DESIGN SCENARIOS: METHODOLOGY FOR REQUIREMENTS DRIVEN PARAMETRIC MODELING OF HIGH-RISES

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ABSTRACT: This paper introduces a collaborative, parametric performance-based design methodology that enables teams to systematically generate and analyze high-rise building design spaces based on multi-stakeholder requirements. Building design involves investigating multidisciplinary design spaces with a high number of project-specific variables and constraints. In practice at leading architecture firms today, conceptual design methods support generating very few options that respond to a limited number of design requirements. As a result, potentially better performing design solutions are overlooked. Our research synthesizes a novel, collaborative design methodology called Design Scenarios (DS). The methodology consists of five process steps: (1) Requirements Model used by a multidisciplinary team to collect, weigh and prioritize multi-stakeholder requirements, (2) Design Strategy used to formally transform into parametric models the identified requirements by proposing potential enabling design parameters and identifying conflicting and enabling relationships amongst requirements and design parameters, (3) Parametric Process Model used to generate, manage and communicate the complex structure of a resultant parametric product model from these relationships; (4) Parametric Model used to generate design spaces responsive to identified requirements, (5) Decisions Model used to support the consensus-building and documentation of the best decision by visually reporting the design options' performance back to the designers and stakeholders. We applied DS on a case study presented in this paper. The research is unique in its development of a method to formally generate parametric models from requirements, and for its industrial-scale, practice-based integration and testing of formal design and decision making methodologies for high-rise building design. Improvements are anticipated both in the quality of the design process by reducing uncertainty and inefficiency, and in the resulting product by enabling more options to be considered from more perspectives.

KEYWORDS: design space, parametric modelling, process modelling, requirements engineering.

1. OBSERVED PROBLEM
   The market economy requires project teams to design quickly and cheaply; however, research shows that successful design is largely a function of clear definition of end-user requirements (Rolland, 2005) and the generation and multidisciplinary analyses of a large quantity of options (Kelley 2006). Every project comes up against an inevitable tension between design exploration and process efficiency. Take high-rise design for example. We recently conducted a benchmarking survey of existing conceptual high-rise design practice to determine the performance of leading design teams. We found that on average a multidisciplinary team averaging 12 people can normally produce only 3 design options during a design process that lasts on average 5 weeks. Most of this time is spent by architects on generating and presenting a small number of design options. Little time is dedicated to establishing / understanding project goals and running multidisciplinary analysis. These analyses are inconsistent and primarily governed by architectural rather than multidisciplinary criteria (Gane & Haymaker 2008). Better performing designs are likely left undiscovered.

How can high rise building project teams improve design and critical thinking? Understanding and efficiently managing multidisciplinary requirements early in the design process is a major challenge. So is translating these requirements into a wide range of design options that designers can quickly analyze and systematically choose from. Several points of departure partially address these issues. Design Theory helps us understand the general process of design and define strategies to search the design space. Process modeling can help represent and measure goal-driven design processes. Requirements engineering can help design teams define and manage their building design
criteria in terms of formally structured goals and constraints. Parametric modeling can help efficiently generate geometric options. High-rise Design Methods help categorize the types of high-rises and elicit a list of design constraints, criteria and performance metrics that each category entails (we summarize these in Gane & Haymaker, 2008).

Even with these theories and methods, our benchmarking study shows that the Architecture Engineering Construction (AEC) industry still lacks a methodology that enables project teams to efficiently integrate them into practice. They lack a methodology to define and prioritize requirements, translate these requirements into geometrically flexible parametric models, to analyze these models efficiently from multiple perspectives, and to understand the multidisciplinary tradeoffs of individual options and spaces of options. In another paper we describe how the lack of such a method substantially reduces the effectiveness of parametric methods and stalls multidisciplinary design and decision making processes (Gane & Haymaker 2007). This research establishes such a methodology and begins to test its impact in practice.

2. THEORETICAL POINTS OF DEPARTURE
In this section we describe the fundamental points of departure for this research.

2.1 Design theory
Design is a creative process, where part of the task is to formulate the problem itself (Simon 1969). Design teams are aided by multi-stakeholder value-based design and decision making methodologies (Lewis et al 2007, Jin & Danesh 2007, Keeney & von Winterfeldt 2007). AEC focused researchers are developing related theory and methodologies, describing the design as (1) identifying a set of requirements; (2) prioritizing among these requirements; (3) developing preliminary solutions; (4) evaluating solutions; (5) establishing final design requirements, preferences and evaluation criteria (Akin 2001). Others are applying these concepts in formal design and decision making methodologies (Ellis et al 2006, Haymaker & Chachere 2007).

While designing, teams construct a design space, formulated as the sum of the problem space, solution space, and design process (Krishnamurti 2006). Two prevailing strategies emerge to describe the process of constructing a design space: breadth first, depth next or depth first, little breadth. Designers typically consider a very small number of alternatives as a result of cognitive limits (Woodbury and Burrow 2006). Therefore, they are forced to make decisions that are not optimal but only satisfactory according to a pre-set aspiration level. In contrast, expert designers prefer the breadth first, depth next strategy (Akin 2001). As a result, multiple alternatives help reveal new directions for further exploration that the designer wouldn’t have thought of otherwise. Design teams need dynamic rule-driven systems that help them set up and manage design generation processes with the right balance of breadth and depth strategies to best address the multidisciplinary requirements.

2.2 Process modelling
Design theory helps us understand the general process of design; however it does not help us determine how specifically to represent and measure design processes. Such understanding can help quantify and compare the performance of existing and proposed processes, as well as provide the tools that help organizations adopt the proposed processes. A widely accepted implementation method is process modeling. Multiple process models for AEC have been proposed (Froese 1996). Among other significant process models are IDEF0 (Integrated Definition Methods) used to model decisions, actions, and activities of an organization or system, the Narratives (Haymaker et. al. 2004) that provide a means to model information and the sources, nature, and status of the dependencies between information, and Value Stream Mapping (Tapping & Shuket 2002) used to illustrate and analyze the flow of actors, activities, and information that produce value in a given process in order to assist in process re-engineering. Despite the wealth of existing process modeling methods, an important need specific to this research is not adequately met – a representation formalism for communicating the structure of parametric models and their multiple levels of multidisciplinary information dependencies.

2.3 Requirements engineering
Poor definition or misunderstandings of requirements are major causes of system failure in software engineering (Rolland & Salinesi 2005), mechanical engineering (Hsu & Woon 1998), and in AEC (Kiviniemi et. al. 2004). Systematic methods to screen and prioritize among design requirements have been proposed (i.e. Quality Function Deployment (Takai & Ishii 2006, Leary & Burvill 2007), PREMISS (Kiviniemi et. al. 2004), MACDADI (Haymaker & Chachere 2007). While some methods help designers translate requirements into feasible design
options (i.e. Chen & Pai 2005), no systematic method exists for reliably generating parametric design spaces from a multidisciplinary requirements model. Requirements Engineering (RE) can help formalize such a process. RE is used as a means to overcome the drawback of traditional software development methods, in which the developed systems are often technically good but unable to appropriately respond to the users’ needs (Rolland & Salinesi 2005). RE helps determine the features the system needs to satisfy, and how the system is to be constructed (Ross and Schoman 1977). Reasoning with requirements can also help resolve conflicts among stakeholders. To develop better solutions designers need to understand how requirements relate to each other as well as to other elements in the requirements model. AND/OR graphs are used to capture goal refinement links (Lamsweerde 2000). While RE provides an actionable method to help designers translate requirements into better solutions, it does not provide a specific means to translate design requirements into options generated with parametric methods – a task that this research proposes to address.

2.4 Parametric modelling
Parametric computer-aided design (CAD) is a design methodology used to create design spaces and manage geometric dependencies within a model. The concept of “features” not present in other CAD systems, encapsulates generic shapes or characteristics of a product with which designers can associate certain attributes and knowledge useful for reasoning about that product (Shah & Mäntylä 1995). Using parametric CAD tools designers can create an infinite number of objects, geometric manifestations of a previously articulated schema of variable dimensional, relational or operative dependencies (Koralevic 2003). However, designing with multiple constraints without an efficient constraints management system is a daunting task. An example of a constraint management methodology are the design sheets, in which design models are represented as constraints between variables in the form of nonlinear algebraic equations organized into bipartite graphs and constraint networks (Reddy et al 1996). Using only design sheets to define high-rise parametric models would be challenging given the overwhelming number of constraints that need to be described at the schema level and the inability to visualize geometry. As a result, in parametric systems, Geometric Constraint Programming (GCP) is used to graphically impose geometric constraints to solve the relevant nonlinear equations without the user explicitly formulating them (Kinzel et al 2007). This research, however, identified the lack of a formal method to determine constraints and parameters for constructing parametric models with sufficient flexibility to respond to a set of multidisciplinary requirements.

2.5 High-rise design methods
This point of departure helps categorize the types of high-rises and elicit a list of design constraints, criteria and performance metrics that each category entails. In prior work we have reviewed many specific goals and methods for high-rise design found in literature (Gane & Haymaker, 2008). Understanding and translating these requirements into quantifiable architectural and energy performance goals and constraint is important in the process of building parametric models.

3. RESEARCH QUESTIONS
Our research proposes to answer the following questions:

• What is a method to generate conceptual parametric models of high-rise design spaces that respond to multidisciplinary performance requirements?
• What is a method to synthesize these requirements models, parametric models, performance analysis models, and decision making models into an effective and efficient methodology for high-rise design practice?

4. RESEARCH METHOD DESCRIPTION
In Figure 1 illustrates the updated conceptual design process called Design Scenarios that we designed to address these questions. Such a process starts with a clear set of architectural and engineering performance requirements that help establish the design space. The identified requirements guide the generation of design alternatives within the established design space. Alternatives are then formally analyzed in discipline specific tools. A bi-directional relationship between alternatives and analyses supports a recurring refinement process. The multi-attribute performance of each alternative helps determine its value and establish a formal decision making process. Analyzed options are then correlated with the requirements to determine their value and choose best option.

The goal of this research is to: help design teams formally identify architectural and engineering performance requirements and translate them into parameters for developing design alternatives with parametric CAD (link between boxes 4.1 & 4.2, 4.2 & 4.3, Fig. 1); help determine the value of each analyzed option in relation to specific requirements (link between boxes 4.1 & 4.4). Parallel research is being conducted at CIFE, Stanford to automate the
engineering performance (i.e. energy, daylight, thermal comfort) analyses generated with parametric CAD (link between Analyses Models & box 4.4), as well as determine importance of design parameters in relation to specific requirements (link between Analyses Models & box 4.3).

FIG. 1: Proposed conceptual design process.

Following is a description of the models comprising the Design Scenarios methodology.

4.1 Requirements Model (RM)
The augmented conceptual design process starts with building a RM. Unlike current practice, in which the architect unilaterally makes most of the early design decisions based on a set of loosely defined requirements, building a RM will require in addition to stakeholders the participation of all design disciplines (architect, structural, and mechanical engineers). The RM is hosted online to facilitate remote definition of a comprehensive set of high-level project requirements by the project users (stakeholders and design team), who prioritize them according to their level of importance. Each participant has to distribute 100 percentage points to each identified goal, which represents their preference. Inputs range from stakeholder defined requirements (i.e. architectural brief, budget, building efficiency) to those established by the multidisciplinary design team (i.e. preferred design language, daylight factor, thermal comfort). The output of this model is a stacked column chart distinguishing the stakeholders’ and design team’s priorities and constraints. Determining a comprehensive set of multidisciplinary requirements that helps eliminate the non productive ambiguity in current early decision making practice is the major benefit of building a RM. The RM also provides the formal value function for evaluating design options.

4.2 Design Scenario Model (DS)
Building a DS will help the design team map requirements to design strategies (i.e. determining means of achieving requirements). The goals and constraints from the RM are grouped and serve as the initial inputs into the Design Scenario environment. A DS consists of five levels of hierarchically built information – (1) the RM-established high-level requirements; (2) Action items; (3) Strategies; (4) Parameters; (5) Parametric constraints.

- **Requirements** - Building on concepts defined in the RM, the DS further categorizes and defines the requirements in terms such as: Quantifiable (i.e. maximize use of daylight in 50% of interior space, provide 50,000 sq m of usable area) and Non-Quantifiable (i.e. use a specific design language). Requirements are further decomposed into: Goals (objectives – i.e. design within $80m budget) and Constraints (requirements whose satisfaction is compulsory – i.e. 50,000 m² usable area).

- **Actions items** - Discipline-specific design team leaders decompose each relevant high-level requirement into Action Items. These are determined by asking the HOW question for each requirement. Building on concepts from Artificial Intelligence (Lamsweerde, 2001), the DS describes relationships between Action Items through AND/OR links. For example, to provide daylight in 50% of the building interior designers need to: (a) control the building orientation; AND (b) control the lease span; OR (c) introduce shading fins; OR (d) introduce light shelves; AND (e) control window configuration; AND (e) control glass type, etc. All Action Items with AND links are required to satisfy the original requirement, whereas an OR link illustrates a choice of action;

- **Strategies** – In case Action items cannot be directly translated into geometric or material parameters (i.e. choose window configuration), design team leaders further decompose these into Strategies (i.e. butt glazed, expressed mullions, unitized panel, etc).

- **Parameters** - Action Items or Strategies are decomposed into geometric and/or material parameters, the value of which will determine the design’s performance in relation to a specific requirement. For example, to introduce shading fins a designer must create a depth parameter of length type AND an inclination parameter of angle type after anticipating the need to adjust the shading fins’ geometry in response to the provide daylight
in 50% of interior quantifiable goal. Parametrically controlling the depth and inclination of shading fins offers efficient means to refine the geometry after a formal daylight analysis is performed.

- **Parametric constraints** – When identified parameters are required to be within specific ranges, these parameters are decomposed into *Parametric constraints* (i.e. No. Floors parameter decomposed into Lower limit – 30 floors; Upper limit – 50 floors parametric constraints).

The DS will also allow design teams to model relationships between the above concepts. The explicit definition of parameters will help determine potential interdependencies. For example, the *shading fins depth* input parameter will impact the *shading fin area* output parameter, which in turn will determine the *shading fin cost* parameter used in calculating the overall design cost. Potential conflicts among requirements may not become apparent just by developing a Requirements Model, but can be identified when Action Items and Parameters are determined and related. For example, *introduce shading fins* Action Item can potentially conflict with *design within $80m budget* quantifiable goal given the additional cost of external fins. A DS will explicitly show such conflicts and help the design team mediate an updated set of requirements with the stakeholders, thus avoiding costly design revisions common in current practice. Knowledge of these dependencies will guide the CAD specialists (i.e. parametric modelers) in creating a model that is optimally constructed to address the identified requirements. The DS model output is a bipartite graph whose orientation, level of detail, and format are user determined.

### 4.3 Parametric Process Model (PPM)

PPMs help the design team illustrate and manage the logical construct and technical implementation of a DS in a parametric CAD model. CAD specialists build PPMs. Input, output and constrained parameters and the relationships/dependencies established in the DS serve as the initial inputs. A PPM also consists of *Components* made of geometric and construction elements, *PowerComponents* made of generic components grouped and intended to be used in unique contexts, *Geometric Constraints* used to establish relationships among geometric elements and parameters, *Information Dependencies* (i.e. Component A dependent on Component B or Component A dependent on input parameter(s), etc). A PPM is a formal roadmap to building a parametric model. Parameters and relationships established in the PPM are used as inputs to automate their generation in a chosen parametric modeler (i.e. Digital Project, Generative Components). The output of the process is a bipartite graph whose orientation and format is user determined and the beginning of a parametric model that requires the CAD specialists to build the components described in the PPM graph and link the automatically generated parameters.

### 4.4 Options Analysis Model (OAM)

OAMs help the design team evaluate how each option generated from a parametric model and analyzed in discipline specific tools (i.e. daylight in Radiance) ranks in relation to the high level requirements identified in the RM. Scores measured in percentage points are assigned to each option based on low and high benchmarks (i.e. high benchmark – minimize cost to $80m, low benchmark – minimize to $100m). If an option achieves a goal, it receives 100% score. If it exceeds it (i.e. $70m, it receives the percentage scored above the high benchmark – 112.5%, etc). This allows design teams to determine the impact of each option’s performance against the RM goals. Goals, however, ranked in terms of their importance to each discipline are also measured in percentage points. To determine the final value of each option, the impact score for each goal is multiplied with the appropriate goal importance score and summed into a final value function score. The outputs of OAM are spider diagrams and column graphs. An OAM offers design teams a formal unifying structure and communication tool for describing and managing the quantitative and qualitative analyses of options.

### 5. CASE STUDY – HIGH-RISE IN SAN FRANCISCO, CA

We are developing a web-based Design Scenarios software platform to significantly improve the DS modelling process by partially automating the generation of each consecutive model and feed the generated parameters into a parametric modeller. Prospective validation of DS in practice is expected in 2010-2011. Our research method involves using an embedded researcher (Hartmann et. al. 2008) who will spend approximately one month in an AE firm. DS will be introduced in several training sessions. Studio members will have prior experience of using parametric modelling on several projects. DS will be used by the trained team on several case studies (office towers), in which the conceptual design process lasts about three weeks. Our goal is to improve DS through iterative implementation by testing it against the following metrics: (1) goal definition clarity; (2) concept design duration; (3) No. generated options; (4) team size / composition; (5) total man hours per discipline; (6) time per task; and (7) explicit analyses performed. We describe our validation of the Design Scenarios using retrospective data and a
A hypothetical high-rise project in San Francisco. The illustrated models are abbreviations of larger models for the purpose of this paper.

5.1 Requirements Model (RM)

The project commenced with a meeting between the stakeholders (developer team) and the senior design team members (architect, mechanical and structural engineers). The designers’ objective was to elicit a comprehensive list of project requirements and help the developers determine target metrics for those requirements that traditionally fall outside of their domain of expertise (i.e. energy efficiency). The stakeholder-defined architectural brief was used to establish the initial requirements, most of which were determined to be constraints (i.e. area requirement, height limitation). Several quantifiable and non-quantifiable goals were also identified (i.e. maximizing building efficiency to 85%, minimizing construction cost based on the project budget of $80m, design to be widely recognized in San Francisco). The benefit of this new meeting format became apparent in the subsequent discussion, when the senior mechanical engineer (normally not present in the first few meetings) suggested several additional goals for improving the building’s energy efficiency and supported by target metrics (i.e. maximize the use of daylight to 500lux – optimal for office spaces; maximize thermal comfort to a range between 22-26°C; minimize energy consumption to 600MJ/m²/year (~1000MJ/m²/year is the current average). Once the list of goals was accepted by all parties, every participant individually ranked each goal according to his/her preference, measured in percentage points. This helped determine the most important goals and the weighting preferences for each discipline. For example, the developer team, the architect and the structural engineer saw the recognizable design as their leading requirement whereas the mechanical engineer gave more weight to daylight, thermal comfort and energy consumption goals. The outcome of the meeting was a good understanding of what the project requirements were and their level of importance to each discipline. These were formally represented in the Constraints and Goals models (Fig. 2).

![FIG. 2 – a) Project constraints whose satisfaction was mandatory; b), c) Ranked project goals - participants had to distribute a percentage of preference (totaling 100%) to each identified goal](image)

5.2 Design Scenario Model (DS)

Back in the studio the senior design team organized another meeting, in which the high-level requirements from the RM served as the starting point for building the DS. The meeting lasted one day, during which the constraints and goals were first grouped and decomposed into Action Items (AI). The process was collaborative given that some constraints and goals resulted in multiple AIs suggested by one or several disciplines. For example, two AIs were proposed for Recognizable design goal - creating an aesthetically unprecedented design (architect) and a structurally unprecedented design in San Francisco (structural engineer). These AIs were acknowledged as vital to the project given the importance level of the parent goal to the developer and the design team. Both AIs were assigned an AND Link and therefore required to be implemented in the final design. In case of multiple OR Links, one option must be selected. Similarly, the mechanical engineer developed AIs for his relevant goals. For example, for the maximize daylighting goal he proposed three AIs with appropriate goal refinement links (control building orientation...
FIG. 3 – Case study project Design Scenario Model (DS)
The architect proposed additional three for the same goal (choose window configuration – AND Link; control the lease span – AND Link; introduce central atrium – OR Link). The architect assigned an OR Link to the central atrium AI because of his knowledge of how important minimizing construction cost and maximizing efficiency were to the developer. This understanding helped identify a potential goal conflict. An atrium in a project constrained by height and site setback made it impossible to achieve the efficiency and potentially the construction cost goals. Design Scenarios, however, is built as a recursive process. Therefore, the atrium option was kept in the design scenario in case the preferences for high-level goals changed.

Some AIs required further decomposition into Strategies. For example, after evaluating the site and its context, the architect suggested three possible strategies for the aesthetically unprecedented design AI – round OR rectilinear footprint, AND mainly glass exterior. Once all AIs and strategies were finished, each discipline proceeded to decomposing these into input and output parameters. For example, for the Tower height range constraint the architect proposed one AI – determine No. floors, which was decomposed into Total No. floors AND Floor height input parameters. When constraints were specified, parameters were further decomposed into Parametric constraints (i.e. Total No floors -> Lower limit – 30, Upper limit – 50). When appropriate, parameter interdependencies were specified for determining output parameters (i.e. Floor height will determine the Window height output parameter).

Without formal knowledge of parametric modelling, the senior design team was able to describe Action Items in terms of parameters and parameter interdependencies. The abbreviated DS model is illustrated in Fig. 3.

5.3 Parametric Process Model (PPM)

Fig. 4 illustrates the case study PPM. Each component that has a visual preview is numbered. The input variables and geometric constraints for each component are lettered and their location is shown in the component preview.

The completed DS model served as a starting point for parametric CAD specialists to build the PPM. The AIs helped determine the goals and constraints that affected the initial decisions of how to build a parametric model. Input and output parameters were correlated with the appropriate AIs before building PPM components. For example, the senior architect specified two geometric possibilities for the aesthetically unprecedented design AI - curved or rectilinear footprint, which required the parametric model to support changes in geometric topology. Therefore, the Ground footprint (1) (component (1), Fig. 4) was composed of BSpline of order 2 that supported such transformation. Being a linear BSpline it can either be a line or a curve depending on how it is geometrically constrained to other geometric elements. The choice of geometry helped determine the geometric constraints controlling the component and assign the appropriate parameters established in the DS. For example, building side length (B) input parameter controls the length between the BSpline endpoints, which use a concentric (E) and tangency (F) constraint to a skeleton of construction (dashed) lines. Tangentially constraining the BSpline endpoints to the construction lines will change the geometry’s topology. The construction lines’ endpoints are coincidently (C) constrained to establish a pin connection. The lines use a perpendicular constraint (D) to avoid arbitrary rotation. In response to control building orientation AI the rotation angle (A) parameter is introduced by constraining the angle between the construction line end point and the chosen axis of the user coordinate system.

Having established the ground footprint allows the dependent components to be constructed. For example, Building core footprint (2) is constrained through length to exterior wall (A) parameter to the ground footprint (1) BSplines, which established a component dependency. Changes in the footprint impacted the core unless the length to exterior wall parameter was adjusted to compensate the increase or decrease in the building length parameter. The remaining components were similarly built.
5.4 Options Analysis Model (OAM)

The design team used the resultant parametric model to generate over 1,000 design variations in one week by operating the values of several key input parameters (i.e. building side length, lease span, floor height, lightshelves depth, window width). Building an OAM required them to analyze the options to formally understand their performance. However, most of the options were discarded after not meeting constraints that were defined as output parameters (i.e. No. floors, building net area, and building efficiency). The options that passed these requirements were visually analyzed by the senior designers, who chose 20 options (5 shown in this paper) for further formal analysis outside of the parametric model.

For example, to calculate the daylight performance, mechanical engineers used Autodesk Ecotect. Key parameters that determined the performance for each option were Lease span, Floor height, Light Shelf depth, and Window width. The analyses results were compared against the target value of 500lux. However, no formal model based analysis was performed for thermal comfort and energy consumption. Currently, a widely accepted tool for performing such analysis is EnergyPlus by the US Department of Energy. Interoperability and model preparation issues make the use of this tool in early stages of design daunting. As a result, the mechanical engineers evaluated the thermal comfort and energy consumption performance of the selected options by analyzing a combination of geometric parameters used to generate each option. For the Minimize energy consumption goal, for example, each option was evaluated in terms of four key parameters: Lease span, Floor height, Lightshelves depth, Window width. A deeper lease span, a taller floor height, and a smaller light shelf (used to block direct sunlight along the building perimeter) meant greater volume to condition with mechanical systems and greater variation in internal temperature, which made the option less energy efficient.
The OAM required building the impact and value models of each analyzed option. After performing each analysis on all selected options, the senior designers determined the low benchmark for each discipline specific goal and then assigned a score representing the performance measured in percentage points. For example, any option that resulted in an average daylight value of 500lux scored 100% (benchmark determined in the Requirements Model), and 0% if it had an average of 0lux. The impact score for each option was determined by summing the scores of each goal for that option (i.e. Option 1 = 515 - Fig. 5a). However, as determined in the RM, goals were ranked according to their level of importance to the stakeholders and the design team (i.e. Recognizable design = 115 points – Fig. 2b). The OAM required determining the option total value score before choosing a winning design. The sum of each goal in the RM was translated into a percentage of importance from the total of 400 points that the four participants had to distribute (i.e. Recognizable design goal scored 115 points or 29% overall importance – Fig. 2c). Multiplying each goal’s preference score to the impact score determined the goal value of each option (i.e. Option 1, Recognizable design – 29% x 70 = 20). Summing the value of all goals resulted in the overall value per option (i.e. Option 1 = 86 - Fig. 5b, 5c) Fig. 5d illustrates the parameter values determining the 5 selected options and total value scores.

<table>
<thead>
<tr>
<th>Options’ impact scores (%)</th>
<th>Options’ value scores (%)</th>
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</thead>
<tbody>
<tr>
<td>Recognizable design</td>
<td>Option 1</td>
</tr>
<tr>
<td>Maximize daylight</td>
<td>100</td>
</tr>
<tr>
<td>Maximize thermal comfort</td>
<td>95</td>
</tr>
<tr>
<td>Maximize leasable area</td>
<td>80</td>
</tr>
<tr>
<td>Minimize construction cost</td>
<td>70</td>
</tr>
<tr>
<td>Minimize energy consumption</td>
<td>100</td>
</tr>
</tbody>
</table>

| Recognizable design | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 |
| Maximize daylight | 20 | 16 | 14 | 22 | 23 |
| Maximize thermal comfort | 15 | 13 | 11 | 10 | 10 |
| Maximize leasable area | 7 | 5 | 6 | 5 | 9 |
| Minimize construction cost | 7 | 9 | 10 | 9 | 8 |
| Minimize energy consumption | 14 | 12 | 10 | 10 | 8 |

515 455 390 405 455

86 74 60 67 75

FIG. 5 – a), c) Case study OAM impact model; b), d) value model used for final decision making – option 1 scored the highest and was considered the winning design.

6. CONCLUSIONS

In previous work (Gane & Haymaker 2008) we have benchmarked current conceptual high-rise design processes in terms of the metrics listed in Fig. 6. This paper presented a new collaborative design methodology called Design Scenarios and illustrates a case study of applying DS on a high-rise project. We compare the metrics of current practice with anticipated metrics from the case study. We investigate how a high degree of goal definition clarity can help a multidisciplinary design team build parametric models and explore and analyze a much larger segment of the design space in less time. Unfortunately, based on the presented case study of implementing DS we cannot claim generality of our findings. However, the Design Scenarios methodology and defined metrics can guide research and development efforts to improve these measurements, and can serve as a benchmark for comparing new design methods, tools, and processes.
7. REFERENCES


