort. To resist a wind, the tower main spine was decided to be a "reinforced concrete core wall system". In addition, to improve the tower performance against lateral wind a "ductile perimeter moment frame system" was used [38].

After modelling: Further studies were conducted such as "High Frequency Force Balance and Aeroelastic tests" to measure the spire aeroelastic effects and the effect of wind on cladding system [38].

5.12 Scenarios of handling the wind constraint in the formation of Greenland Group Suzhou Tower

The Greenland Group Suzhou Center, Suzhou, in Wujiang, China, designed by Skidmore, Owings & Merrill LLP (SOM), is a dynamic, curvilinear tapering geometry. The influences of aerodynamic digital formation techniques on the tower form can be summarized as follows:

Before modelling: The elliptical shape of plan and the tapering section helped to reduce wind vortex shedding. In addition, the direction of prominent wind was one of the factors behind the design decisions to position the building at the east-west [39].

Through modelling: The initial design was subjected to wind tunnel experiment in the early phases of design to fine tune the building geometry. The convex and concave facades were shaped to increase the natural ventilation via windows at the eastern and western facades [39].

After modelling: The prevailing winds were utilized to support natural ventilation in the eastern and western elevations of the atrium. The CFD simulations of wind pressure were linked with hourly weather forecasting data to calculate the atrium's microclimate with controlled openings at the upper and lower levels of the atrium [39].

6. RESULTS

The results of wind-based design scenarios in case studies are summarized in Table 2. The finding showed that different scenarios were applied in case studies. In eight of twelve cases the wind constraint had a significant effect in deriving new morphologies. Through modelling, the wind in eight cases had an active role in the refinement of the initial architectural and structural design. In ten of twelve cases the wind constraint was one of the design criteria for the evaluation of the initial model. In seven of twelve cases the wind constraint was an influential factor in optimizing and enhancing the design performance. Lastly, in eleven of twelve cases, tower designs were tested against wind forces and the wind was one of the design approval criteria.

The comparison of cases designed by the same architectural office showed that different scenarios were applied to deal with wind in the design of high rise buildings.

In most cases, the design process of handling wind constraint was iterative processes through modelling and after modelling. The output of the evaluation was feedback into the modification or refinement of the initial design; and the output of the test simulation was feedback into the optimization or enhancement processes of the design.

Table 2. Results of wind handling scenarios in the design process of case studies

Scenarios of wind-based constraint in the derivation of tower morphology	Before modelling		Through modelling				After modelling				
	shaping processes		shaping processes		validation processes		shaping processes		validation processes		
	Proposing a new form	Proposing a typical form	Developing the initial form	Refining the initial form	Evaluating the initial form	Selecting the initial form	Optimizing the model	Enhancing the model	Testing the model(s)	Filtering the models	Approving the model
Shanghai Tower	●	●					●	●	●	●	●
Nakheel Tower	●			●	●		●	●	●		●
Vienna Donau			●		●	●			●		●
Lotte World Tower	●			●	●			●	●		●
Kingdom Tower	●	●		●	●		●		●		●
Akhmat Tower			●	●	●		●		●	●	●
FKI Tower				●	●	●					
Burj Khalifa Tower	●		●		●	●	●	●	●	●	●
Tianjin Tower		●					●	●	●	●	●
Pearl River Tower	●		●	●	●		●		●		●
One World Trade Tower	●			●	●			●	●		●
Suzhou Center Tower	●			●	●			●	●		●

7. CONCLUSIONS

The paper focuses on the use of constraints as an approach in the architectural design process. In digital generative design, constraints play significant roles in the generation and exploration of design solution space. The paper classified design scenarios driven by constraints into shaping processes and validation processes through different stages of design process. Design concept driven by constraints can be the starting point of morphological generation. In the pre-modelling phase, constraints can shape the physical attributes of a design by suggesting a new form or a typical form. Both through modelling and after modelling, there is an iterative process between shaping and validation processes. Shaping processes applied through modelling develop or refine the initial design in response to constraints. The validation processes applied through modelling seek to satisfy a constraint by evaluating initial designs in the solution space, and selecting one of the initial design solutions. On the other hand, shaping processes applied after modelling aim to optimize or enhance a design model to meet constraints. The validation processes applied after modelling aim to test a design model, filter design models in the solution space, and approve the design model compliance with a constraint.

In architectural design, the word constraint may indicate an unpleasant restriction on the designer's free will, inspiration, and creativity. Also, it is often believed that environmental constraints are more effective in the later stages of the design process. However, the case studies revealed that imposing a wind constraint upon design solutions has effectively contributed in driving innovative formal decisions. In fact, the wind was the motivation to bring new ideas in eight cases. In addition, applying the same constraint to the same building type revealed different wind-based scenarios among the case studies. Lastly, the design team applied different scenarios in dealing with the same constraint to the same building type.

For future research, the scenarios of formation driven by constraints can be investigated in other building types and for other constraints. Also, the effects of multi constraints on the design formation can be investigated in tower designs or other building types.

REFERENCES

[1] Lawson, B. (2005). How designers think - the design process demystified. Architectural Press, Oxford, pp. 336-336. https://doi.org/10.4324/9780080454979

[2] Kilian, A. (2006). Design innovation through constraint modeling. International Journal of Architectural Computing, 4(1): 87-105. https://doi.org/10.1260/147807706777008993

[3] Rowe, P.G. (1990). Design Thinking. (Third edition). MIT Press, Cambridge, Massachusetts.

[4] Oxman, R. (1997). Design by re-representation: A model of visual reasoning in design. Design Studies, 18: 329-347. http://dx.doi.org/10.1016/S0142-694X(97)00005-7

[5] Gross, M.D. (1986) Design as exploring constraints. PhD thesis, Massachusetts Institute of Technology, Cambridge.

[6] Niemeijer, R.A., De Vries, B., Beetz, J. (2010). Designing with constraints-Towards mass customization in the housing industry. In 10th International Conference on Design & Decision Support Systems.

[7] Wang, L., Janssen, P., Ji, G. (2018). Efficiency versus effectiveness-A study on constraint handling for architectural evolutionary design. Paper presented at the Learning, Adapting and Prototyping - Proceedings of the 23rd CAADRIA Conference, Tsinghua University, Beijing, China.

[8] Gao, H., Medjdoub, B., Luo, H., Zhong, H., Zhong, B., and Sheng, D. (2020). Building evacuation time optimization using constraint-based design approach. Sustainable Cities and Society, 52(101839): 37-63. http://dx.doi.org/10.1016/j.scs.2019.101839

[9] Wang, L., Janssen, P., Ji, G. (2019). Progressive modelling for parametric design optimization - An example of how parametric design optimization can

support reflection. Paper presented at the Intelligent & Informed - Proceedings of the 24rd CAADRIA Conference, Victoria University of Wellington, Wellington, New Zealand, pp. 383-392.

[10] Bollmann, D., Bonfiglio, A. (2013). Design constraint systems - A generative approach to architecture. International Journal of Architectural Computing, 11(1): 37-63. http://dx.doi.org/10.1260/1478-0771.11.1.37

[11] Caldas, L., Norford, L. (2001). Architectural constraints in a generative design system: Interpreting energy consumption levels. In Seventh international IBPSA conference, pp. 1397-1404.

[12] Fivet, C., Zastavni, D. (2014). Interactive shaping of forces. Paper presented at the ACADIA 14: Design Agency, pp. 347-356.

[13] Yao, J.W., Lin, Y.Q., Zheng, J.Y., Yuan, P.F.A (2018). A "dynamic form-finding" approach to environmental-performance building design. International Journal of High-Rise Buildings (IJHRB), 7(2): 145-151. https://doi.org/10.21022/IJHRB.2018.7.2.145

[14] Irwin, P. (2013). Designing for wind. In: Parker, D. & Wood, A. (eds.). The Tall Buildings - Reference Book, pp. 249-260.

[15] Xia, J., Poon, D., Mass, D. (2010). Case Study: Shanghai Tower. CTBUH Journal, 2: 12-19. https://global.ctbuh.org/resources/papers/download/12-case-study-shanghai-tower.pdf.

[16] Xia, J., Peng, M. (2012). The parametric design of Shanghai Tower's form and façade. In Proceedings of the CTBUH 2012 9th World Congress, Shanghai, China, pp. 19-21. https://global.ctbuh.org/resources/papers/download/1006-the-parametric-design-of-shanghai-towers-form-and-facade.pdf.

[17] Lau, G.L. (2015). Sustainable high-rise construction in shanghai case study–shanghai tower. Doctoral dissertation, Thesis to obtain the Master of Science Degree in Civil Engineering, Tecnico Lisboa.

[18] Arch2O (2015). Case Study: BIM implementation in Shanghai Tower. https://www.arch2o.com/case-study-bim-shanghai-tower/, accessed on 27/7/2021.

[19] Mitcheson-Low, M., Rahimian, A., O'Brian, D. (2009). Case study: Nakheel Tower-the vertical city. CTBUH Journal, 2: 16-24. https://coast.nd.edu/jjwteach/www/www/2011_spring_flyers/Nakheel%20Tall%20tower.pdf.

[20] Rahiman, A., Moazami, K., Sullivan, B. (2010). Nakheel super tall tower. STRUCTURE Magazine, pp. 30-33.

[21] Bollinger, K., Grohmann, M., Berger, A. (2015). The Vienna Donau City Tower-2000mm Flat Slabs as Outrigger Structure for Unique Landmark Building. In Proceedings of the CTBUH 2015 International Conference «Global Interchanges: Resurgence of the Skyscraper City», pp. 540-547.

[22] Maurer, A. G. (2015). Semi-active dampers respond to various load. Online report. https://www.maurer.eu/fileadmin/mediapool/03_news/downloads/PR_Donau_City_Tower_engl_0715.pdf, accessed on 8/5/2021.

[23] Park, K., Holt, N. (2010). Parametric design process of a complex building in practice using programmed code as master model. International Journal of Architectural Computing, 8(3): 359-376. http://dx.doi.org/10.1260/1478-0771.8.3.359

[24] Kim, H.G., Jeon, W.H., Kim, D.H. (2016). Wind resource assessment for high-rise BIWT using RS-NWP-CFD. Remote Sensing, 8(12): 1019. http://dx.doi.org/10.3390/rs8121019

[25] Klemperer, J.V. (2018). Lotte world tower: Seoui's first supertall. CTBUH Journal, (1): 12-19.

[26] Weismantle, P., Stochetti, A.H. (2013). Kingdom tower, Jeddah: Meeting the challenges of a One-KILOMETER tower. CTBUH Journal, (1): 12-19.

[27] CW-Staff. (2011). RWDI Providing Wind Analysis on Kingdom Tower. Construction Week Online. https://www.constructionweekonline.com/article-14191-rwdi-providing-wind-analysis-on-kingdom-tower, accessed on 4/3/2021.

[28] Stochetti, A., Beardsley, S., Peronto, J., Cerone, M. (2018). Technical considerations of AKHMAT tower. CTBUH Journal.

[29] Beardsley, S., Stochetti, A., Cerone, M. (2018). The design of AKHMAT tower. In E3S Web of Conferences, 33: 01022. https://doi.org/10.1051/e3sconf/20183301022

[30] Peronto, J. (2017). The Ultra-Modern FKI tower. International Journal of High-Rise Buildings, 6(4): 315-322. https://doi.org/10.21022/IJHRB.2017.6.4.315

[31] Baker, W.F., Korista, D.S., Novak, L.C. (2008). Engineering the world's tallest–Burj Dubai. In Proceedings of CTBUH 8th World Congress "Tall & Green: Typology for A Sustainable Urban Future", Dubai, pp. 3-5.

[32] Lee, B., Baker, W., Rhee, I., Johnson, R. (2016). Next-generation supertall tower form determinants: A study of the Tianjin CTF Finance Centre. Cities to Megacities: Shaping Dense Vertical Urbanism (CTBUH), pp. 1256-1263.

[33] SOM. (2019). Reinventing the Skyscraper- The World's Eighth-Tallest Structure is Anything but Conventional. https://medium.com/@SOM/reinventing-the-skyscraper-5ed77dd266b1, accessed on 20/1/2021.

[34] SOM. (2021). Pearl River Tower – Sustainable Design. https://www.som.com/projects/pearl_river_tower__sustainable_design, accessed on 6/2/2021.

[35] Frechette, R., Gilchrist, R. (2008). Towards zero energy: A case study of the Pearl River Tower, Guangzhou, China. In CTBUH: Proceedings of the council on tall buildings and urban habitat's 8th world congress, pp. 7-16.

[36] RWDI. (2021). Pearl River. https://rwdi.com/en_ca/projects/pearl-river-tower, accessed on 7/5/2021.

[37] Tomlinson, R., Baker, W., Leung, L., Chien, S., Zhu, Y. (2014). Case study: Pearl river tower, Guangzhou. CTBUH Journal, Jun (II).

[38] Rahimian, A., Eilon, Y. (2015). The rise of one world trade center. Paper presented at the CTBHU - Global Interchanges: Resurgence of the Skyscaper City.

[39] Wimer, R., Baker, W., Nagis, M., Mazeika, A. (2012). Case study: Greenland's Suzhou center, Wujiang. CTBUH Journal, 2012(III): 12-19.