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By

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Abstract

Quality designs generally emerge from a conceptual design process that generates and communicates large design spaces of objectives, alternatives, impacts, and values. Parametric modeling is a popular means for generating large alternative spaces but it is difficult to use effectively when the other spaces are not well generated. We apply a framework for measuring design space clarity and quality to traditional non-parametric practice, and to two applications of parametric modeling, on high-rise projects. The framework reveals deficiencies in both the quality and clarity of the design spaces that building designers are able to construct using traditional and parametric methods. We describe a fourth industry case study illustrating the application of a formal methodology called Design Scenarios developed to address these shortcomings. The case studies illustrate the potential for significant impact that parametric modeling can have on the overall conceptual design process performance, particularly when supported by methodologies to better generate and communicate design spaces.

1 Introduction – the need for effective conceptual design processes

Last decade has witnessed increased awareness about the negative impact buildings have on the environment. In the U.S. over 70% of the electricity, 40% of raw materials, and 12% of water consumption is attributed to buildings [i]. The situation is not improving – the lifecycle performance of many new buildings is below that of older buildings and often below code requirements [ii]. While design costs (5-8%) are typically dwarfed by construction costs (60-80%) [iii], the biggest impact and opportunities for lifecycle performance improvement are with decisions made during conceptual design, when the building's orientation, massing, materials, components, and systems and their properties are proposed [iv].

Conceptual design processes generate and communicate *design spaces* of *objectives, alternatives, impacts,* and *values*. The process requires integration of knowledge and simultaneous satisfaction of many objectives [v]. Research shows that successful designs require an early understanding of such objectives and the ability to explore and analyze a large quantity of alternatives [vi]. However, design spaces quickly become unmanageable, testing the bounds of designer rationality [vii]. To make the design space more manageable, designers normally adopt a *scenario* – a collection of structures and behaviors that represent the design intent [viii]. Research identifies two primary search methods through a design space: *high breadth*, *low depth* (multiple scenarios with a broad spread of options but little analysis) and *high depth*, *low breadth* (few scenarios with a low spread of options but more comprehensive analysis) [ix, x]. Design theory indicates that ideally scenarios and alternatives within each scenario are generated and analyzed broadly and deeply.

In spite of this increased awareness about the impacts of buildings, the importance of conceptual design, and areas for improving the design process, current multidisciplinary design processes have not changed dramatically. In [xi], we determined that existing conceptual design processes are inefficient. We conducted case study observations and a benchmarking survey to determine the performance of leading design teams. We found that during a design process that generally lasts 5 weeks a multidisciplinary team averaging 12 people can normally produce small alternative spaces, in which on average 3 design alternatives are generated. Very little of their time is dedicated to establishing / understanding the objective, impact, and value spaces. The performed analyses are inconsistent and primarily governed by architectural rather than multi-stakeholder criteria (i.e., structural & energy efficiency), which may often lead to major and costly redesigns when results fail to satisfy such requirements [xii]. Decisions are made and changed frequently as specifications change and new ideas come forward, yet much of the decision making rationale is lost in the due process, or presented to the client as descriptive narratives, in which important inter-related topics are difficult to identify and comprehend [xiii]. These process deficiencies lead to design solutions with often poor initial cost and lifecycle performance.

Such methods as performance-based concurrent engineering [iii], Quality Function Deployment [xiv], or parametric modeling [xv], which emerged in aerospace and automotive industries, can help designers formally create and explore large design spaces. However, these methods are not used broadly in conceptual Architecture Engineering Construction (AEC) design. In part this is caused by a sequential process of decision making in multidisciplinary design teams and the limited ability of CAD experts to capture the designers' rationale, identify key design parameters, and communicate and manage the complex structure of parametric models. This makes the design process dependent on few experts and the expert knowledge hard to disseminate. To maximize the efficiency of the conceptual design process and improve the life-cycle performance of the resulting designs, our intuition is that AEC industry **needs** a significantly more structured and concurrent process of constructing and communicating:

(1) **Objective spaces –** capture, prioritize, communicate, and manage design requirements (constraints and goals);

(2) **Alternative spaces –** translate such requirements into geometrically flexible parametric CAD models used to generate design alternatives;

(3) **Impact spaces** – evaluate performance of alternatives against the project requirements and

(4) **Value spaces –** determine the value of alternatives to support improved decision making.

Our review of other research revealed many points of departure, but no integrated solution that sufficiently covered all four spaces [xvi]. Some methodologies, like Requirements Engineering [xvii] and MACDADI [xviii], communicate objective, impact, and value, spaces, but do not communicate alternative spaces sufficiently. Other methodologies, like parametric modeling, excel at generating alternative spaces, but fail to communicate these spaces and relate them to objectives and impacts. With Design Scenarios Gane and Haymaker [xvi] proposed to enable multi-stakeholder and multidisciplinary design teams to streamline the alternative generation and decision-making processes by providing a methodology for building and managing requirements driven design spaces with parametric tools. DS consists of four consecutively built interdependent models: (1) a *Requirements Model* that allows stakeholders and designers to explicitly define and prioritize context specific design requirements; (2) a *Scenarios Model* that helps designers formally transform these requirements into actions necessary to achieve them, and then into geometric and material parameters, interrelationships, and potential conflicts; (3) a *Parametric Process Model* that helps CAD experts communicate the structure of a parametric model for building requirements-driven alternative spaces and facilitate its technical implementation; and (4) an *Alternative Analysis Model* that helps designers to analyze impacts and visually report value back to the stakeholders.

To gauge the impact of such a process, the paper proposed a framework for measuring design space clarity and quality, which consists of the following metrics:

- **Objective Space Size –** what is the number of project goals and constraints considered?
- **Objective Space Clarity –** is the value function explicitly and broadly communicated? The clarity is determined through documented statements describing stakeholders, goals, constraints, and preferences.

- **Objective Space Quality –** are the project goals and constraints determined by all key stakeholders? A low quality denotes participation of <50% of stakeholders; medium quality: 50-80%; high quality: 80-100%.
- **Number of Scenarios –** what is the number of design scenarios considered?
- **Total Options Space Size –** what is the total number of options comprising a scenario? The total number is determined by multiplying the constrained range of values of input parameters (i.e., building length between 30m and 40m) and their reasonable increment (i.e., 1m for building length).
- **Generated Option Space Size –** what is the number of the generated design options for a scenario?
- **Options Space Quality** – the ratio of Total Options Space Size to Generated Options Space Size. A 1.0 ratio is ideal because it covers the complete Design Space for a given scenario.
- **Alternative Space Size –** what is the number of the generated design alternatives for a scenario?
- **Alternative Space Clarity** – are the design scenarios and the parameters describing these scenarios clear?
- **CAD Model Clarity –** is the structure of the CAD model communicated?
- **CAD Model Quality** – how many CAD models were generated for each design scenario? One CAD model is the target and denotes high quality and responsiveness. A new model is built when it cannot satisfy a requirement.
- **Impact Space Size –** what is the number of performed analyses used to determine the value of each alternative?
- **Impact Space Clarity –** is the process of performing each analysis explicitly depicted (i.e., repeatable)?
- **Impact Space Quality –** what is the ratio of Impact Space Size to Objective Space Size? A 1.0 ratio is ideal (i.e., for each requirement a formal analysis was performed).
- **Value Space Size –** what is the number of alternatives that have been analyzed and valued?

- **Value Space Clarity –** is the total value of each generated alternative explicitly defined?
- **Process Duration –** how long did the conceptual design process last? Designers favor shorter durations because it positively impacts the firm's profitability.

In the remainder of the paper we populate this framework with data sets collected from four case studies, summarized at the end in Table 8. In [xvi] we described and quantified traditional high-rise conceptual design processes in which no parametric modeling or methodology addressing the needs outlined in section 1 were used, and these case study and survey data are used to populate the first column in Table 8. In section 2 we describe two industry applications of parametric modeling on high-rise projects in which no formal methodology to address the above needs was used. The framework reveals deficiencies in both the quality and clarity of the design spaces that designers are able to construct. In section 3 we describe a final industry case study illustrating the application of a formal methodology called "Design Scenarios" developed to address these shortcomings. In section 4 we compare the four data sets to illustrate the potential for significant impact that parametric modeling, supported by methodologies to better generate and communicate design spaces, can have on the design space quality and clarity. We used the action research method [xix] on the three case studies designed by the same leading AE firm, in which the first author of this paper had the role of the parametric CAD expert.

2 Conceptual design process using parametric modeling with no formal implementation method

We now discuss two conceptual design process case studies, called Tower 1 and Tower 2, in which designers used parametric modeling in alternative generation and decision-making.

2.1 Tower 1 test case

Tower 1 is a residential high-rise currently being built in the Dubai Marina. The analysis in this paper is based on the conceptual design process only. Table 1 summarizes a selection of project facts and requirements that guided the design process. The primary stakeholder (client) and design stakeholders (architect and structural engineer proposed several qualitative and quantitative goals and constraints, although we retrospectively made the distinction among types of requirements. Actual target values for the identified requirements are not shown in compliance with the client's privacy request.

Table 1: Tower 1 project facts and requirements. No formal method to gather and prioritize requirements was implemented.

Project Facts	
Project Phase	Competition (Conceptual design), 2005, currently under construction
Project Type	Residential high-rise, 307m, 73 floors
Team size and composition	1 researcher (CAD expert), 1 senior architect, 1 project architect, 1 intern, 1 structural engineer
Software tools	CATIA V5R14, Rhinoceros, AutoCAD, 3D Studio Max, ETABS

Requirement Description	**Requirement type**	**Identified By**
Modern, symbolic architecture	Goal (qualitative)	Client (developer)
Minimize construction cost	Goal (quantitative)	
Gross area	Constraint (quantitative)	
Building efficiency	Constraint (quantitative)	
20m setback from adjacent site	Constraint (quantitative)	
Minimize heat load	Goal (quantitative)	Design stakeholders
Maximize views	Goal (quantitative)	
Use parametric CAD	Goal (procedural)	

The designers began the process by evaluating the client project brief, in which requirements without any distinction between goals and constraints were presented in narrative form and distributed among different sections of the brief. Next, designers clarified the objective space during informal meetings, in which the following goals were identified: need to address the local climate (*minimizing heat load*), site properties (*maximizing views*), and process efficiency in exploring multiple design alternatives (*using parametric CAD*). The choice to use parametric CAD was made in response to the client's objective to build a contemporary, unique building exemplifying the technological complexity of the 21st century (*modern, symbolic architecture*), but governed by simple rules that supported rationalization for effective construction and modularization for reducing costs. None of the requirements or the rationale used by designers to propose the requirements was explicitly captured.

Figure 1 illustrates the project site. The site's irregular shape and planning codes determined the building's irregular footprint, the *20m setback* constraint from the adjacent site, and the *gross area* constraint.

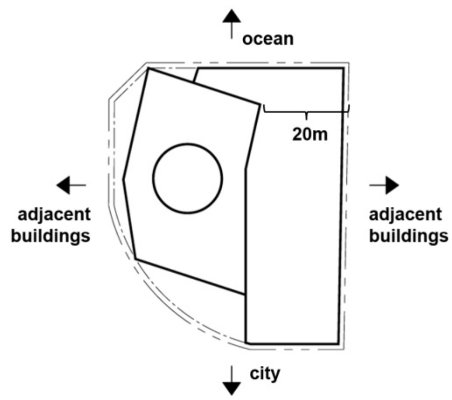


Figure 1: Tower 1 site configuration, initial tower/podium footprint, and the required 20m setback.

The architect then proposed a design scenario of a twisting tower because the narrow sides of the footprint faced the best views (i.e., ocean and city as opposed to adjacent buildings). The twisting scenario helped to address the *maximizing views* goal by exposing the wide sides in the tower's top third, where the most expensive units were located, to the best views. The CAD expert identified a set of key geometric parameters and relationships in the CAD model that could enable generating the scenario-specific range of geometric variations. For example, the architect anticipated needing to refine the building twist and footprint configuration, and identified such parameters as *tower rotation* ranging from 0 to 90 degrees, *angle* controlling the kink, and the *individual side lengths*. The CAD expert decomposed the model into components containing geometric elements, parameters, and constraints. The model decomposition was implemented in CAD and not explicitly visible to team members other than the CAD expert. Figure 2 illustrates the components and relationships of the parametric CAD model determined retrospectively. For example, the tower footprint with all the driving parameters and geometric constraints was assembled into a component and instantiated twice to enable the tower rotation (Figure 3a). The CAD expert only reassigned the parameter controlling the tower rotation to the middle and top footprints at the time these were instantiated. He made the top footprint rotation an input parameter and the middle footprint rotation an output parameter, with its value always being half of the top footprint rotation. The three footprints were used to create the tower envelope (Figure 3b).

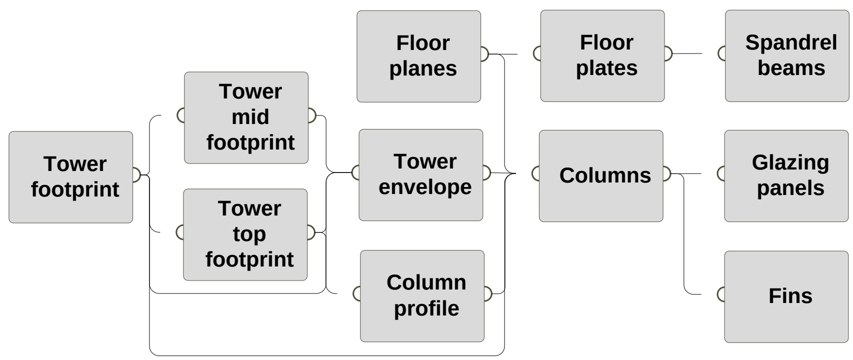


Figure 2: Components describing the high-level structure of the Tower 1 parametric CAD model.

To model the structure, the CAD expert converted a column profile controlled by global *length* and *width* input parameters into a component and instantiated it along the building footprint perimeter (Figure 3c). Next, he added two additional input and output parameters – the *number of columns* and *spacing* in between them, followed by floor planes controlled by the *number of floors* and *floor height* input parameters. He then extruded the column profiles to create 3D columns that depended on the tower envelope (used as a construction element) and the floor planes as extrusion limits (Figure 3d). He used a similar process to create the rest of the model's components (i.e., glazing panels, fins, floor plates, spandrel beams). The final model described a detailed, generic floor with the geometric flexibility required to generate and assemble the three floor types with unique heights – typical residential, penthouse, and mechanical (Figure 3e).

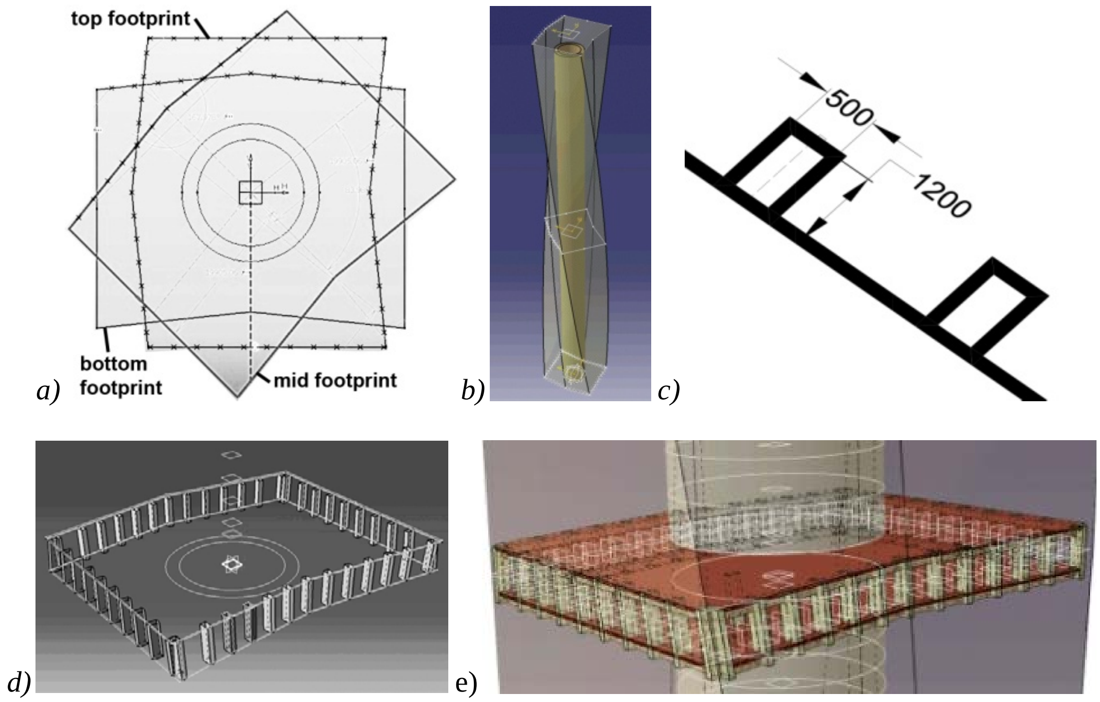


Figure 3: Tower 1 parametric model: a) the tower footprint (plan view) instantiated twice with input parameters controlling the tower rotation; b) tower envelope (perspective view) lofted from the three footprints; c) small section of the footprint with a column component and the driving parameters (perspective view); d) columns extruded along the footprint (perspective view); e) final model of a single floor used to create ~1,000 design options (perspective view).

By updating the values of *building side length* and *floor height* parameters, the design stakeholders were able to investigate which alternatives satisfied the *gross area* and tower *efficiency* constraints, both established as output parameters in the CAD model. To address the *minimizing the construction cost* goal, designers altered the input parameter values determining the *spandrel beam depth* and *column length & width*. Structural Engineers formally analyzed the resulting design alternatives in ETABS to determine structural viability and cost. As a result, the structural design evolved from the initial columns with double curvature to columns with single curvature, which dramatically reduced the cost but maintained the original architectural design intent (Figure 4). The final solution required amending the CAD model by adding a stepped extension to allow the rebar connections between columns. Output parameters calculating the surface area of components such as glass and cladding, and the volume of components such as columns and spandrel beams, were used to dynamically calculate rudimentary cost estimates.

a) *b)* *c)*

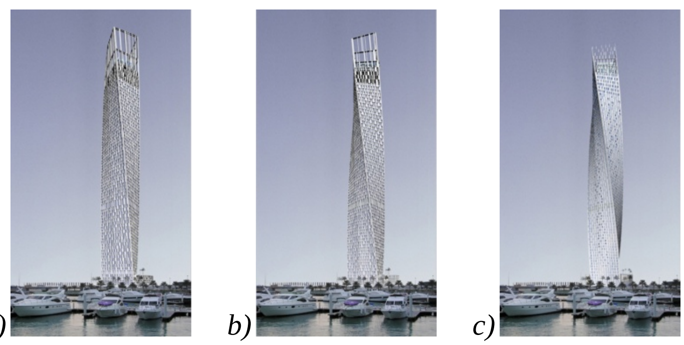
Figure 4: The team investigated three structural alternatives using the same parametric CAD model: a) originally proposed solution with expensive double curvature; b) intermediate solution with single curvature but with architecturally unappealing columns; c) final solution with single curvature stepping columns, in which fins cover the step from top to bottom column. Column and fin sizes were varied to minimize the heat load. The glazing offset from exterior wall was adjusted to satisfy the ***gross area*** *&* ***efficiency*** *constraints.*

To address the *minimize heat load* goal designers iterated the values of parameters determining the *window setback* in relation to the building's exterior face, as well as the *column size*, which controlled the fin size. The objective was to minimize the glazed surface area impacted by direct sunlight. The actions taken to address this goal were carefully coordinated with the *gross area* and *efficiency* constraints.

The CAD model was operated through 13 input parameters illustrated in Table 2 and used to generate 15 alternatives (Figure 5 – 3 alternatives only are shown). The model enabled the research team to determine the Total Option Space Size metric for the scenario-specific design space by multiplying the total number of steps for the input parameters by the input parameters' increment (see Table 8).

Table 2: Input parameters and constrained ranges.

Input parameter name	Constrained range	Parameter increment	Total steps
Core diameter	13-15m	1m	3
Circulation corridor diameter	17-18m	1m	2
Tower width	30-40m	1m	11
Tower length	20-30m	1m	11
Tower rotation	45-90deg	1deg	46
Building side angle	150-170deg	1deg	21
Tower height	300-330m	1m	31
Column spacing	3.0-3.6m	0.5m	14
Column length	0.5-1.0m	0.1m	6
Column width	0.5-0.9m	0.1m	5
Floor height	3.6-4.5m	1m	9
Slab depth	0.2-0.3m	0.1m	2
Spandrel beam depth	0.5-0.9m	0.1m	5



a) b) c)

Figure 5: Multiple Tower 1 alternative twist values were parametrically investigated during the design process. a) 60 degree twist; b) 90 degree twist; c) final design featuring a 90 degree twist and smaller glazing setback.

2.2 Tower 2 test case

Tower 2 was a high-rise competition in San Francisco.

Table 3 summarizes a selection of project facts and requirements that guided the design process. Two types of requirements were considered: qualitative constrains proposed by the primary stakeholder (client), and one procedural goal by the design stakeholders (architect and structural engineer).

Table 3: Selection of Tower 2 project facts and design requirements

Project Facts

Project Phase	Competition (Conceptual design), 2007
Project Type	Multiuse high-rise (office, hotel, residential), 1375ft
Team size and composition	1 researcher (CAD expert), 2 senior architects, 3 mid-level architects, 2 senior structural engineers, 1 structural engineer, 2 mechanical engineers
Software tools	DigitalProjectV1R2, Rhinoceros, AutoCAD, 3D Studio Max, ETABS, Ecotect, Flovent, Virtual Wind

Requirement Description	**Requirement type**	**Identified By**
Office gross area	Constraint (quantitative)	Client (developer)
Office 1st floor gross area	Constraint (quantitative)	
Office last floor gross area	Constraint (quantitative)	
Hotel gross area	Constraint (quantitative)	
Use parametric CAD	Goal (procedural)	Design Stakeholders

The design process started with a poorly defined objective space containing only a limited set of constraints proposed by the client. The design stakeholders did not explicitly delineate any design scenarios they were interested in exploring at the outset, but rather pursued the conventional practice of gradual, informal clarification of the design intent through iterative generation of alternatives.

Designers generated a total of 20 alternatives from six different parametric models. Figure 6 shows a selection of seven alternatives generated with four of the six models. For each model, the CAD expert required one week to understand the senior architect's emerging scenario and translate it into a CAD model through a technical process similar to the one described in Tower 1 case. The major distinction, however, was in how design stakeholders and CAD experts interacted. The senior architect occasionally reviewed the in-progress CAD model generated by the CAD expert, who was not clear of the design scenario, and made improvised suggestions. For example, the CAD expert built the first model based on a design precedent that the senior architect developed for another project and adapted it to address the client constraints (Figure 6a). However, it was soon determined that the resulting aspect ratio of 1:10 and the lease span on multiple floors were unacceptable. A relatively quick check could have helped invalidate this segment of the design space had these requirements been explicitly defined early on. As a result, the senior architect decided to investigate a geometrically and structurally different scenario (Figure 6b). This invalidated the original CAD model, which given its geometric and relational complexity took significant time to build. A similar process was repeated on all consecutive models. This lack of procedural rigor dramatically reduced the effectiveness of parametric CAD tools in a conceptual design process that lasted longer than average (see Table 8).

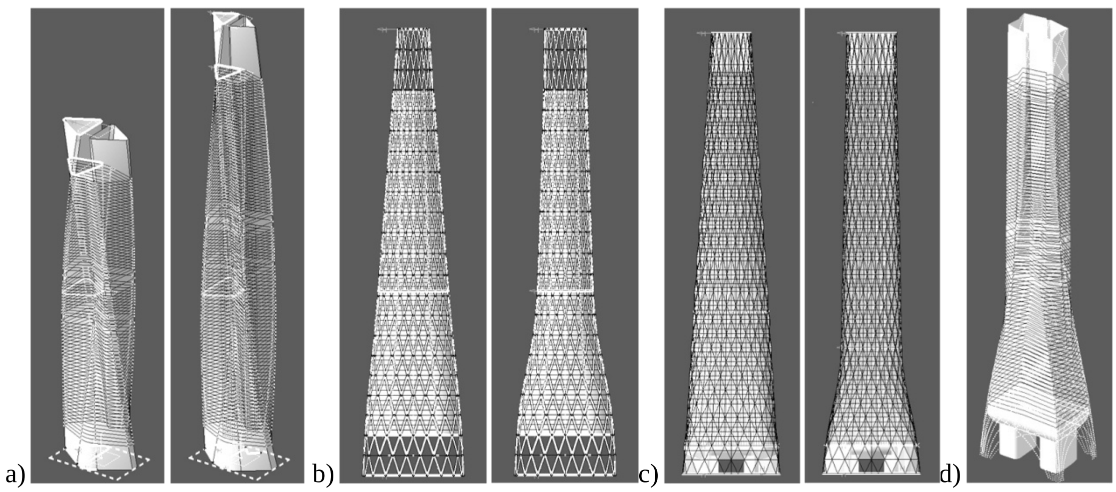


Figure 6 (a – d): 7 alternatives from over 1,000 generated options. The lack of a formal methodology for defining and translating design requirements into parametric models led to the construction of six unique models to generate 20 alternatives.

The CAD expert operated the CAD model in Figure 6a through 9 input parameters and ranges illustrated in Table 4, which enabled the research team to determine the Total Option Space Size metric. Table 8 summarizes the third data set describing the resulting conceptual design process performance.

Table 4**:** Input parameters and constrained ranges describing the model in Figure 6a.

Input parameter name	**Constrained range**	**Parameter increment**	**Total steps**
Bot. triangle base length	170-190ft	1ft	21
Bot. triangle side length	160-170ft	1ft	11
Top triangle side length	90-100ft	1ft	11
Bottom triangle chamfer	20-30ft	1ft	11
Chamfer angle	60-90deg	1deg	31
Bottom centroid offset – origin	50-65ft	1ft	16

Top centroid offset – origin	50-60ft	1ft	11
Office floor height	13-15ft	1ft	3
Residential floor height	10-12ft	1ft	3

2.3 Summary

In summary, both case studies illustrated an effectively new conceptual design process in which with parametric CAD design teams build systems for developing large design spaces rather than point solutions. However, neither case represents a methodology that would enable designers to optimize or repeat the process. The designers had no formal method to capture, manage, and rationalize design requirements into effective parametric CAD models. They were unable to make the structure and rationale of those models clear to the entire team, which renders the process they developed hard to integrate with analysis, and to repeat even within the same firm. For example, as Tower 1 progressed into the next phase a few months after the concept design submission, even the CAD expert who built the CAD model required a substantial time investment to restore his understanding of the model structure and the means to operate it. The lack of such a method in larger teams leads to significantly poorer results as was illustrated in the Tower 2 test case. In both cases design stakeholders finished the conceptual design process without a clear understanding of the potential value of the alternative space.

Overall, Tower 1 proved more successful [xx, xxi]. In spite of a demanding schedule, the design stakeholders effectively addressed the project requirements and delivered a geometrically complex and architecturally engaging design that mostly addressed economic requirements (Figure 5). In three weeks, a single CAD model was built for one scenario and used to investigate nearly 1000 design options refined into 15 alternatives. Designers made this possible by implicitly defining the objective space, translating requirements into key parameters, and following a scenario that remained largely unchanged throughout the design process. The success of the project was due in part to the small team size with few design stakeholders (architect and structural engineer only, making it an objective space of medium quality), the expertise in using parametric CAD (one architect built and operated the model), and its diligence in observing the project requirements with which it started the design process.

Next we discuss the application of Design Scenarios (DS) methodology on a third high-rise case study. DS was implemented into a web-based software prototype to help enhance the application of parametric CAD in conceptual design and enable design stakeholders to generate and communicate clearer and better design spaces. DS consists of four consecutively built interdependent models. With the *Requirements Model (RM)* project stakeholders explicitly define the context specific objective space and prioritize goals. With the *Scenarios Model (SM)* design stakeholders build the logical alternative space by formally transforming the objective space into geometric and material parameters, establishing parameter interrelationships and identifying potential conflicts. With the *Parametric Process Model (PPM)* CAD experts build the geometric alternative space by illustrating the technical implementation of a SM in a parametric model used to generate design alternatives. With the *Alternative Analysis Model (AAM)* design stakeholders analyze alternatives to determine the impact and value spaces.

3 Conceptual design process using Design Scenarios (DS) to clarify design spaces

We tested the impact of Design Scenarios methodology on an industry supported case study called Tower 3 – a mixed use project in Jeddah, Saudi Arabia consisting of two towers – an all residential (Tower 1) and a mixed use (Tower 2 - hotel and serviced apartments). The project team developed four scenarios using traditional concept design methods. The research team concurrently built and shared DS models with the project team for two of these scenarios. Several project facts are summarized in Table 5. Next, we describe the DS process and the resulting models, followed by a comparative discussion of the four case studies.

Table 5: Project facts.

Project Facts	
Project Phase	Conceptual design

Project Type	2 high-rises – hotel and mixed-use
Team size and composition	1 researcher (CAD expert), Client (developer), Design Architect, Technical Architect, Mechanical Engineer, and Structural Engineer
Software tools	Digital Project V1R4, Rhinoceros, 3D Studio Max, Ecotect, Radiance

3.1 Summary of Tower 3 design team process

While the research team was building the Requirements Model, it became apparent that the design team had no common understanding of what were the project requirements, how to address them, or what was the reasoning used to formulate these requirements. For example, one such requirement was the 145m height to last inhabited floor constraint defined by the client. The site's proximity to the airport required the client to pay the city for any additional floor above 145m, which would negatively impact the profit margins. Most of the design team was not aware of this fact. Furthermore, designers did not distinguish between goals and constraints or the difference in their importance level. The team often had to wait for instructions from the design architect on how to proceed, making the process highly inefficient. The four design scenarios were generated ad-hoc based on precedents of high-rise typologies and not the project's guiding requirements. Architects were the only contributors in the design process. As a result, during the first progress meeting with the client two weeks into the project, the team was unable to successfully convey the reasoning used to address the client's primary goal of maximizing views and the difference in the performance of the presented alternatives. This invalidated most of the design team's work, which had to start over. The team used traditional, non-parametric CAD to generate one option per design scenario, which confirmed our benchmarking study of current conceptual design process performance (see Table 8).

3.2 Requirements Model (RM)

The DS process started with project stakeholders clarifying the objective space by building the RM. All five project stakeholders were asked to determine and record relevant project constraints and goals. First, designers analyzed the contextual constraints (i.e., site, geographic location, climate) and determined the design scenarios to be explored.

The test case site is located between the city center and the airport and is irregularly shaped as a *"half teardrop"*. The design architect proposed four design scenarios to be explored – half teardrop to mimic the site configuration, triangular, oval, and tapered. The research team developed two scenarios in DS (half teardrop and triangular). Figure 7 illustrates the site for the first scenario.

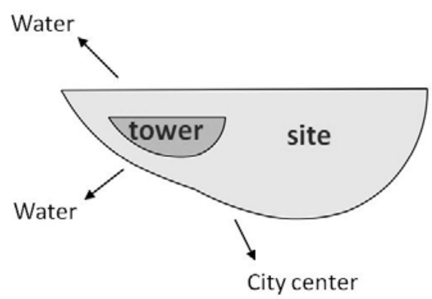


Figure 7: Test case "half teardrop" site and the "half teardrop" scenario tower footprint.

The research team started building the RM by first examining the requirements used by the project team to commence the design process. The only available formal resource was a booklet specifying the following **three constraints:** (1) *Gross area for Tower 1* (55,000 sq m - residential), (2, 3) *Gross area for Tower 2* (40,000 sq m – hotel, 50,000 sq m – serviced apartments). We engaged various members of the architectural team and identified six additional requirements not formally captured before **- four constraints**: (1) *Maximum tower height to last inhabited floor – 145m*, (2) *Maximum site coverage – 60%*, (3) *North site setback – 12m,* (4) *South site setback - 3m*, and **two goals**: (1) *Maximize exposure to water of 100% units,* (2) *Sleek design*. Unlike the project team, we also engaged the lead Mechanical Engineer to identify **three** additional **goals** determined by the climate conditions in Saudi Arabia: (1) *Minimize direct sunlight in 100 % units* (to address undesired brightness), *(2) Minimize solar heat load in 100% units* (to help minimize the building cooling costs), *(3) Maximize exposure to prevailing wind of 100% units* (to help naturally cool the building exterior envelope). Engaging the Technical Architect and Structural Engineer did not reveal any additional requirements that these decision makers were interested in pursuing. The Mechanical Engineer, however, was very excited about his contribution and commented that "Every project should start this way".

Using the RM tabular interface, the research team recorded the discovered constraints and goals (both quantitative and qualitative) along with the responsible stakeholder and discipline (Figure 8 a-b). All five decision-makers were then interviewed to determine their preferences with respect to the identified goals (Figure 8 c).

Discipline	Constraint +	Limit
Devel	Tower 1 - residential	55,000 sq m
Devel	Tower 2 - hotel (250 keys) - identical footprint	40,000 sq m
Devel	Tower 2 - serviced apartments	50,000 sq m
Devel	Maximum tower height to last inhabited floor	145 m
Planning	Maximum site coverage	60 %
Planning	Site set back North side	12 m
Planning	Site set back South side	3 m

a)

Discipline	Goal +	Target
Devel	Maximize unit exposure to water	100 %
Mech Engg	Minimize direct sunlight in units	100 %
Mech Engg	Minimize solar heat load	100 %
Mech Engg	Maximize exposure to prevailing wind	100 %
Devel	Sleek design	

b)

Goal	Importance	
	Relative	Pct
Maximize unit exposure to water	50	50
Minimize direct sunlight in units	10	10
Minimize solar heat load	10.0	10
Maximize exposure to prevailing wind	5.0	5
Sleek design	25.0	25

c)

Figure 8: Requirements Model inputs. Project stakeholders: (a) determined 7 quantitative constraints and (b) 5 quantitative and qualitative goals; (c) each stakeholder indicated his/her preference for the 5 identified goals by distributing 100 percentage points. Note that this example is showing only the Design Architect preferences.

Figure 9 illustrates the system generated goal importance graph, in which stakeholder preferences were normalized to 100 points. The graph enabled the research team to understand individual preferences, as well as the overall relative importance of each goal. *Maximizing unit exposure to water* emerged as the leading goal with 46% out of

100 of overall preferences, while *maximizing exposure to prevailing wind* became the least important goal with only 7%.

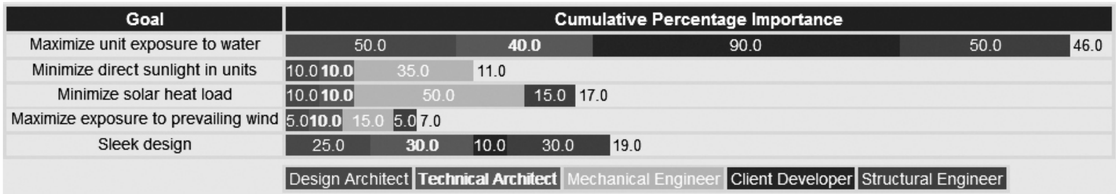


Figure 9: Requirements Model outputs - the system generates the goal importance graph and normalized decision makers' preferences to 100 points.

Building the RM enabled the research team to determine the Objective Space Size of 12 requirements (7 constraints and 5 goals). The process of aggregating stakeholder requirements, assigning preferences, and building the RM lasted 1 day.

3.3 Scenarios Model (SM)

The SM is a process model built by design stakeholders to explicitly determine the logical alternative space, in which requirements are decomposed into enabling parameters and relationships. Constraints and goals determined in the RM are mapped by the system into the SM, where design stakeholders concurrently decompose requirements into *action items* (actionable descriptions of how to achieve requirements), *strategies* (decision making process required to achieve an action item), *parameters* (variables denoting either geometric or material properties that impact a design requirement), *parameter constraints* (fixed value or range of values shown as lower and upper limit nodes that a parameter might be required to be within), and first order logic *gateways* (describe relationships between actions, strategies, and parameters; AND – all on, OR – at least one on, XOR – at least one on and one off). The SM ontology was implemented in the software prototype as visual representations that build on Unified Modeling Language object diagram formalism. The research team engaged design stakeholders to explicitly capture the rationale each design discipline used in addressing individual constraints and goals and determine how these logically interrelate. The following section depicts this process for one constraint only.

A similar process was used to rationalize the remaining constraints and goals, which we illustrate in the Appendix section of this paper.

Constraint No. 1 – Tower 1 Gross Area

To enable CAD experts to address this constraint in a parametric CAD model, the research team (acting as the Design Architect) proposed three action items: *"Control the half teardrop configuration"*, *"Calculate gross area"*, and *"Control number of floors"* (Figure 10). An "AND" relationship indicates that all three items were required to be implemented. The research team further clarified the first action item by proposing three strategies for how to control the building configuration – *"Straight base only"*, *"Curved sides only"*, and *"Individually all sides"*. Interested in attaining geometric flexibility, the design architect chose only the third strategy, illustrated through a "XOR" relationship. The system faded the two strategy nodes that were not chosen.

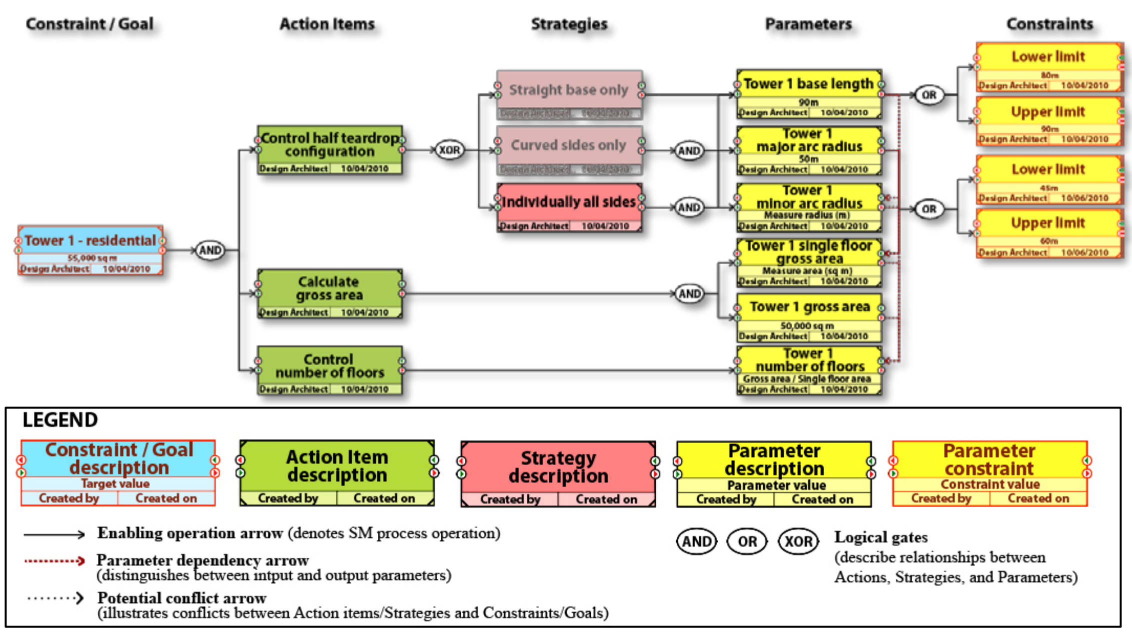


Figure 10: "Half teardrop" Scenarios Model for constraint No. 1 – design architect decomposed the constraint into Action Items, Strategies, Parameters, and Parameter Constraints and determined how these relate to each other. Faded nodes indicate strategies considered, but not chosen to be implemented in the parametric model.

The design architect now had enough information to determine the parameters that address each action item or strategy. Given the chosen *"half teardrop"* design scenario, researchers identified three key parameters to enable controlling all sides individually – *"Base length"*, *"Major arc radius"*, and *"Minor arc radius"*. However, one of the arcs could not be user controlled because of the required geometric continuity represented by a tangency relationship between the two arcs. The design architect decided the *"Base length"* and *"Major arc radius"* to be input parameters and the *"Minor arc radius"* an output parameter. Next, the architect experimentally through sketches determined constrained ranges beyond which the input parameters would result in invalid solutions. For example, any value below 45m for minor arc radius resulted in a footprint that violated the site set back constraints.

Similarly, the design architect identified two parameters that enable *"Calculating the gross area"* action item. The *"Single floor gross area"* output parameter was calculated by measuring its value in CAD when either of the two footprint input parameters were modified. The *"Gross area"* became a user defined input parameter that enabled calculating the *"Number of floors"* output parameter, which addressed the third and last action item.

SM outputs

Clarifying this rationale enabled its analysis. Figure 11 illustrates the impact of actions on requirements. *"Controlling half teardrop configuration"*, for example, is the action with the impact on the most number of requirements. As a result, when searching through the design space, designers focused on but were not limited to the following input parameters addressing high impact action items: *"Tower 1 base length"*, *"Tower 1 major arc radius"*, *"Tower rotation"*, and *"Unit width"*.

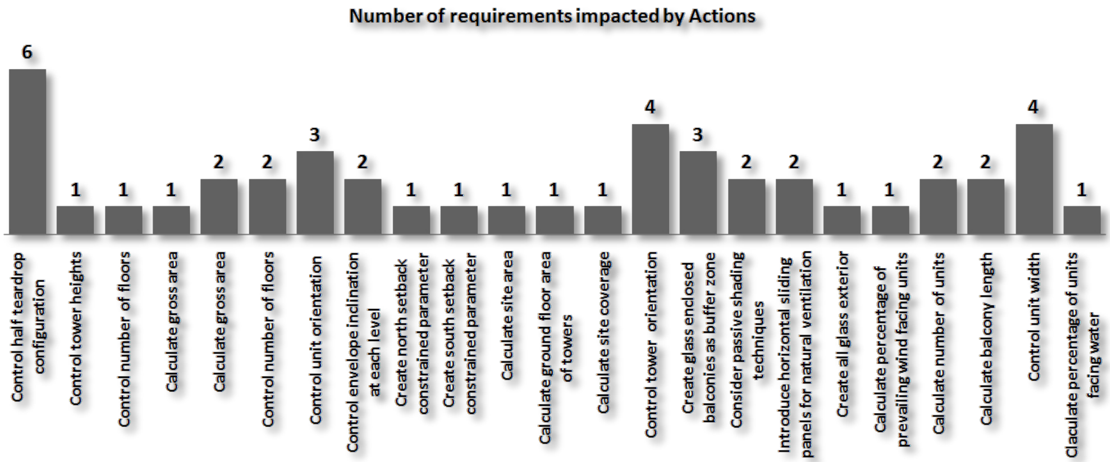


Figure 11: SM output – Actions impact on requirements graph. 'Control half teardrop configuration", " Control tower orientation and "Control unit width" emerged as Action Items that impacted most project requirements.

Building the SM enabled determining the Total Option Space Size metric for the *"half teardrop"* scenario. Table 6 illustrates the 13 input parameters used to operate the parametric model (see the complete SM model in the Appendix section for parameter sources).

Table 6: Input parameters and constrained ranges.

Input parameter name	Constrained range	Parameter increment	Total steps
base length	80-90m	1m	11
major arc radius	45-60m	1m	16
Unit width	4.2-4.6m	0.1m	5
floor height	3.0-3.6m	0.1m	7
South units view vector	30-50deg	1deg	21
North units view vector	50-60deg	1deg	11
City units view vector	50-60deg	1deg	11
Tower rotation	0-10deg	1deg	11
Frit density	20-50%	10%	4
South wall inclination	1-5deg	1deg	5
East wall inclination	1-5deg	1deg	5
West wall inclination	1-5deg	1deg	5
North wall inclination	1-5deg	1deg	5

The process of aggregating individual stakeholder inputs on how to address requirements and building the SM for both scenarios lasted 1 man-day.

3.4 Parametric Process Model (PPM)

The PPM is a process model built by CAD experts to explicitly determine the geometric alternative space, in which the structure of dependencies between parameters, geometric constraints, CAD operations, and geometry is established. Parameters identified in the SM are mapped by the system into the PPM and used to control the CAD model's geometry. The PPM aims to make the CAD model structure clear and disseminate expert knowledge needed to enhance the application of parametric CAD in conceptual design. The PPM consists of two levels of information abstraction implemented as process model nodes in the software prototype – (1) *components*, which are information containers describing the component-level decomposition of the CAD model, and (2) detail-level description of the components' composition, in which *input* and *output parameters* determined in the SM are first linked to *geometric elements* (predetermined geometric primitives used to create the geometric representation of the intended design), then relationships among geometric elements are established through *geometric constraints* (e.g., tangency, parallelism), and *CAD operations* (e.g., extrude, join) are used to modify geometric elements in the direction specified by *reference elements* (e.g., XY plane).

The CAD expert used the *"half teardrop"* scenario determined in the SM to first organize the parametric CAD model structure into 18 components (Figure 12). The graph communicates the hierarchical dependency of components (i.e., any change to the "*Floor Plate*" will affect the "*Slabs*" component) and the CAD model construction sequence (i.e., "*Slabs*" can be built only after the "*Floor Plate*" was built). Unlike the process of building traditional, static CAD models, such distinction is critical when building parametric models.

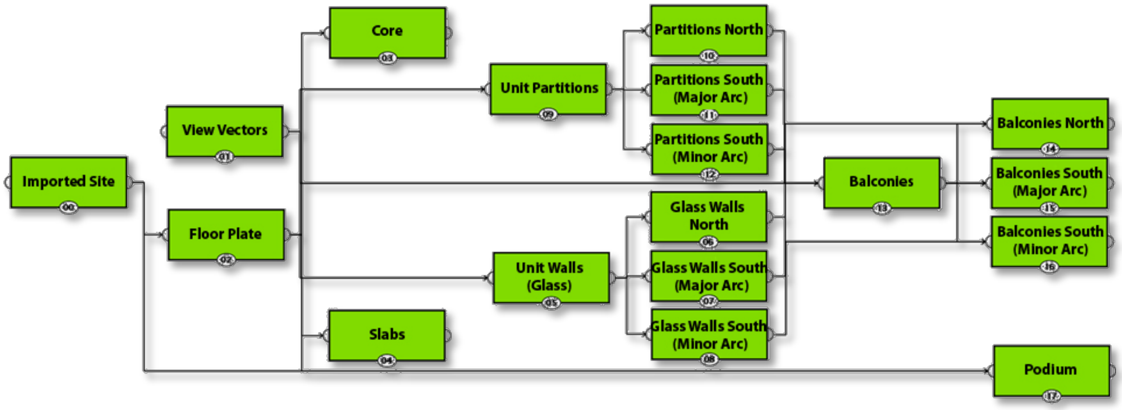


Figure 12: Component-level PPM showing the parametric model structured into 18 components.

Figure 13 a & b illustrate the detail-level description of the *"Floor Plate"* component only and its graphical preview. The CAD expert used the "XY Plane" as the reference needed to determine the orientation in space of the *"Ground Floor Sketch"*, composed of *"Line.01"*, which defines the tower straight base, *"Major Arc"*, and *"Minor Arc"* defining the curved sides of the tower. He used three input and one output parameters mapped by the system from the SM to geometrically control the footprint. For example, *"Tower 1 base length"* controlled the length of *"Line.01"*, etc. *"Line.02"* was a horizontally constrained construction element used only as a reference when rotating the tower footprint. The *"Tower rotation"* input parameter defined the angle between *"Line.01"* and *"Line.02"*. The CAD expert tangentially constrained the *"Major Arc"* and *"Minor Arc"* at the overlapping vertices. He extracted the value of *"Tower 1 minor arc radius"* output parameter by measuring the radius of the *"Minor Arc"*, which updated each time the *"Major Arc"* radius value was changed. He coincidentally inter-constrained the vertices of *"Line.01"*, *"Major Arc"* and *"Minor Arc"* to enable applying parametric adjustments globally (without these constraints, changing the *"Tower rotation"* value will reposition only *"Line.01"*).

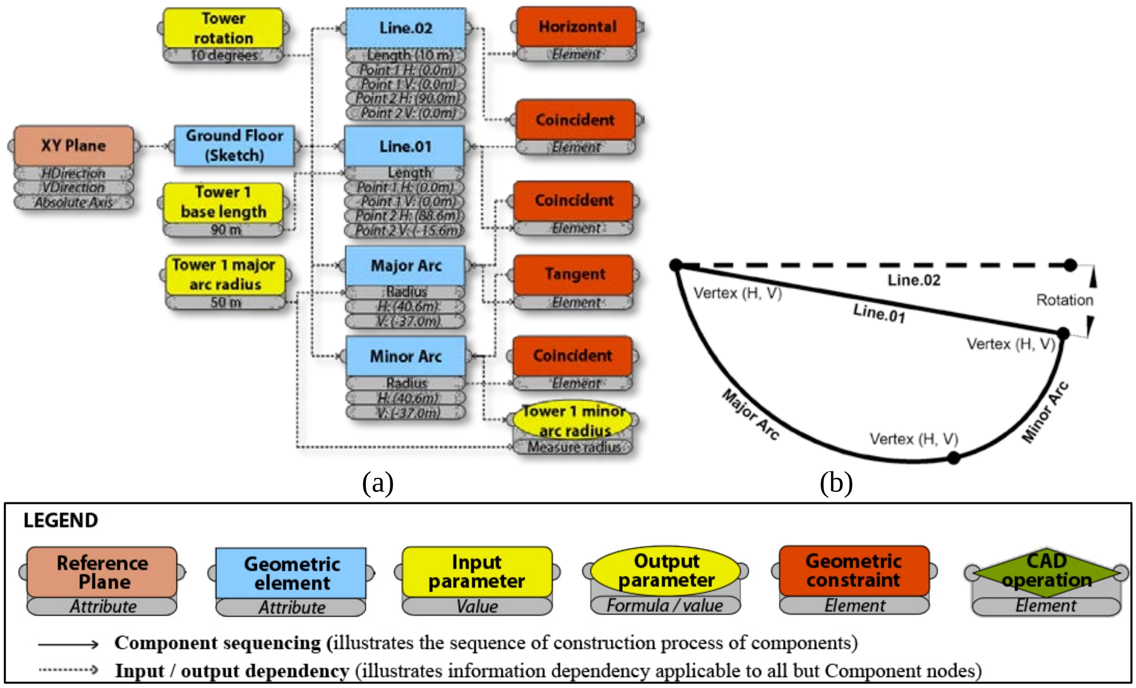


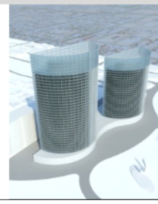
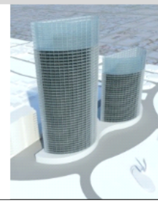
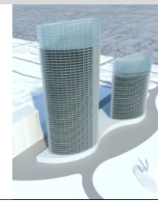
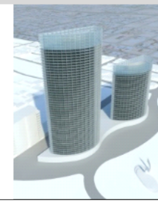
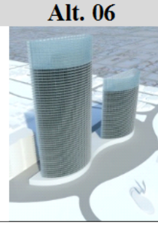
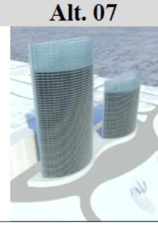
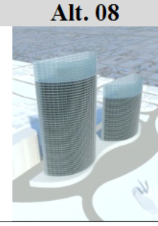
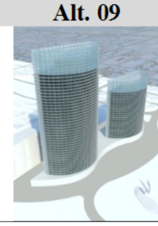
Figure 13: a) Detail-level PPM for the "half teardrop" scenario showing the composition of the "Floor Plate" component; b) Test case tower floor plate preview.

The CAD expert used a similar method to construct the remaining 16 components not shown in this paper. Note that component 1 represented the imported 2D geometry of the project site. The complete PPM can be accessed online by contacting the authors. The process of building the PPM for both scenarios lasted 2 man days.

Parametric CAD model

The PPM specifies the structure of the parametric CAD model built by the CAD expert and used to explore the design space. Table 7 illustrates a selection of 10 alternatives that satisfied the project constraints from ~1100 generated options, and the key input parameter values used to generate these. A total of 13 input parameters were modified during the option generation process (4 main parameters only are shown below).

Table 7: 10 design alternatives and a selection of input parameters used to generate each alternative.

Parameter	Alt. 01	Alt. 02	Alt. 03	Alt. 04	Alt. 05
					
Tower 1 base length	90m	85m	80m	80m	84m
Tower 1 major arc rad.	50m	55m	52m	52m	52m
Tower rotation	10deg	10deg	10deg	10deg	5deg
Unit width	4.2m	4.6m	4.6m	4.6m	4.5m
Parameter	**Alt. 06**	**Alt. 07**	**Alt. 08**	**Alt. 09**	**Alt. 10**
					
Base length	87m	89m	86m	88m	83m
Major arc radius	54m	55m	51m	51m	45m
Tower rotation	5deg	5deg	7deg	7deg	0deg
Unit width	4.4m	4.8m	4.4m	4.3m	4.3m

The CAD model building process for both scenarios lasted 3 man days, while the generation of design options and alternatives lasted 2 days.

3.5 Alternatives Analysis Model (AAM)

The AAM is a tabular model that provides design stakeholders with the framework to determine and understand the scenario's impact and value spaces. It is a tool to compare the quantitative and qualitative analyses of design alternatives and determine their relative value to enable an objective decision making process. Building the AAM requires design stakeholders to evaluate how each design alternative ranks in relation to the goals identified in the RM A simple scoring system was designed for this purpose. A design alternative receives 100% score for a given requirement if it meets its target value, which serves as a benchmark for determining the score when the target value is not met or is exceeded.

Using the DS framework, the research team first assessed the geometry-based requirements by means of output parameters. In other words, the SM enabled building a CAD model that served in assessing all seven constraints and three goals. Each time a design option was generated, the research team assessed real-time whether constraints were met and discarded the non-conforming options. For example, all generated options satisfied the *"Gross area"* constraint for both towers because "*Tower gross area"* input parameter value was kept constant. However, changing the value of *"Tower base length"* or *"Tower major arc radius"* high impact parameters determined the values of *"Tower single floor area", "Tower number of floors",* and *"Maximum tower height to last inhabited floor"* output parameters, which in turn impacted five constraints and five goals.

To determine how well each of the ten design alternatives satisfied the two goals related to energy and daylight required conducting model-based analysis in specialty tools. The process wasn't automated and the research team extracted the geometry for all ten alternatives in a format optimized for the required analysis tools (i.e., meshed exterior only with no material properties assigned - for Incident Solar Radiation (ISR); meshed with material properties of both exterior and interior - for daylight). Autodesk Ecotect™ was used to calculate the ISR. Figure 14 illustrates three of the ten analyzed alternatives. Three floors only were analyzed because the site was not surrounded by any tall buildings that might have impacted the analysis results.

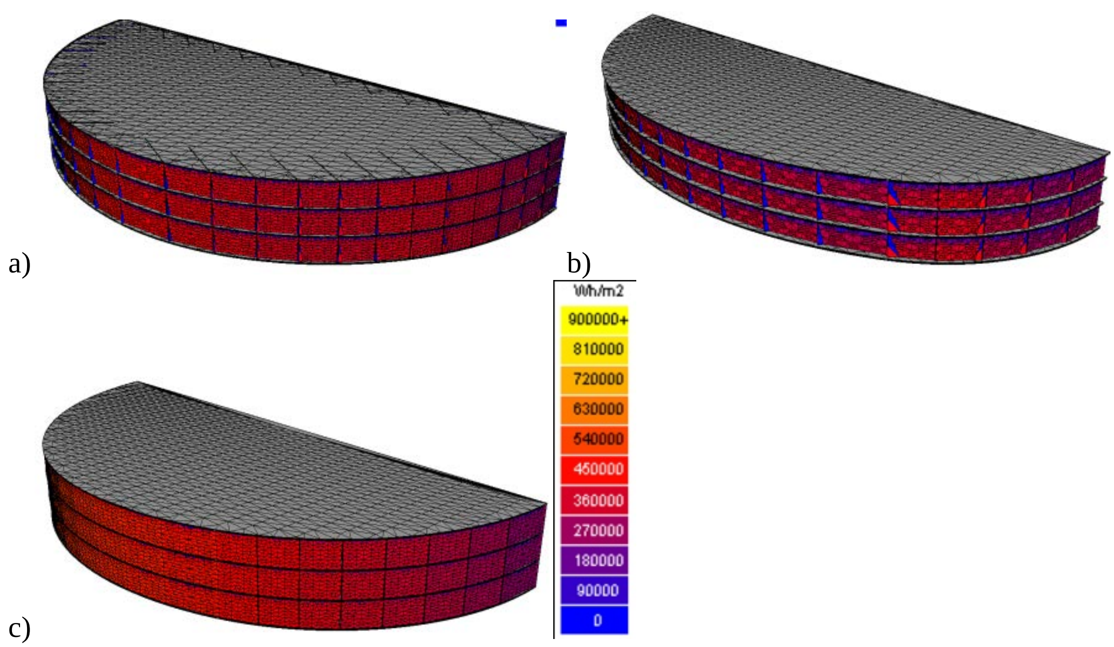


Figure 14: ISR analysis false color map (blue indicates less radiation, red – more); a) Alternative 1 – Worst (197,090 Wh/m2); b) Alternative 7 – Best (107,143 Wh/m2); c) Alternative 10 – surprising outcome (168,436 Wh/m2).

The goal of ISR analysis was to determine which alternative accumulated the smallest amount of direct solar radiation annually from 8am to 6pm – one of the most important goals of the project. Alternative 7 emerged as the best, given its floor plate configuration, orientation, floor height (h), slab offset from exterior glazing (d), and the balcony exterior face inclination (α) (Figure 15). The cumulative value in Wh/m^2 was calculated from individual data points of the analysis mesh. Alternative 10 was expected to be the worst performer given the vertical balcony exterior face and the slab flushed with exterior glazing. However, a 0.1m reduction in the floor height was significant enough to make Alternative 10 perform better than Alternative 1.

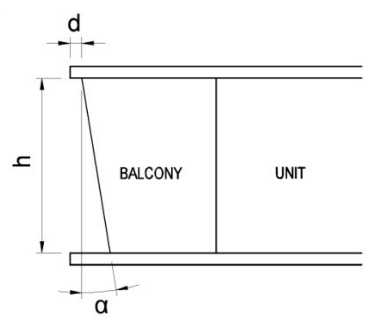
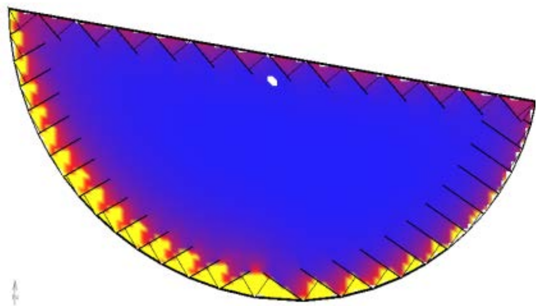
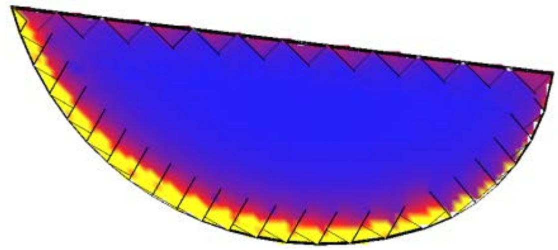


Figure 15: Key parameters affecting the amount of direct solar radiation accumulated by the tower's exterior.

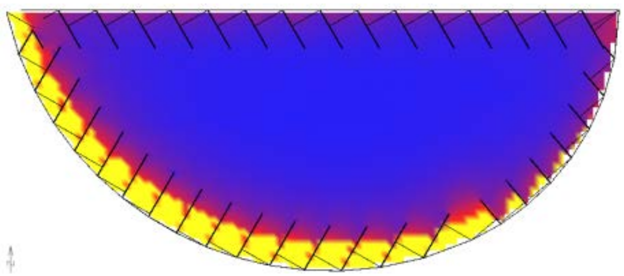
Radiance [xxii] was used to calculate the daylight values and determine the alternative with least direct sunlight in units. Figure 16 illustrates simplified floor plates with partitions denoting hotel units for three of the ten analyzed alternatives. Alternative 8 emerged as the best and Alternative 1 the worst, because Alternative 1 has 60cm smaller floor height, 20cm deeper slab offset from exterior glazing, 15deg larger city center view vector angle, 30deg larger south view vector angle, and 3deg smaller tower rotation angle.



(a) Alternative 1



(b) Alternative 8



(c) Alternative 10

Figure 16: Daylight analysis – false color map (blue indicates less daylight, yellow – more); a) Alternative 1 – Worst (4,022,200 lux / floor); b) Alternative 8 – Best (2,205,150 lux / floor); Alternative 10 – surprising outcome (3,411,600 lux / floor).

Figure 17(a, b) summarizes the performance scores for all ten alternatives on all of the requirements. First, the design stakeholders added 10 alternatives to the tabular model and assigned impact scores to the five project goals mapped by the system from the RM. Then, designers used best performing alternatives as benchmarks for goals 2, 3, and 5, which enabled scoring the remaining alternatives' performance. Goal 5 was the only qualitative requirement. It was assessed by comparing all ten alternatives and selecting the preferred one (Alternative 5 – 100% impact score) used as a benchmark against which others were compared. The evaluation was based on such criteria as overall proportions (i.e., building length vs. height, crown height vs. inhabited section height), and tactile quality of the exterior envelope (i.e., slab depth and inclination of balcony exterior face) – a subjective assessment by a human designer.

a)

Goal	Alternatives' Impact Scores									
	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8	Alternative 9	Alternative 10
Maximize unit exposure to water	68 %	71 %	72 %	74 %	83 %	86 %	89 %	79 %	82 %	79 %
Minimize direct sunlight in units	18 %	34 %	56 %	53 %	59 %	49 %	43 %	100 %	15 %	45 %
Minimize solar heat load	16 %	48 %	71 %	81 %	75 %	91 %	100 %	61 %	86 %	43 %
Maximize exposure to prevailing wind	66 %	62 %	63 %	59 %	54 %	54 %	54 %	65 %	59 %	60 %
Sleek design	55 %	65 %	70 %	90 %	100 %	95 %	85 %	80 %	75 %	60 %

b)

Goal	Alternatives' Value Scores									
	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8	Alternative 9	Alternative 10
Maximize unit exposure to water	31.3	32.7	33.1	34	38.2	39.6	40.9	36.3	37.7	36.3
Minimize direct sunlight in units	2	3.7	6.2	5.8	6.5	5.4	4.7	11	1.7	5
Minimize solar heat load	2.7	8.2	12.1	13.8	12.8	15.5	17	10.4	14.6	7.3
Maximize exposure to prevailing wind	4.6	4.3	4.4	4.1	3.8	3.8	3.8	4.6	4.1	4.2
Sleek design	10.5	12.4	13.3	17.1	19	18.1	16.2	15.2	14.3	11.4
Total Value Score	51.1	61.3	69.1	74.8	80.3	82.4	82.6	77.5	72.4	64.2

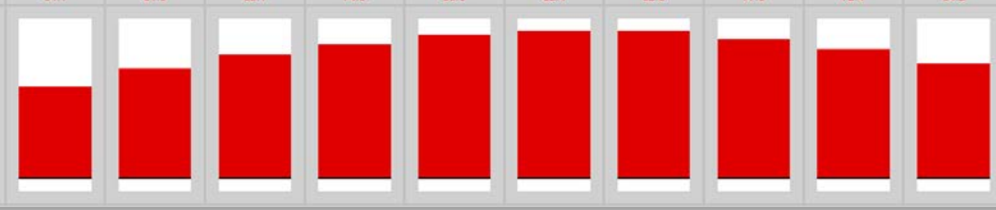


Figure 17: AAM "half teardrop" design scenario; a) impact scores for 10 design alternatives and 5 goals; b) system generated value scores – overall, Alternative 7 emerged as the most successful.

After all the impact scores were assigned, the system generated the alternatives' value scores, calculated by multiplying the alternative's impact score for every goal by the importance percentage of each goal determined by the project stakeholders in the RM and summing these into a total value score. For example, Alternative 1 received a 68% impact score for *"Maximizing unit exposure to water"* goal. Its relative value score was 31.3 (68*46%=31.3).

A similar process was used to generate ten design alternatives for the *"triangular"* design scenario and determine the total value sores of each alternative. Figure 18 illustrates one of the ten alternatives, and Figure 19 summarizes the value scores.

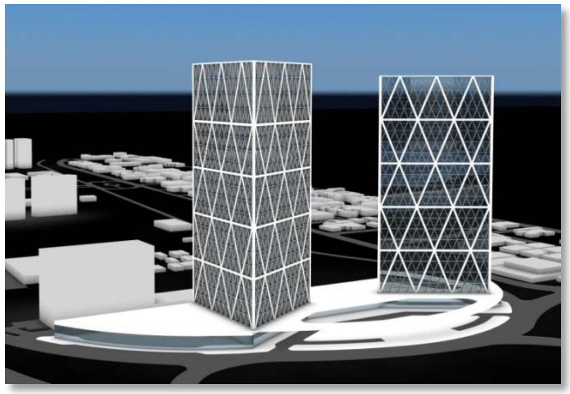
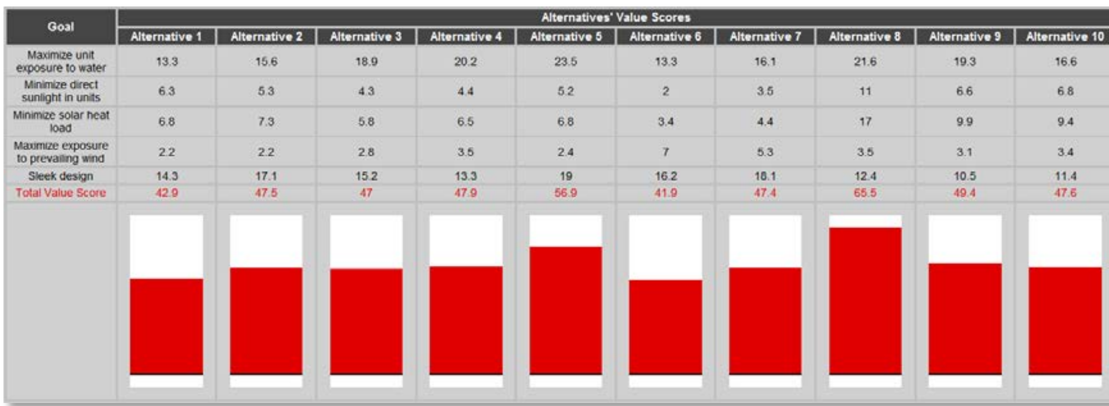


Figure 18: Alternative 1 of “Triangular” design scenario.



Goal	Alternatives' Value Scores									
	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5	Alternative 6	Alternative 7	Alternative 8	Alternative 9	Alternative 10
Maximize unit exposure to water	13.3	15.6	18.9	20.2	23.5	13.3	16.1	21.6	19.3	16.6
Minimize direct sunlight in units	6.3	5.3	4.3	4.4	5.2	2	3.5	11	6.6	6.8
Minimize solar heat load	6.8	7.3	5.8	6.5	6.8	3.4	4.4	17	9.9	9.4
Maximize exposure to prevailing wind	2.2	2.2	2.8	3.5	2.4	7	5.3	3.5	3.1	3.4
Sleek design	14.3	17.1	15.2	13.3	19	16.2	18.1	12.4	10.5	11.4
Total Value Score	42.9	47.5	47	47.9	56.9	41.9	47.4	65.5	49.4	47.6

Figure 19: AAM “Triangular” design scenario; System generated value scores – overall, Alternative 8 emerged as most successful.

4 Conclusions and future opportunities

This paper presented three industry test cases, in which designers used parametric modeling to search through large design spaces. Tower 1 and 2 cases employed parametric modeling without any formal method of eliciting requirements, translating requirements into input and output parameters, and determining the value of the generated design alternatives. Tower 3 case illustrated the application of a formal method called Design Scenarios. Table 8 compares the three new data sets with the earlier benchmarked current practice.

Design theory has extensively looked into the design space exploration topic. Woodbury and Burrow [ix] distinguish three main areas of research, all of which were in part or fully addressed in the presented test cases: (1) the premise that exploration is a good model for designer action; (2) strategies and tools that amplify designer action in exploration; (3) development of computational structures to support exploration and represent the design space. Conceptual design offers most opportunities for design space exploration [xxiii]. Akin [xxiv] defines conceptual design in terms of several process steps: (a) identify requirements; (b) prioritize requirements; (c) develop preliminary solutions; (d) evaluate solutions.

Our analyses of "traditional" current practice as well as emerging parametric practice illustrates that process steps (a), (b), and (d) are not consistently implemented and clearly communicated in current practice. The case studies, however, indicate a substantial improvement in the Option Space and Alternative Space size over current practice. The Impact Space Quality metric for both cases is lower than in current practice. It is essential, however, to view this metric in conjunction with Objective Space Quality, which in current practice is lowest.

Table 8: A comparison of four case studies quanstifying conceptual design process performance. Items in bold denote significant improvements over current practice.

Metric	**Current practice**	**Tower 1 case**	**Tower 2 case**	**Tower 3 case**
Objective Space Size	3	8	5	**12**
Objective Space Clarity	No	No	no	**yes**
Objective Space Quality	Low	Medium	medium	**high**
Number of Scenarios	3	1	**6**	2
Total Option Space Size	Unknown	**821.8 bil**	**1.37 bil**	**430.44 bil**
Generated Option Space Size	3	**~900**	**~1200**	**~1100**
Options Space Quality	Unknown	913.11 mil	1.14 mil	391.31 mil
Alternative Space Size	3	**15**	**20**	**10**
Alternative Space Clarity	No	Partial (scenario only, parameters retrospectively)	no (parameters determined retrospectively)	**yes**
CAD Model Clarity	No	No	no	**yes**
CAD Model Quality	3	1	6	**1**
Impact Space Size	3 (area, aesthetics, efficiency)	4 (area, efficiency, FEA, cost)	4 (area, FEA, CFD, ISR)	**12**
Impact Space Clarity	No	No	no	**partial**

Impact Space Quality	1	0.5	0.8	**1**
Value Space Size	0 (no formal valuation	0 (no formal valuation	0 (no formal valuation	**10**
Value Space Clarity	No	No	no	**yes**
Process Duration	5 weeks	**3 weeks**	6 weeks	**3 weeks**

The fourth case study describes a process in which the design space was clarified using the DS methodology and shows improvement in several additional metrics. The SM enabled design stakeholders to make the Objective and Alternative Spaces clear by explicitly capturing the value function for each design scenario described through input and output parameters, formulas used to define parameters, and the range of acceptable parameter values; CAD experts to construct parametric models used to search the requirements specific segment of the design space; and, design stakeholders to identify high impact action items by means of upstream and downstream dependency propagation. The PPM clarified the parametric CAD model structure. This clarity should help disseminate expert knowledge, which has been an impediment in the wide adoption of this modeling technique in practice. By utilizing the SM-determined parameters, the PPM can also help improve the CAD model quality metric by eliminating the need to construct multiple models for a given design scenario. However, building and communicating scenarios explicitly may impact the number of scenarios that designers are able to construct. More research is needed to determine this impact.

The DS AAM enabled the design stakeholders to make the impact and value spaces clear by analyzing the performance of all generated alternatives against all project goals. The research team used the outputs for both design scenarios to perform an objective comparison and determine which scenario overall performed better for the same set of constraints and goals, as well as identify the winning design alternative. In 9 out of 10 cases the *"half teardrop"* scenario performed better and its winning Alternative 7 had a substantial value score difference in comparison with the winning Alternative 8 for the *"triangular"* scenario. AAM enables design teams to make objective decisions when faced with lots of choices, something that was impossible in test cases 1 and 2.

Design Scenarios received some accolades from the AE firm's design stakeholders. The Sustainable Design Group leader highlighted that "DS is a tool to quantitatively compare the results of different teams. It helps guide the team, document decisions and the reasons." A Technical Architect and Studio Head pointed out that "DS has given us the ability to provide the client with a better product". The Computational Design Leader stated that "DS encourages participation from people that otherwise get involved later in the design process."

The merit of this paper was to provide evidence that increasing the design space clarity and rationale used to construct these spaces leads to improved application of parametric modeling and enables an efficient and objective design decision making process. We created a test bed to systematically investigate the question of how much rationale needs to be made explicit in different contexts [xxv]. However, we acknowledge several important opportunities to further the research presented in this paper. Table 8 illustrates that we did not have enough data to complete the proposed metrics set. For current practice, no distinction was made between scenarios and alternatives when we collected the data. That is, we collected the number of scenarios, and number of alternatives, but not the number of alternatives within each scenario. Furthermore, our survey asked to retrospectively quantify traditional conceptual design process performance. However, current design methods do not enable practitioners to quantify the number of input parameters and constrained ranges to help determine the Total Option Space Size and Options Space Quality metrics. More research is required to both determine the comprehensiveness of the proposed set of metrics and concepts in DS, as well as to ask questions such as which method leads to better design – Design Scenarios or parametric modeling with no formal method of clarifying design spaces.

The impact of Design Scenarios can be further expanded by addressing the following opportunities: (1) use the PPM to fully automate the parametric CAD model generation from PPM nodes by leveraging the parametric modeler's Application Programming Interface; (2) use Process Integration and Design Optimization methods [xxvi, xxvii] to automate the process of performing multidisciplinary analyses and determining the impact scores in the AAM. The anticipated impact is a substantial increase in the Option and Alternative Space size, Options Space Quality, Value Space Quality, and a further reduction in the overall conceptual design process duration

5 Appendix

The section contains the explanation of how the requirements not covered in section 3 of this paper were addressed.

Constraint No. 2 & 3 – Tower 2 Gross Area (hotel and serviced apartments)

The design scenario called for the footprints of both towers to be identical. Tower 2, however, was described by two programmatic constraints – hotel (40,000 sq m) and serviced apartments (50,000 sq m) summed to a total gross area of 90,000 sq m. Fig. 20 illustrates how the design architect rationalized constraints 2 and 3.

An "AND" relationship indicates that all six succeeding action items were required to address both constraints. Given the identical footprints for both towers, the first action and the dependent strategies and parameters from constraint 1 applied to constraints 2 and 3. *"Calculate gross area"* was the second action further decomposed into two strategies – *"Hotel tier"* AND *"Residential tier"*. Each strategy was addressed through a pair of parameters – *"Single floor area"*, an output parameter to be measured in the CAD model and dependent on the *"Tower1 base length"* and *"Major arc radius"* parameters, AND *"Gross area"*, an input parameter with a constant value. The third action, *"Control number of floors"*, was addressed through two output parameters – *"Total number of hotel floors"* AND *"Total number of residential floors"*. Both were calculated by dividing *"Gross area"* to *"Single floor area"* for the hotel and residential tiers respectively. The fourth action, *"Calculate number of units"*, was decomposed into two strategies – *"Hotel tier"* AND *"Serviced apartments tier"*, addressed through three output parameters – *"Number of units north"*, *"Number of units south major arc"*, *"Number of units south minor arc"*. The fifth action, *"Calculate balcony length"*, was introduced in response to *"Create glass enclosed balconies as buffer zones"* action addressing three goals introduced later in the following sections.

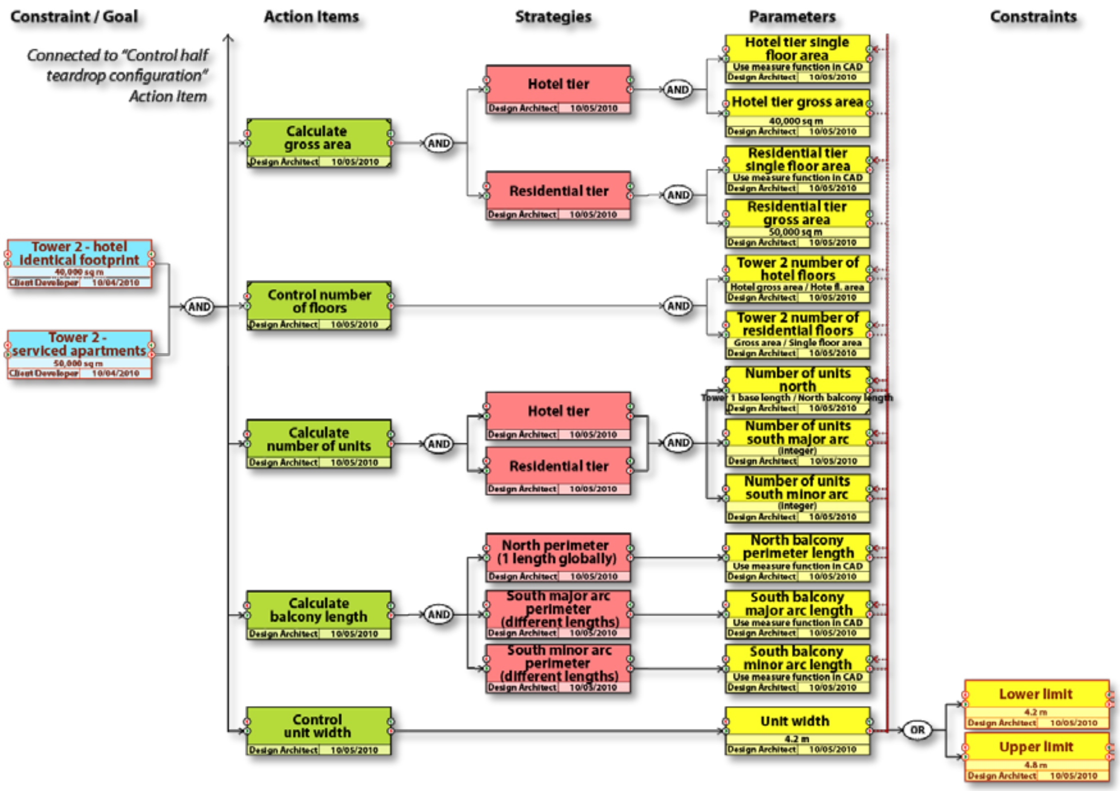


Figure 20: Scenarios Model for constraints No. 2 & 3.

The fifth action was decomposed into three strategies – balcony length along *"North perimeter"*, in which *"North balcony perimeter length"* parameter applied globally because the tower's north side footprint was a straight line (Figure 21a), *"South major arc perimeter"*, and *"South minor arc perimeter"*, in which the *"South balcony major arc length"* and *"South balcony minor arc length"* parameters were unique for every balcony (Figure 21b).

a) b)

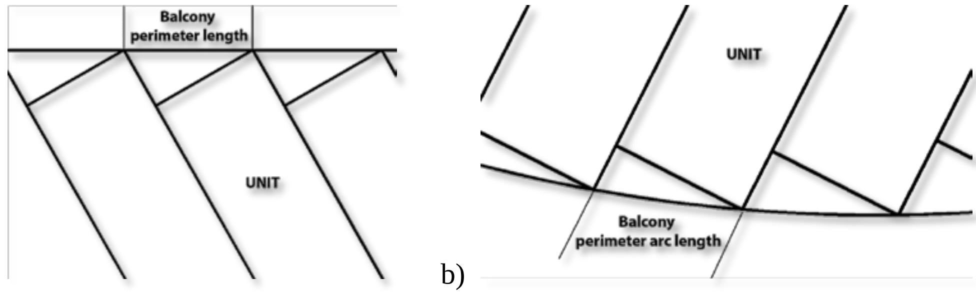


Figure 21: Diagrams illustrating how the balcony lengths were calculated balcony perimeter length on north side; b) balcony perimeter arc length on south sides.

The final action, *"Control unit width"*, was addressed by *"Unit width"* input parameter, which had its values constrained between 4.2 – 4.8m.

Constraint No. 4 – Maximum tower height to last inhabited floor

To address constraint 4 (Figure 22), the design architect proposed only one action – *"Control tower height"*, further decomposed into two strategies: *"Individually"* and *"Globally"*. The XOR relationship communicated that only one strategy had to be chosen given the mutual exclusiveness of these. To attain more flexibility, the architect chose the first strategy addressed through the following five parameters. *"Tower 1 floor height"* was an input parameter with values ranging between 3.0–3.6m (expert knowhow was used to determine this range), *"Tower 1 height"*, an output parameter calculated by multiplying *"Tower 1 No. floors"* from constraint 1 with *"Tower 1 floor height"*. Similarly, *"Tower 2 hotel floor height"* AND *"Tower 2 residential floor height"* were input parameters with values ranging between 3.0–3.6m and used to calculate the *"Tower 2 height"* output parameter.

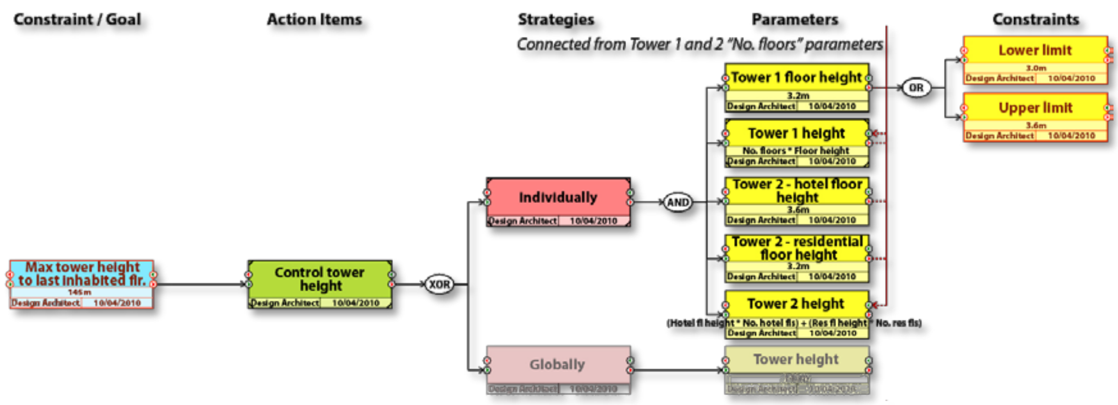


Figure 22: Scenarios Model for constraint No. 4.

Constraints No. 5, 6, 7 – North and South site setbacks, Maximum site coverage

The next three constraints were straightforward to rationalize (Figure 23). The *"Setback north"* and *"Setback south"* parameters (with values greater or equal to 12m and 3m respectively) were the only ones needed to address the site setback constraints. The design architect proposed three required actions describing the *"Maximum site coverage"* constraint: *"Calculate site area"*, addressed through *"Site area"* output parameter calculated by measuring the site area in CAD, *"Calculate ground floor area of both towers"*, addressed through *"Tower 1 and 2 single floor area"* output parameter, and *"Calculate site coverage"*, addressed through *"Percentage of site coverage"* output parameter.

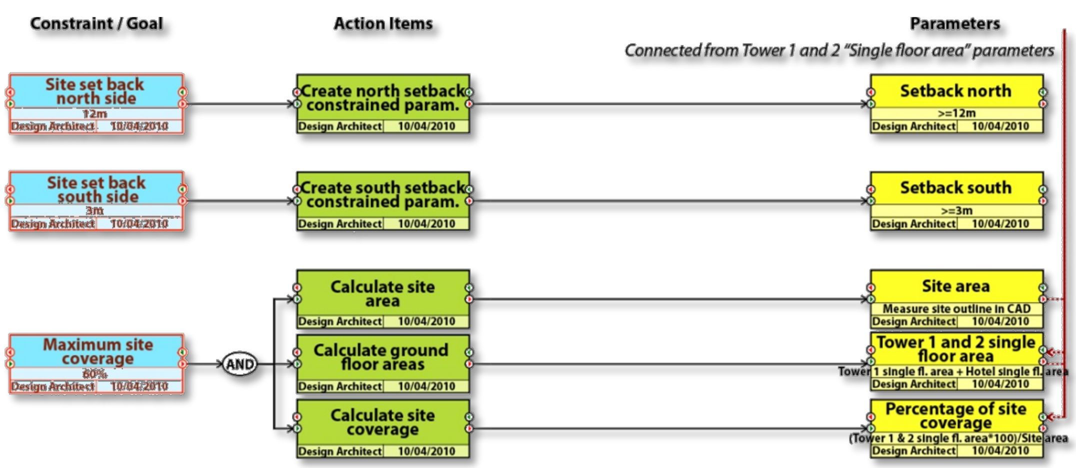


Figure 23: Scenarios Model for constraints No. 5, 6, 7.

Goal No. 1 – Maximize unit exposure to water

The design architect and mechanical engineer proposed three required actions to address the project's most important goal (Figure 24). First, *"Control unit orientation"* was further decomposed into three required strategies – south, north, and city *"facing units"*. Each strategy was addressed by a *"View vector"* input parameter with the angle range determined by the architect based on the site's perpendicular orientation to the water. Second, *"Calculate percentage of units facing water"* was addressed by the *"Percentage of units facing the water"* output parameter calculated through an algebraic expression captured in the parameter node. Third, *"Control tower orientation"* was further decomposed into two strategies – *"Globally"* OR *"Each tower individually"*. The design architect decided to have one input parameter *"Tower rotation"* with an angle ranging between 0-10 degrees applied to both towers.

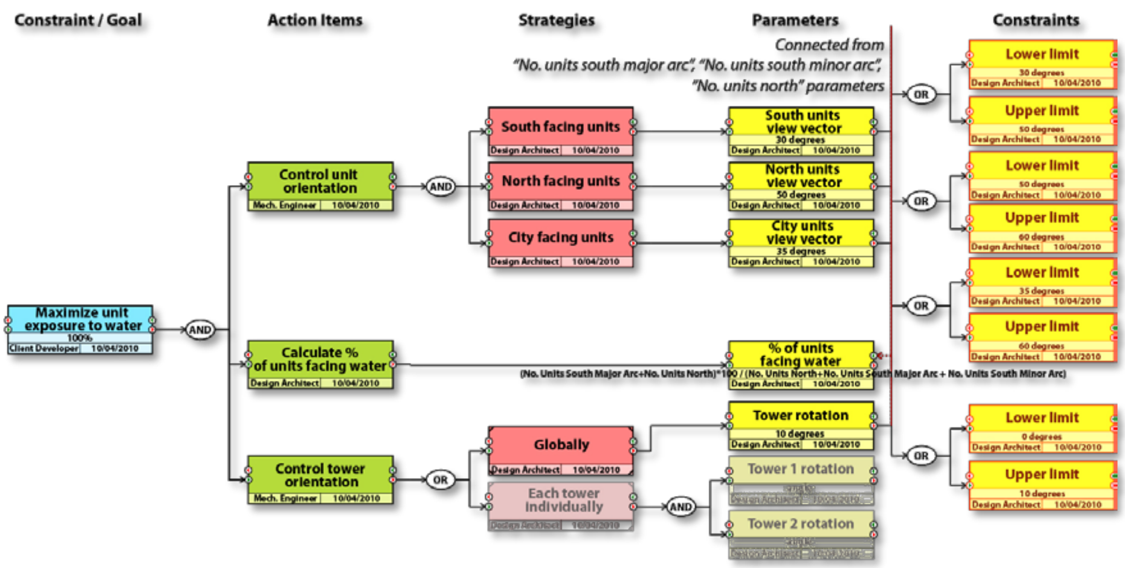


Figure 24: Scenarios Model for Goal No. 1.

Goals No. 2 & 3 – Minimize direct sunlight in units and Minimize solar heat load

To address Goals 2 and 3, the design architect and mechanical engineer proposed eight required actions (Figure 25). *"Control tower orientation"*, *"Control unit width"* from Goal 1 AND *"Control unit width"* from Constraints 2 and 3 also addressed Goals 2 and 3. The fourth action, *"Consider passive shading techniques"*, was decomposed into four strategies. The first two indicated the requirement for top AND bottom balcony sections to be shaded. The architect proposed three output parameters determining the *"Shaded section height"* in Tower 1 and the hotel and residential tiers of Tower 2. The other two strategies offered a choice between two materials – reflective metal vs. fritted glass illustrated through an XOR relationship. The design architect chose the fritted glass strategy in support of two other goals – *"Maximizing unit exposure to water"* and *"Sleek design"*. The *"Frit density"* input parameter explicitly communicated the architect preferred frit range later used in daylight simulations. The fifth action, *"Control balcony depth"* was retracted soon after being proposed because of a conflict with *"Control unit orientation"* action from Goal 1, which already helped determine the balcony depth.

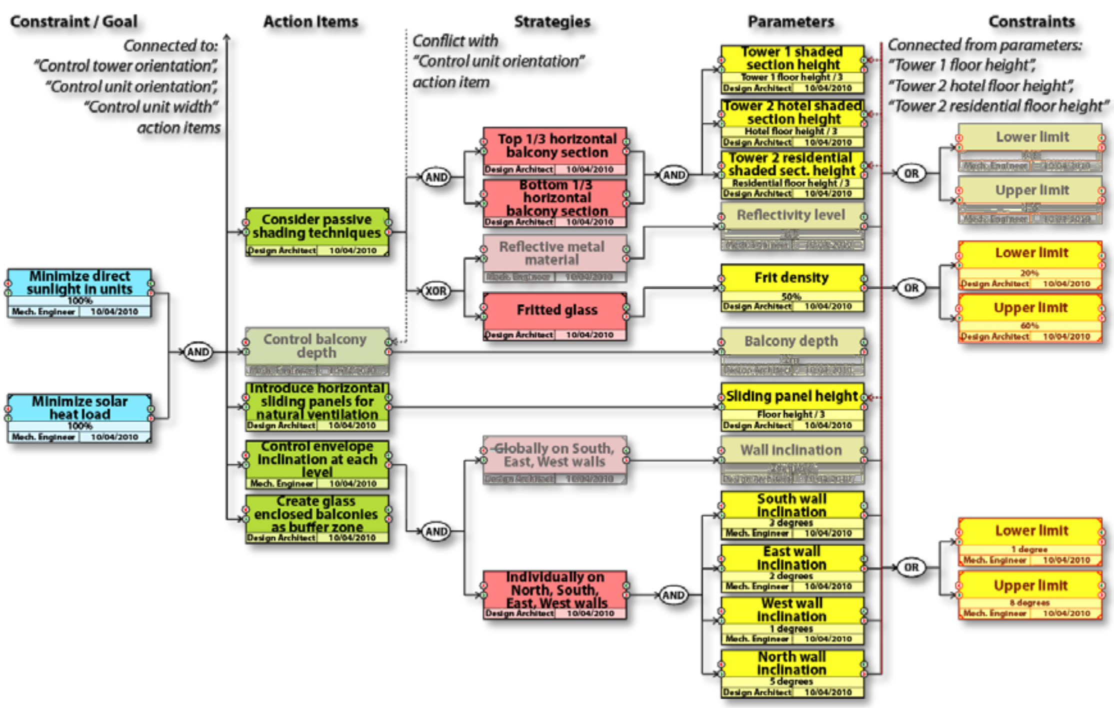


Figure 25: Scenario Model for Goals No. 2, 3.

The sixth action, *"Introduce horizontal sliding panels for natural ventilation"*, was addressed through *"Sliding panel height"* output parameter. The seventh action, *"Control envelope inclination at each level"*, was decomposed into two strategies – globally OR individually on "North, South, East, West walls". The design architect decided on the second strategy in order to attain greater flexibility in exploring design options for the exterior envelope. The mechanical engineer proposed four required input parameters matching the building orientation with an inclination angle ranging between 1–8 degrees.

Goals No. 4 & 5 – Sleek design and Maximize exposure to prevailing wind

The design architect proposed two required actions to address the "Sleek Design" qualitative goal – "Create glass enclosed balconies" from goals 2 & 3 AND "Creating an all glass exterior" complementary action.

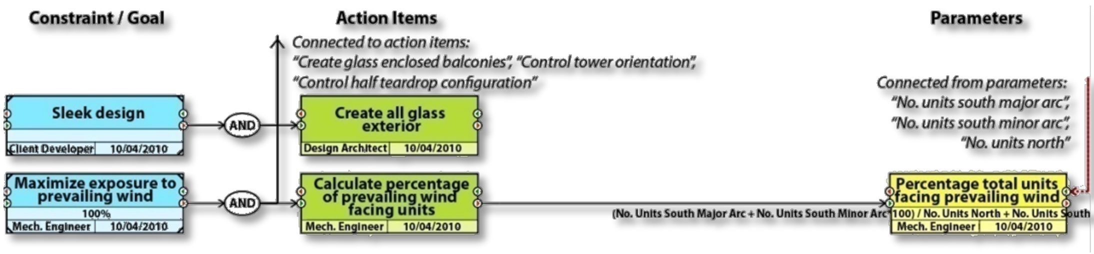


Figure 26: Scenario Model for Goals No. 4, 5.

The design architect and the mechanical engineer decomposed the last project goal into three required actions – *"Control tower orientation"* AND *"Control half teardrop configuration"* from Constraint 1 and Goal 1, AND *"Calculate percentage of prevailing wind facing units"*, assessed through *"Percentage of total units facing prevailing wind"* output parameter. The mechanical engineer proposed the last action after he determined the prevailing wind direction, information also used to write the formula for calculating the output parameter (Figure 26).

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