



**CIFE** CENTER FOR INTEGRATED FACILITY ENGINEERING

# Benchmarking Conceptual High-rise Design Processes

By

**Victor Gane & John Haymaker**

**CIFE Technical Report #TR174  
OCTOBER 2008**

**STANFORD UNIVERSITY**

**COPYRIGHT © 2008 BY**  
**Center for Integrated Facility Engineering**

If you would like to contact the authors, please write to:

*c/o CIFE, Civil and Environmental Engineering Dept.,  
Stanford University  
The Jerry Yang & Akiko Yamazaki Environment & Energy Building  
473 Via Ortega, Room 292, Mail Code: 4020  
Stanford, CA 94305-4020*

# **Benchmarking current conceptual high-rise design processes**

Victor Gane<sup>1</sup>, John Haymaker<sup>2</sup>

<sup>1</sup> PhD Candidate, Center for Integrated Facility Engineering, Civil and Environmental Engineering, Stanford University, [vgane@stanford.edu](mailto:vgane@stanford.edu)

<sup>2</sup> Assistant Professor, Center for Integrated Facility Engineering, Civil and Environmental Engineering, Stanford University, [haymaker@stanford.edu](mailto:haymaker@stanford.edu)

## **Abstract**

This paper presents an analysis of current conceptual design processes for high-rise buildings. We synthesize a method to document and measure these processes and use it to analyze data from several case studies and a survey of leading architectural and engineering design firms. We describe current high-rise conceptual design process in terms of: design team size, composition, and time investment; clarity of goal definition; number and range of design options generated; number and type of model-based analyses performed; and the criteria used for decision making. We identify several potential weaknesses in current design processes including lack of clarity in goal definition and a low quantity of generated and analyzed options. We argue that potentially higher performing designs are being left unconsidered, and discuss the potential reasons and costs.

## **Keywords**

High-rise, conceptual design, design exploration, multidisciplinary analysis, work process mapping

## **Introduction – the need for effective conceptual high-rise design processes**

The twentieth century experienced an unprecedented demographic shift. The world population more than doubled in the last 40 years. A 2004 United Nations report [1] predicts that by 2050

the world population is expected to exceed 9 billion, and by 2010 the world's urban population for the first time will surpass the rural one. Across the globe, low-density urban sprawl is the solution to population growth. There is mounting consensus among the scientific community that urban sprawl has significant negative social, economic and environmental implications [2, 3]. Four billion additional people will need housing and work places in just a few decades. An immediate way to address population growth is for cities to support high-density buildings, particularly high-rises. Over the past century, high-rises have successfully and increasingly responded to this need. We calculate that housing for 4 billion people will require constructing close to 4 million 40-storey high rise buildings (each with 1,050 occupants in 350 units).

Yet most high-rises perform poorly in terms of lifecycle cost, environmental impact and social benefit. According to Yeang [4], in a 50-year lifecycle of a high-rise, energy costs contribute 34% of the total cost. Close to 50% of energy use in high-rises comes from artificial illumination [5]. Kaplan [6] indicates that a typical high-rise building is made of poor quality materials and is aesthetically mundane. Successful high-rise designs need to use a minimum of nonrenewable energy, produce limited pollution, and minimize their carbon footprint, without diminishing the comfort, health, functional needs, and safety of the people who inhabit them.

To respond to these mounting environmental, economic, and social pressures, the Architecture, Engineering, and Construction (AEC) industry needs to revise traditional high rise design and analysis methods. Recent advances in computer-based methods promise vastly improved design processes, but current teams are ill equipped to take advantage of these new opportunities. To help them understand the reasons behind current inefficiencies and develop and implement more integrated design and analysis methods we must first document and measure existing conceptual

high-rise design processes in terms of quantifiable metrics on which to base and compare the performance of prospective improvements.

Little research has been carried out in this area; the goal of this paper is to fill the gap. Through literature review and industry-based case studies, this paper develops a definition and relevant metrics describing conceptual high-rise design processes, and applies this definition and metrics to a set of contemporary case studies and survey data. We find that conceptual design teams generally operate with low project goal clarity, and generate very few formal design options and analyses that neglect environmental and life-cycle economic considerations. We conclude with a discussion about the potential causes and costs of today's greatly underperforming high-rise design processes.

**Points of departure: What are current high-rise design processes and how do we document and measure them?**

In this section, we look to design theory for a theoretical definition of high-rise design processes; to process modeling for a method to describe and measure these processes; and to high rise-specific literature for classification and key design criteria.

### **Design theory**

Akin [7] formulates conceptual design as a five-step process: 1) identifying a set of requirements; 2) prioritizing among these requirements; 3) developing preliminary solutions; 4)

evaluating solutions; and 5) establishing final design requirements, preferences and evaluation criteria. Haymaker and Chachere [8] further formalize these distinctions in the MACDADI (Multi-Attribute Decision Assistance for Design Initiatives) framework, which includes: 1) *organizations* – a project’s stakeholders, designers, gatekeepers and decision makers; 2) *goals* – these organizations’ constraints, objectives, and preferences; 3) *options* – design options and methods to generate them; 4) *analyses* – the methods, timing, and types of analyses performed; and 5) *decisions* – rationale and process for making decisions. This paper is structured using these MACDADI distinctions.

Design is an unbounded process; there are infinite numbers of organizations, goals, options, analyses, and decisions that a team potentially can consider. Simon [9] in his behavioral theory of bounded rationality describes people as partially rational when making decisions, due to computational limitations in gathering and processing information. Woodbury and Burrow [10] also argue that designers typically consider a very small number of alternatives in their work as a result of cognitive limits. As a result, designers often make decisions without fully understanding their implications.

To develop solutions, designers first establish a design space. Krishnamurti [11] defines a design space as the sum of the problem space, solution space, and design process. A *problem space* includes only the candidate solutions that satisfy the established design requirements. A *solution space* includes all candidate solutions for a given design problem. A *design process* consists of methods used to develop candidate solutions from requirements. The extent of the design space is highly dependent on the designer’s interpretation of the design problem, the choice of design

criteria (project goals and constraints), and the employed design process. Two prevailing strategies emerge to describe the design process: *breadth first, depth next* or *depth first, little breadth*. The breadth first strategy entails generating multiple design options first, and then analyzing them to determine which ones meet the sought requirements. Depth first strategy entails generating a single option and analyzing it in depth.

Goldschmidt [12] argues in favor of the depth versus breadth strategy, in which both known architects and novice students deliberately choose a limited design space to conduct their exploration. The goal is refining and enriching a “strong idea” supported by well-developed design rationale. In contrast, Akin [7] argues that in solving problems expert designers prefer the breadth first, depth next strategy. As a result, multiple alternatives help reveal new directions for further exploration. Each strategy has significant implications in the way teams generate designs. Currently there is no consensus about which strategy performs best, although in light of rapidly evolving project teams, goals, options, and analyses, many researchers argue that the sheer quantity of options generated by a breadth first search enables designers to find more successful solutions in terms of multi-criteria and multidisciplinary performance [41].

Design theory helps us understand design processes, but it does not help us understand how to specifically represent and measure them. A widely accepted method for this kind of representation and analysis is *process modeling*.

## **Process modeling**

There are three general applications for process models: a) *descriptive*: for describing what happens during a process; b) *prescriptive*: for describing a desired process; and c) *explanatory*: for describing the rationale of a process [13]. Froese [14] presents a comprehensive overview of AEC-specific process models, including IRMA (Information Reference Model for AEC, BPM - Building Project Model), ICON (Information / Integration for Construction), and GRM (Generic Reference Model). Most of these are based on EXPRESS-G modeling language [15], which provides a foundation for graphically representing process models. Other significant process modeling languages relevant to this paper are: IDEF<sub>0</sub> [16], used to model decisions, actions, and activities of an organization or system; Narratives [17], which model information and the sources, nature, and status of the dependencies between information; and Value Stream Mapping [18], which describe the flow of actors, activities, task duration, and information that produce value in a given process.

With these process-modeling languages, we can describe design processes but not establish process measurement metrics. To address this problem various techniques have been proposed; for example, to evaluate BIM (Building Information Model) users practices and processes [19], to measure benefits from VDC (Virtual Design and Construction) use and factors that contribute to its successful implementation [20], or to simulate the impact of improvements to the engineering design process [42].

In spite of the wealth of existing process modeling languages, none can describe and measure design processes in terms of all the distinctions included in the MACDADI framework. This paper later synthesizes a process model and metrics to describe high-rise design team size and

composition, the clarity of their goal definitions, the number of design options they generate and analyze, the prevailing objectives used in their decision making, the conceptual design duration, and the discipline-specific time invested.

### **High-rise classification and key design criteria**

In the late 19<sup>th</sup> century a wave of innovations in the building industry led to the development of the first high-rises in Chicago and New York [21]. The elevator, the steel frame, and later the curtain wall and HVAC, along with the demand for new office space on expensive and limited land, made the development of high-rises possible and necessary. Despite the success of high rises, the AEC industry lacks a consistent definition of the building type. The American Society of Heating, Refrigeration and Air-conditioning Engineers (ASHRAE) defines high-rises as buildings in which the height is over three times the width [22], whereas structural engineers define high-rises as buildings influenced primarily by wind loads [23]. High-rises can be categorized according to their function, structural system type, and environmental control strategies. From a functional standpoint, there are four types: residential, commercial, hospitality, and mixed-use. This section briefly describes what is currently known about the organizations, goals, options, and analyses of high-rise design processes.

### ***Organizations***

In high-rise design the developer is often the main decision maker. The developer outlines the architectural program and the budget constraints, and may specify a desired design language and construction start date. Future tenants are often involved at the conceptual design stage, and

many cities require a design to be approved by neighbors. Gatekeepers such as city planning and building departments determine building height and construction limitations.

Design firms involved in the design process include architects, structural and mechanical engineers; later design phases include other consultants such as landscape, egress or LEED. The majority of design firms are single disciplinary, offering either architectural or engineering services, and are typically organized in a hierarchy. Fig. 1 illustrates a representative design team hierarchy commonly found in high-rise design practice. A design director makes high-level design decisions that help determine the design space and therefore guide the design team, and represents the firm in client review meetings. Any decisions made at such meetings are then conveyed verbally or through sketches to the senior design and technical architects who oversee the design process. Most of the drawings and calculations are done by mid level and intern architects. The coordination between engineering and architectural drawings is generally done by the senior technical architect.

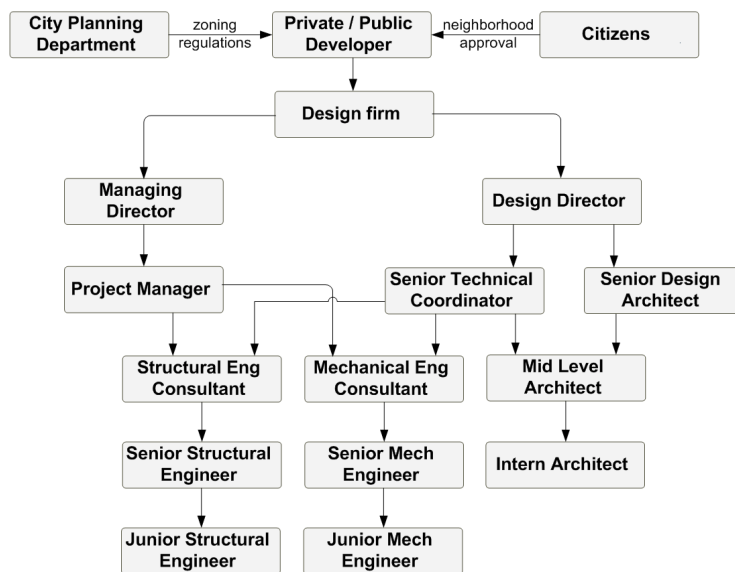


Fig. 1 – Diagram illustrating typical stakeholders and design team organizational hierarchy.

### ***Goals (design criteria)***

Several key design criteria must be considered when designing a high-rise. The *Floor-Area-Ratio* (FAR) is calculated by dividing the gross floor area allowed on a site by the net area of the site. FAR helps designers determine the maximum allowable building height. *Building area efficiency* is calculated as a subtraction of the building's non-sealable area (core, circulation corridors, etc.) from its gross area. Generally, this number must be at least 75% and represents the net saleable or rentable area. The *lease span*, defined as the distance from the unit's inner wall to the exterior glazing, varies according to the building function. For residential high-rises, a maximum lease span of 10m is recommended given the daylight factor considerations. Office buildings with an open plan allow for deeper spans of up to 14m or more when atriums are provided. In the case of modular office layout a building depth of over 13m is considered excessive [24].

The main criterion in choosing a load-bearing system is the lateral stiffness for resisting the wind and earthquake forces, which is governed by the total height [25]. Additional criteria include building height-to-width aspect ratio, floor-to-floor height, interior layout, exterior wall, foundation systems, fire safety, construction methods, and budget constraints.

The criteria in choosing the foundation type are the gravity loads, quality of the site's subsoil, water table level, and wind loads. Wind loads lead to significant vibration in the upper floors, which provides additional stresses on the bed soils [26]. The foundation piles often determine the location of the structural grid and therefore may affect the overall building efficiency.

Fire safety is another important criterion. The core design needs to satisfy the number and size of escape stairwells by determining the building occupancy, as well as address the smoke extraction. Budget constraints often influence the structural material choice.

Multiple design criteria exist to help improve environmental control strategies of high-rises. High level concepts include maximizing reliance on natural ventilation and daylight illumination, while -- depending upon the season and geographical location -- minimizing or maximizing the heat gain from direct sunlight along the building's perimeter areas.

### ***Options***

Facades have a significant influence on the aesthetics and symbolism of high-rises [23]. Two main types can be distinguished: curtain wall (butt glazed, conventional mullion system, composite - glass and cladding), and facades as expression of structure (reinforced concrete, prefabricated panels, exoskeleton, etc.).

Circulation patterns influence the building's efficiency. They are determined by the configuration, number, and positioning of the *service core(s)* (i.e., single or multiple internal or external). A typical core includes elevators (i.e., passenger, service, dedicated to specific functions), fire-protected stairs, electrical / cable closet, riser ducts, and sometimes washrooms. The core positioning will determine the floor plan configuration, given the maximum allowable distance from the outermost point of the corridor to the escape stair(s). When designing cores an important consideration is the *elevator cab aspect ratio*. The preferred range is between 1:2 and 1:3 for maximizing loading and unloading efficiency [4].

The Council on Tall Buildings and Urban Habitat (CTBUH) defines three major structural systems: steel, reinforced concrete, and composite. The choice of structural system determines the building aspect ratio limitations. Until recently, a 6:1 aspect ratio was a constraint [27]. Currently, there are precedents for 10:1 or higher [28]. Floor heights in residential high-rises are generally smaller than in commercial, and range between 2.5-3.5m. In commercial high-rises, floor heights range between 3.3-4.5m. To maximize efficiency, interior layouts may often seek a minimal presence of structural elements, which help choose alternative strategies (exoskeleton, concrete tube, etc.). Generally, the architect's choice of exterior wall system will impact the structural solution. Until recently, the rule of thumb in curtain wall-based high-rises was to vertically divide the façade into 1.5m increments due to ease of assembly, cost savings, and flexible planning. Today, geometrically complex high-rise designs demand variability in the exterior wall panel sizes and novel structural solutions [29].

Engineers can choose among multiple foundation types depending on the building design and soil properties. Examples include cast-in-place telescoping piles, caissons, slab-pile, piled-raft, mat foundation, etc.

Cost often can determine the design's final choice of material. For example, reinforced concrete is preferred in the developing world, given its cheaper cost and lower construction skill requirements than for steel structures.

Two types of high-rises can be distinguished according to employed environmental control strategies. First relies entirely on mechanical systems and is a net energy consumer. The second type responds to the climate and site context.

The Chartered Institution of Building Services Engineers CIBSE [5] distinguishes four types of natural ventilation systems: a) *cross ventilation*, with windows on both sides; b) *single-sided ventilation*, with all the windows on one side; c) *stack ventilation*, in which fresh air is drawn through windows and hot air is exhausted through the roof; d) *mechanically assisted*, to increase the airflow in any of the first three systems. In high-rises stack ventilation is the preferred strategy given that the building's height helps create a chimney effect. However, a good understanding of the environmental conditions is important, as, for example, in hot and dry climates the stack effect may not function during the day.

Light shelves or reflectors can be used to diminish the energy use in high-rises. Their performance is subject to optimal orientation, determined by the building orientation and geometry. Joachim [30] presents an extensive study of how daylight is affected by the high-rise geometry and the floor plan proportions as related to the core design. He concludes that triangular footprints perform best by having the least amount of dark spaces within a 10m span, followed by the square and circular configurations. This study, however, is limited to centrally located cores. Yeang [4] stresses the importance of peripheral core location on east and west facades used as thermal "buffer-zones," leading to important reductions in air-conditioning loads and operation costs. Additional benefits include access to daylight and natural ventilation into the

core area, making the building safer in case of power failure, and eliminating the requirement for mechanical fire-fighting pressurization ducts.

Considering their height and external surface area, high-rises are well suited to take advantage of emerging energy generation technologies. Integrating photovoltaic cells (PVs) into the building's exterior wall or louver system, for example, may become feasible after understanding the local climate and context. This knowledge helps choose optimal building orientation and location of PVs (i.e., non-shaded sections of the building). Similarly, given substantial wind velocities at high altitudes, high-rises can be volumetrically shaped to maximize the performance of integrated wind turbines (i.e., Zero Energy Tower in Guangdong, China by SOM). Other technologies include geothermal energy and thermal storage, evaporative cooling systems for arid climates, etc.

### ***Analyses and Decisions***

Designing high-rise buildings is a complex process as illustrated by the criteria discussed above. As a result, many prototypes have been developed in academia and practice to address aspects of the design processes as heuristic rules that automate some of these processes and help designers make decisions more efficiently. Danaher [31] argues that by not being well defined the conceptual design is reserved only to senior, experienced designers. He proposes the use of *knowledge-based expert systems* in facilitating the access of junior designers to expert knowledge, in which the system guides them towards good solutions. Several such systems surveyed by Danaher are Hi-Rise [32], Tallex [33], Conceptual [34], Predes [35], and Archie-II [36].

Ongoing research efforts address various aspects of conceptual high-rise design in practice. Baker [37], for example, explores the use of novel, proprietary computational tools based on evolutionary structural optimization, genetic algorithms, etc. in generating topological structural studies of high-rises. Whitehead [38] develops custom parametric tools to facilitate the design space exploration. The use of such tools has led to new architectural expressions. In addition, such challenging environmental performance criteria as energy, daylight, or natural ventilation can now be understood through the use of discipline specific model-based analysis tools (i.e. EnergyPlus, Radiance, Fluent).

Despite these promising developments, the AEC industry currently lacks case studies describing high-rise design processes and how well these processes perform. This lack of data makes it hard to understand the impact of the above-mentioned or future solutions on the overall conceptual design process.

### **Methods: Documenting and Analyzing Current Practice**

This section explains our methods for describing and measuring the conceptual high-rise design process. We develop and adapt a process modeling language to record and communicate the design process, and collect metrics describing the process performance.

#### **Documenting Current Conceptual Design Process**

Our research method involved using an embedded researcher [39] on several high-rise design teams to observe and document practice. We developed our observations over five cases. Figure 2 describes the observed process used in one of the cases. To document our observations, we synthesized a process-modeling notation from IDEF<sub>0</sub> [16] and Narratives [17]. A typical process node shown in the legend in Fig. 2 captures the actor(s) that performs the action (project manager, architect, structural engineer, etc.), the tool or method used to generate information or make a decision (CAD, team meeting, etc.), the abbreviated description of the performed action, the time range to perform the action, and finally the input information needed to perform the action as well as the resulting output information. If several actors are involved in implementing parts of the same process, the time tab indicates a cumulative value. The arrows to the input or from the output nodes indicate observed information dependencies.

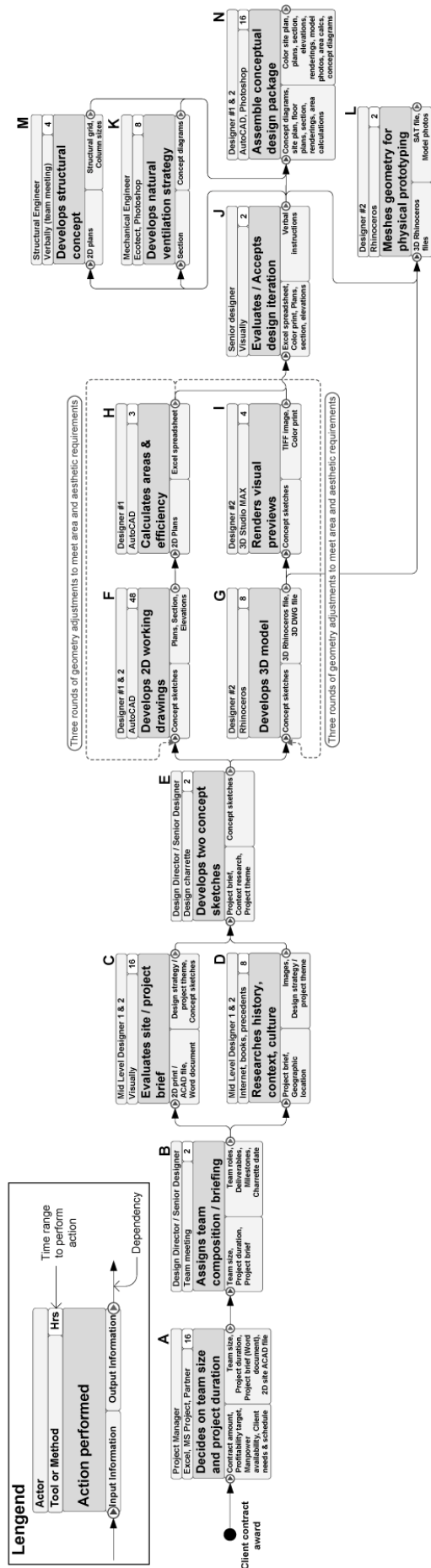
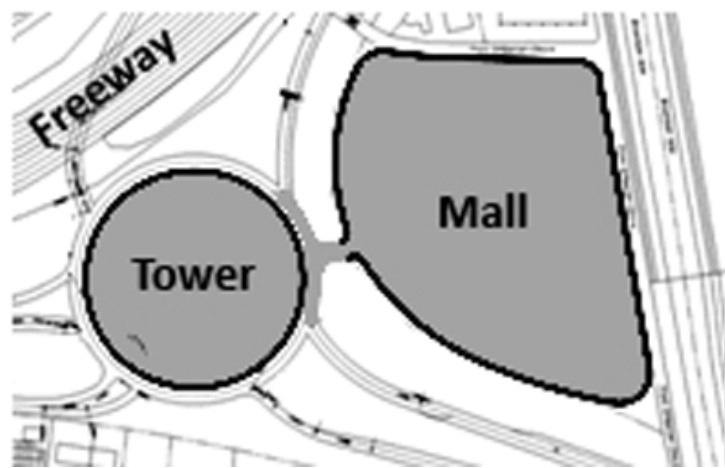


Fig. 2 – Process model describing the Tyrol Tower conceptual design. Nodes A & B describe the early stages, in which decisions about team size, composition, duration, and deliverables were made by the design firm owner, project manager, and senior designer. Nodes C, D, & E describe the process by which the design team evaluated the project context and requirements and proposed the first design concepts in a design charrette. Nodes F, G, H, & I describe the process by which the design team developed 2D working drawings to calculate whether area and building efficiency requirements were met and a 3D model for visual evaluation of the design. Designers repeated the process several times before these requirements were met. Nodes J, K, L, M & N show that only after the senior designer accepted a design option for final development were the mechanical and structural engineers involved, the geometry for physical model prototyping prepared, and the conceptual design package assembled. Mechanical and structural engineers rationalized the design rather than participated from the beginning in decision making.

We use this notation to describe the conceptual design of the Tyrol Tower case study in terms of a process model shown in Fig. 2 and analyzed in the following subchapter. In the case of Tyrol Tower the client commissioned a feasibility study for a multi-tenant hotel and office tower on a complex site in the Tyrolean village of Worgl, Austria. The tower site was contained by a roundabout 150m in diameter intended to serve as an exit hub from the Munich – Verona freeway (Fig. 3).

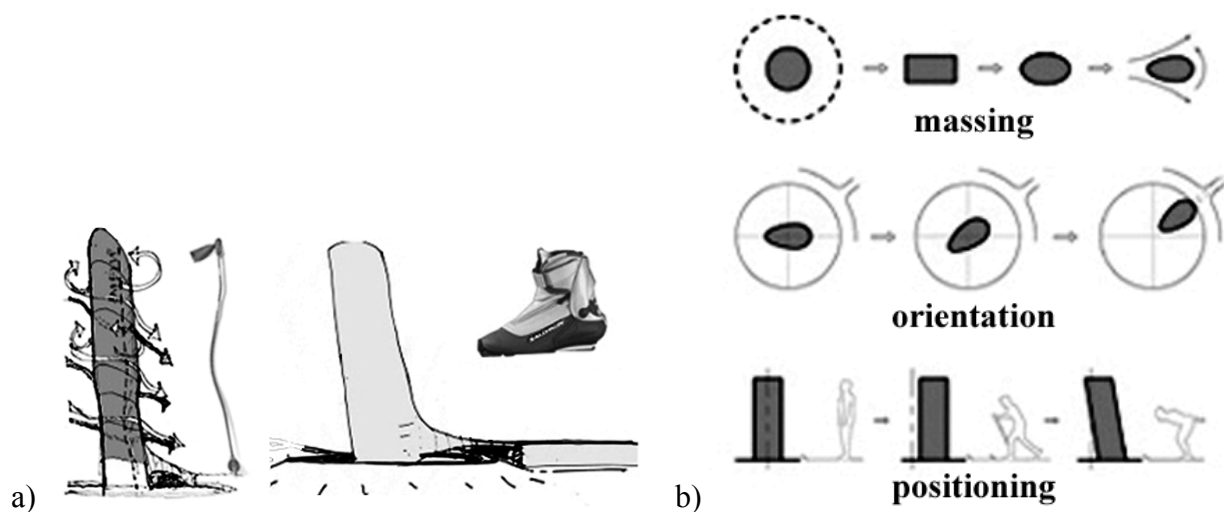


*Fig. 3 – Tyrol Tower site, Worgl, Austria.*

The project duration was set to two weeks. The decision about the team size and project duration was determined by the project manager in conjunction with the firm’s managing partner based on the contract amount, profit target, available personnel, and the client-agreed requirements and schedule. This information was communicated both verbally and by email to the senior designer, who decided in advance on the team composition made of a senior architect, two mid level architects and a project manager. The design process started with a set of loosely defined constraints, such as the architectural program components (2 and 4 star hotel, offices), area requirements, and height limitation. During the kickoff meeting the senior designer assigned

appropriate roles / tasks, established the required deliverables and milestones, and set the first design charrette date.

In between the kickoff meeting and the charrette, the designers researched the historical and cultural background of the Tyrolean region and studied the site context and the project brief. This allowed each individual team member to develop a design strategy before reconvening at the charrette, where after a review of the researched materials (images, maps, facts, etc.), the senior designer sketched two concepts (Fig. 4a).

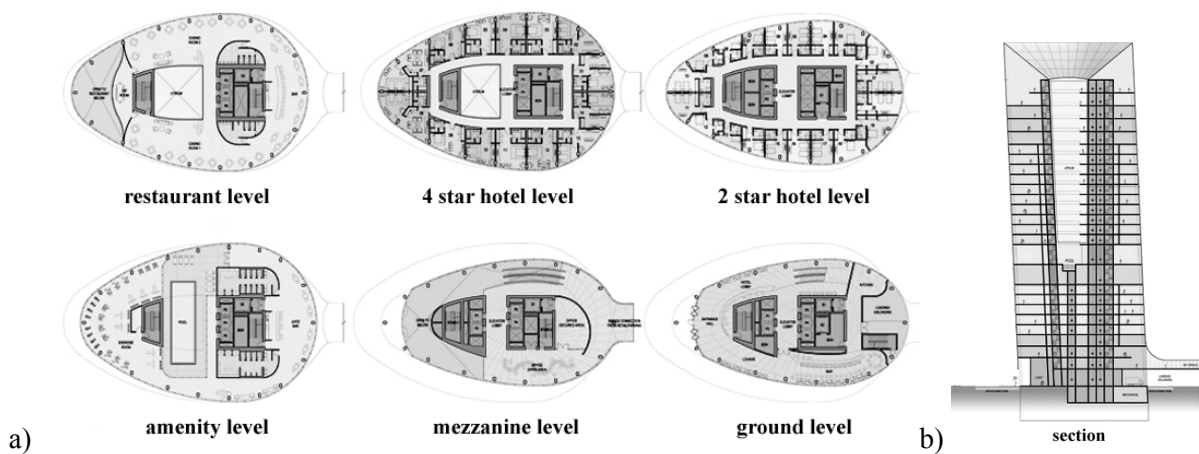


*Fig. 4 – a) Tyrol Tower concept sketches – skiing was the prevailing design theme; the first concept was influenced by the shape of the slalom ski pole, the second abstracted a skier in motion with a 2.5 degree inclination; b) massing, orientation, and tower positioning strategy were influenced by the site geometry, prevailing wind direction, and the need to link the tower to the adjacent site.*

Both concepts reflected the region's strong skiing tradition. The first was inspired by the shape of a slalom ski pole; the curve along the building height supported the architectural transition

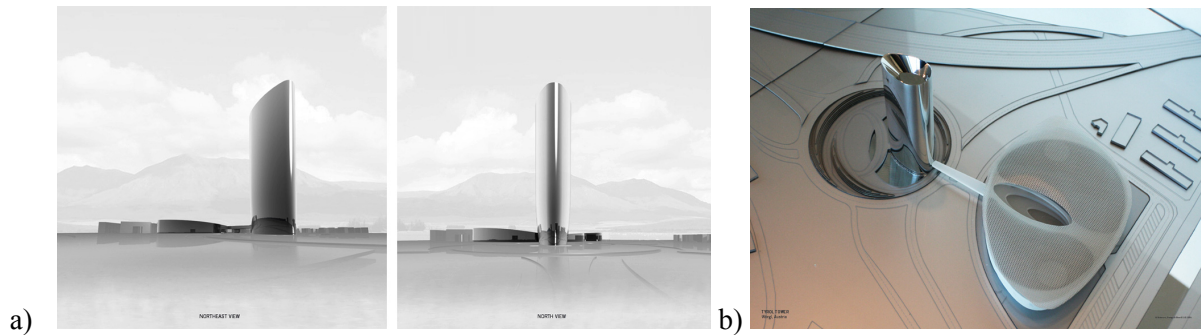
from the area between the 4- and the 2-star hotel (the latter required a smaller lease span). The second concept drew from the idea of a skier in motion, and called for a 2.5-degree forward tilt to convey the notion of speed and movement. Having agreed on the two design themes, the team proceeded to developing strategies for the building's massing and orientation / position within the site (Fig. 4b). The egg-shaped footprint was preferred over round, square, and elliptical configurations, because of the site geometry and the prevailing wind direction. The tower placement on the site was determined by the need to link it to an adjacent site with a bridge.

At the end of the charrette, the team agreed to pursue the second concept for further development. Such architectural considerations as aesthetics and context suitability were the dominant factors. Most of the work at this point was handled by the mid-level architects. Two parallel tasks generally emerged at this stage. First was the development of a set of 2D documents to help illustrate the design. These included preliminary plans of typical and unique floors (4- and 2 star hotel, amenities, mechanical, etc.) as well as the building core, and an axial section for communicating major design features, such as the atrium and the building tilt (Fig. 5a, b). These floor plans made calculating the building area and efficiency possible.



*Fig. 5 – a) Tyrol Tower typical and unique floor plans; b) building section*

The second effort was to develop a 3D model that was graphically rendered and used to evaluate the design visually in its context (Fig. 6a). Renderings initially helped the design team to make design decisions and later to communicate the concept to the client.

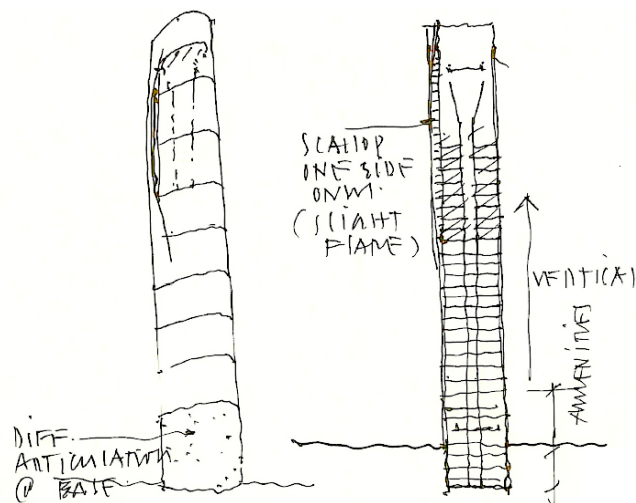


*Fig. 6 – a) Tyrol Tower conceptual renderings; b) physical model*

The two tasks were closely related, considering that both designers needed to constantly coordinate the generated information. Satisfying the area and aesthetic goals required three consecutive geometry adjustments (see Fig. 2, f-i). The 2D drawings required partial reworking as opposed to the 3D model that had to be completely rebuilt.

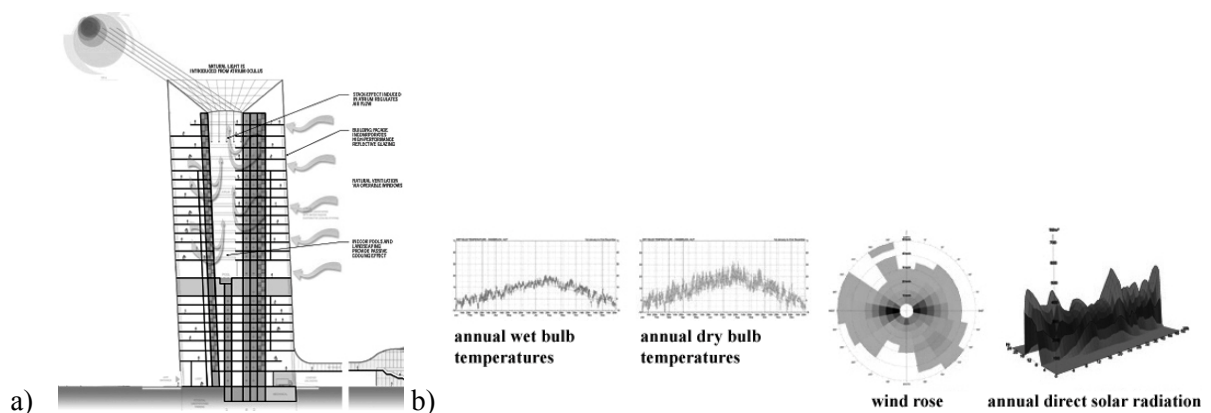
Once the two architects, who developed the technical and visual materials, accepted the design candidate, the senior designer formally evaluated and approved the concept for final development. This process included reviewing color prints of the building renderings, a set of printed 2D floor layouts, a section, and a spreadsheet with area and efficiency calculations. The outcome was a set of minor hand sketched corrections and written recommendations.

However, the senior designer became interested in exploring a new idea, in response to a previously unarticulated goal of supporting natural ventilation. He suggested drastic changes to the geometry to include two scallops on the wide side of the building (Fig. 7). Facing the prevailing winds, these were intended to act as air catchers. Such revision would have invalidated most of the completed work considering the static nature of the generated design information (i.e. 2D and 3D drawings / models) and the subsequent need to regenerate it. Furthermore, validating the newly proposed concept would have required mechanical engineers to run a formal CFD (Computational Fluid Dynamics) simulation. Given the time and effort required to perform such analysis, this task was perceived as unrealistic by the design team. With less than a week left before the submission deadline, the team jointly agreed not to pursue this option, even if it could have led to a more environmentally sound design.



*Fig. 7 – A late concept sketch proposed by the senior designer in response to the previously unarticulated goal of providing the building with natural ventilation. Implementing the proposed side scallops would have invalidated most of the completed work, and because the time constraints the idea was abandoned.*

With natural ventilation becoming an important goal this late in the design process, mechanical engineers were instead asked to recommend a solution strategy for the originally developed option. The existing multidisciplinary collaborative model generally does not support rapid model reuse. In other words, the architect-generated geometry cannot be used by mechanical or structural engineers in their analyses. Consequently, no model-based analysis was performed by mechanical engineers because of the established process and the time constraint. Instead, they reused the architectural section drawing to graphically illustrate the concept of air circulation based on the stack effect (Fig. 8 a, b). Similarly, structural engineers did not generate model-based analyses and were asked to verbally validate the architect-suggested structural concept of a centrally located reinforced concrete core and perimeter column system.



*Fig. 8 – Information produced by mechanical engineers did not include any model-based analyses but rather a set of conceptual, untested recommendations, such as: a) stack effect diagram based on architect’s section; b) standardized graphs of annual wet and dry bulb temperatures, wind rose, and annual direct solar radiation to inform which months of the year were most suitable for natural ventilation.*

After the design director approved the concept design, the 3D geometry was meshed and forwarded to a consultant in preparation for building the physical model. In this case, the material choice for the tower was aluminum and the process of milling the model was outsourced (Fig. 6 b). The site plan, however, was laser cut in house using the earlier produced 2D drawings. In parallel, the team started preparing the final presentation materials, which included coloring the earlier generated plans and section, photographing the physical model, assembling a board with the project metrics, and printing full-scale sheets for foam board mounting.

In summary, as shown in Fig. 9, a team of four architects and three engineers were able to generate three design options in two weeks. The alternatives were variations of one design theme chosen for further development. The design process was primarily based on architectural constraints. No clear goals were established until close to the project submission deadline, making these impossible to implement. The performed analyses addressed only architectural concerns. Architects used metaphoric references on which to base their aesthetic analysis. They motivated the footprint shape and the orientation of the building volume based on knowledge of prevailing wind direction supplied by the mechanical engineers; however, no model-based analysis was performed to understand the airflow and pressure on the chosen design. Structural engineers were only verbally consulted.

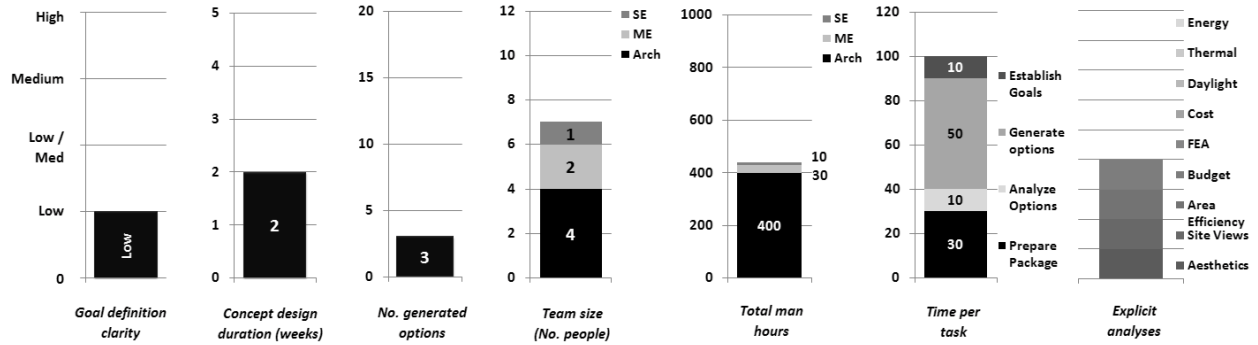


Fig. 9 – Process performance metrics for the Tyrol case study project

The embedded observations enabled a detailed understanding of how current high-rise design processes are performed and managed. However, while our other case studies provided similar results, our sample size was small and limited to one firm on a handful of projects. The next section describes a survey we conducted to provide some evidence for the generality of our field observations.

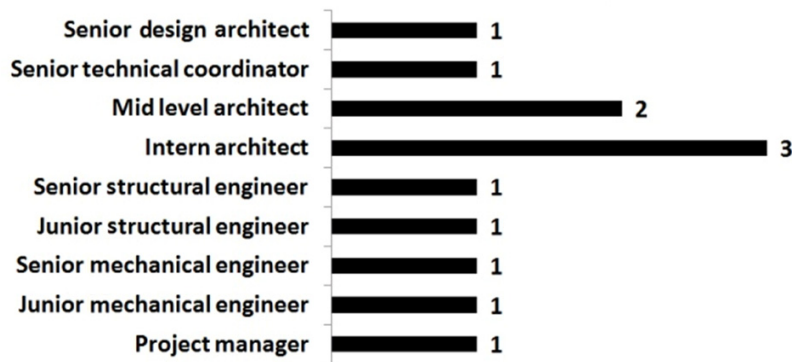
### A survey of industry professionals on current conceptual design process

We conducted an online survey of 20 senior architects and structural and mechanical engineers from several leading AEC practices [40]. The survey contained 20 questions about their project’s team size and composition, goal clarity, number and type of options generated and analyzed, and prevailing goals in decision making. Respondents were asked to specify the high-rise function. All four functional types were part of the survey, but almost 60% of answers were mixed-use type. Fifty six percent rated the projects as moderately complex, and 38% as highly complex. We described a moderately complex designs were defined as single curvature and including new

building systems such as integrated wind generators. A design of high complexity was defined as having double curved geometry and using new materials and building systems.

### ***Organizations***

On average, we found design team size is 12 professionals with 65% being architects (including project managers). Fig. 10 shows on average over 70% of respondents indicated one professional in each of the positions described in Fig 1, with the exception of mid level and intern architects.



*Fig. 10 – Average reported survey results of team size and composition. A typical design team includes 12 professionals, 65% of whom are architects. Most design and engineering positions were generally reported to be filled by a single professional with the exception of intern (3) and mid-level architects (2).*

### ***Goals***

We next asked whether goals were defined and, if so, what were the means to communicate them (Fig. 11a). Twelve percent of respondents' answers indicated a lack of any goal definition, and 82% pointed to goals being defined and communicated only verbally.

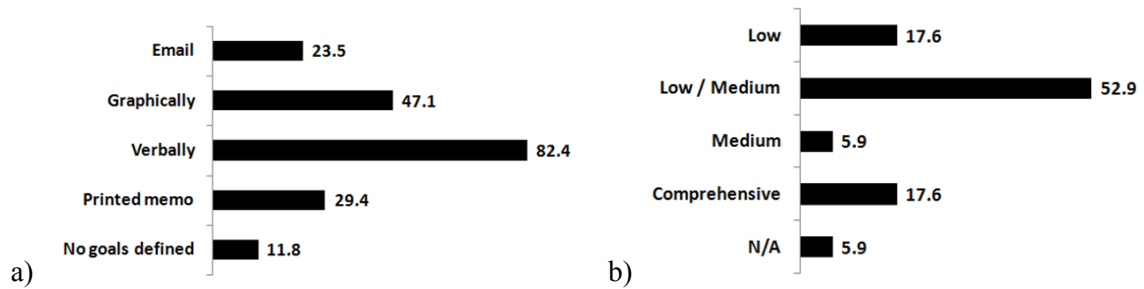


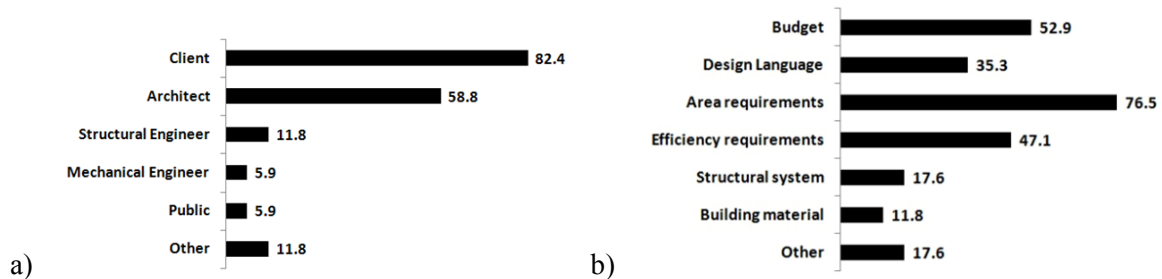
Fig. 11 – Average reported survey results (% respondents) showing: a) the percentage of projects that employed each method of goals communication– goals on most projects were communicated verbally; b) the clarity of the identified goals – most had low to low / medium clarity.

(Note: respondents were allowed to choose multiple answers).

Next, respondents rated the clarity of the identified goals (Fig. 11b). We differentiated among four levels of clarity: *Low* with a partial list without metrics defined; *Low / Medium* with a partial list with partial metrics defined; *Medium* with a complete list without metrics defined; and *Comprehensive* with a complete list with metrics defined. About 70% of answers indicated low to low / medium goal clarity. As one of the survey respondents pointed out, “Internal goals tend to be informal and more conceptual than specific.” The results confirm our observations from the case studies and help identify an important conclusion: even when goals are defined, they often lack clarity of target metrics.

Fig. 12a confirms our field observations concerning those who participate in goal definition. Over 80% of respondents indicated the clients and close to 60% the architects, while structural and mechanical engineers have a low participation in defining goals. This may lead to important design criteria being omitted in early design decision making process and require substantial design adjustments in later design phases. A respondent indicated that “typically, the architect

and the client discuss and agree on project goals and parameters. The contractor and engineering disciplines often contribute to the definition of these goals and refine and assess the metrics.”



*Fig. 12 – Average reported survey results (% respondents) showing: a) who established project goals – mostly clients and architects with little or no participation from engineers. b) major project constraints – most were determined by the developer emphasizing commercial efficiency as opposed to lifecycle efficiency. (Note: respondents were allowed to choose multiple answers).*

Fig. 12b illustrates which goals are generally addressed during conceptual design of high-rises. Most responses indicated a prevalence of traditional, architect-driven goals, such as creating a unique and iconic design, and for developer-driven goals, such as building efficiency, area requirements, and construction budget. Five percent of respondents indicated sustainable construction principles and energy conservation as additional goals.

### ***Options***

Fig. 13a and b show that close to 60% of respondents indicated that only two-to-three options are generally produced, confirming our earlier case study findings. We defined a new design option as any change that requires generating new or updated architectural floor plans, elevations, sections, 3d model for generating simple renderings, conceptual physical model, and a range of

model-based analyses discussed in the next subchapter. Over 90% of respondents indicated using such traditional tools as AutoCAD, 3D Studio, and Photoshop for option generation. Fifteen percent indicated the use of FormZ, Google SketchUp, and MS Access, among other tools. Fifty six percent of respondents did not experience significant differences between the time it took to generate each design option.

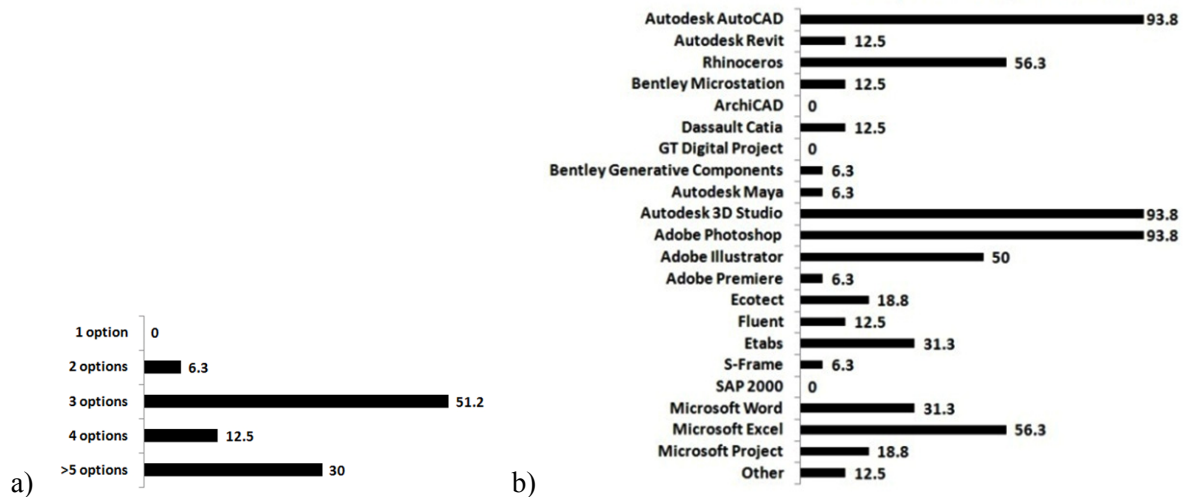


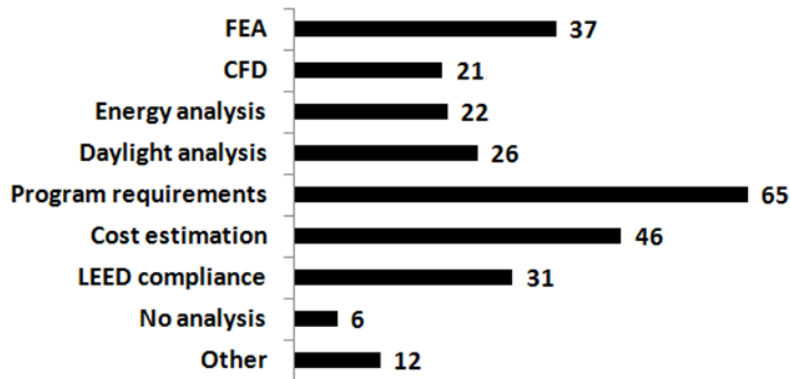
Fig. 13 – Average reported survey results (% of respondents) showing: a) the number of design options generated during conceptual design – majority indicated three; b) tools used are traditional CAD or graphics software that support generating single, static solutions. Very few respondents used emerging technologies, such as parametric modeling or energy analysis tools.

(Note: For question (b) the respondents were allowed to choose multiple answers.)

## Analyses

Fig 14 illustrates that when asked which specific analyses are currently performed at the conceptual stage of a high-rise one quarter of respondents indicated performing Computation Fluid Dynamics (CFD), Energy or Daylight analyses. However, our case study findings were confirmed by close to 78% of respondents, who chose architectural requirements as the leading

analyses criteria. Over 6% indicated no analyses performed. Problems with interoperability of design and analysis tools and schedule constraints make the incorporation of engineering performance concerns difficult in conceptual design.



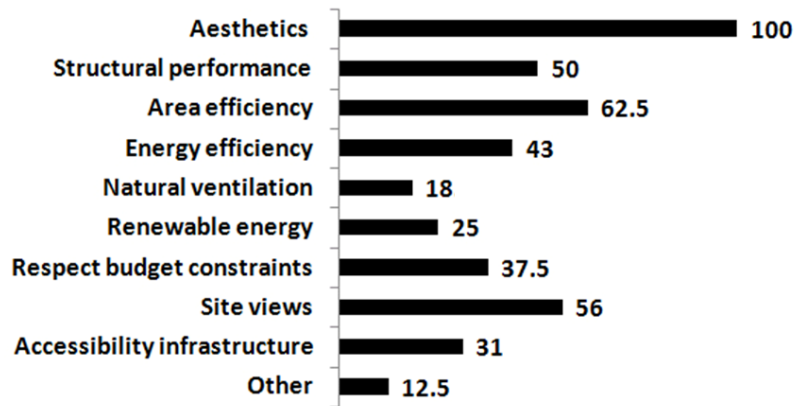
*Fig. 14 – Average reported survey results (% respondents) showing the model-based analyses performed during conceptual design. The performed analyses address predominantly architectural concerns (i.e., budget constraints, program requirements). (Note: respondents were allowed to choose multiple answers).*

Our survey and case study findings both illustrate that the current conceptual design process is dominated by architectural concerns analyzed both in terms of quantifiable (i.e., cost, area, efficiency) and non-quantifiable metrics (i.e., aesthetics, context suitability).

### ***Decisions***

Now that we have discussed the number and clarity of project goals and how design options are generated and analyzed, we need to determine the criteria used in actually making concept design decisions (Fig. 15). The survey results support our earlier findings. Such architectural

criteria as aesthetics (100% of respondents), area efficiency (63%), and site views (56%) are predominantly used in current design decision-making process. A further 13% of respondents indicated it is harder to quantify architectural criteria, such as identity, character, and human values. Less than half of respondents indicated using structural or mechanical engineering performance criteria.



*Fig. 15 – Average reported survey results showing which objectives designers consider when making design decisions. Architectural criteria (i.e., aesthetics, area efficiency, site views) prevail over engineering performance criteria (i.e., energy efficiency, natural ventilation, structural performance).*

### ***Time investment***

Fig. 16 summarizes the overall concept design duration in weeks. While no dominant answer emerged, we conclude that in most conceptual design processes take between 4 and 6 weeks (supported by three quarters of respondents).

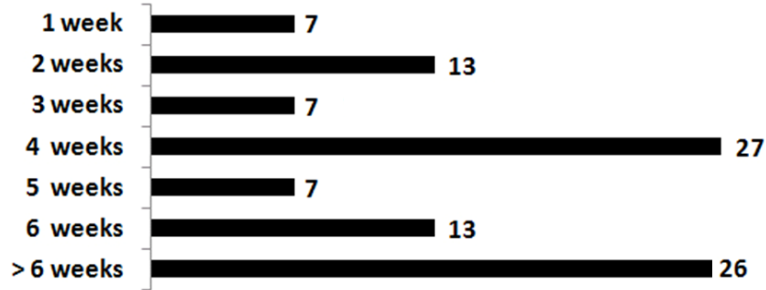


Fig. 16 – Average reported survey results (% respondents) showing conceptual design duration, which predominantly fluctuates between 4 - 6 weeks.

Fig. 17a illustrates the time investment per design team member, while Fig. 17b per discipline. Respondents were also instructed to include extra time invested beyond the 8-hour workday. A disproportionately large amount of the total design time is spent by architects (with an average of 1,850 hours) as opposed to by engineers. The average mechanical engineer contributes 30 hrs, the average structural engineer contributes 50 hrs, the average intern architect contributes 350 hrs, the average mid-level architect contributes 250 hrs, the average senior technical architect contributes 50 hrs, and the average senior design architect contributes 250 hrs.

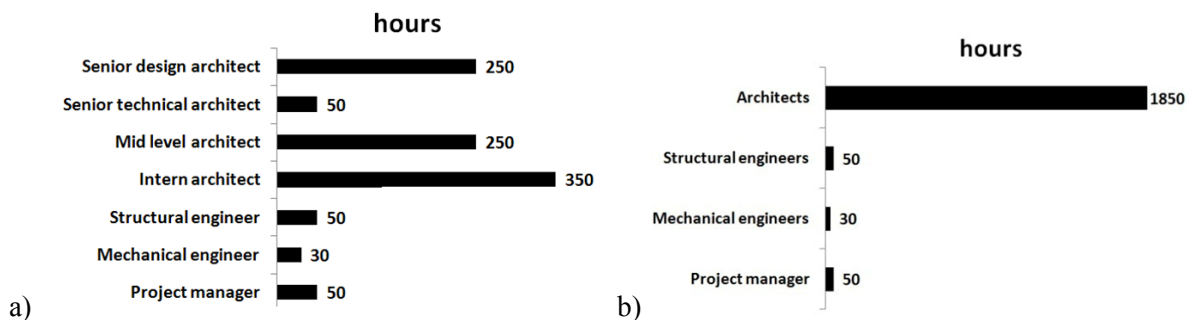
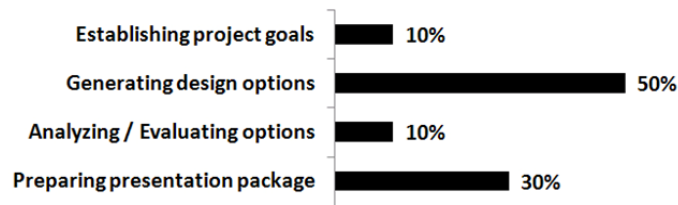


Fig. 17 – Average reported survey results showing: a) total man hours invested by each team member type during concept design phase; b) total number of hours by discipline.

Finally, we asked respondents to distinguish between percentages of the total time invested in each step of the analysis framework used in this paper. The results are shown in Fig 18. Fifty four percent indicated an average 10% of the total time is used on establishing project goals; 40% indicated that 50% of the total time is used on generating design options; 67% specified an average of 10% of the total time is dedicated to analysis of design options; and 74% of respondents specified 30% of the total time is used on final design decisions and preparation of concept design presentation materials. In summary, most of the time is spent on generating design options and preparing presentation materials. The least time is spent on goal definition and analyses.



*Fig. 18 – Average reported survey results showing percentages of the total time spent on goal definition, option generation, analysis, and preparation of presentation materials.*

A summary of averaged survey results is shown in Fig. 19. These triangulating survey results closely corroborate our case study observations presented in Fig. 9.

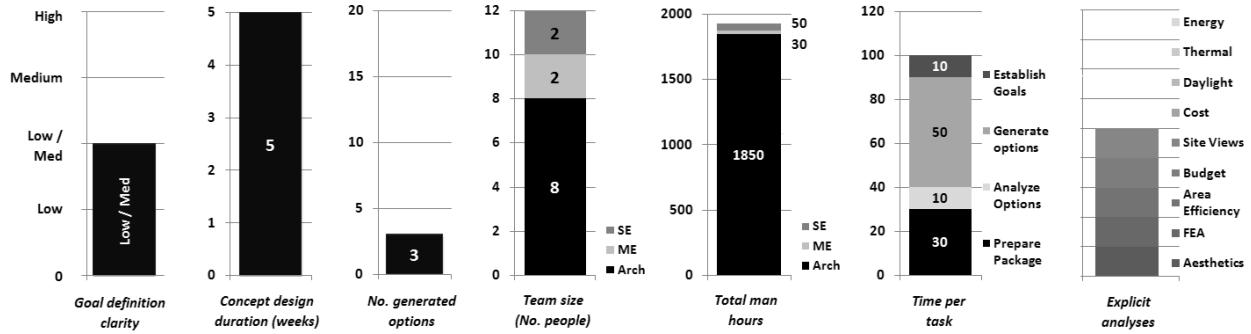


Fig. 19 – Averaged survey concept design process performance metrics

### Conclusion: Potential cost of underperforming conceptual design processes

The contributions of this paper are the new hybrid process models and quantified measurements describing current conceptual design processes. While these findings are limited to high-rise building type and for a limited number of case study and survey participants, which makes it difficult to claim generality, the presented models and metrics can help researchers and decision makers understand how complex architecture-engineering design processes perform, can guide research and development efforts to improve these measurements, and can serve as a benchmark for comparing new design methods, tools and processes.

The market economy requires us to design quickly and cheaply; however, researchers such as Sutton [41] have shown that we can't tell which new ideas will succeed and which will fail at the outset, and that successful design is largely a function of sheer quantity. Current design methods manage only a few potential designs without a deep understanding of their multi-attribute performance. When coupled with increasing complexity in the design requirements and available building technologies, design teams are doomed to produce underperforming buildings.

We conclude this paper with a brief discussion of our intuitions about the causes of these underperforming processes, and discuss potential ways to improve these processes and the potential costs and benefits of doing this.

### ***Organizations***

While we expect no significant changes in the composition of high-rise design teams and stakeholders, a potential area of improvement is the hierarchical organization of design teams, which determine who makes decisions as well as how and when. The AEC industry would benefit from having engineers play a more significant role in early interactions with stakeholders when crucial decisions about a future design are made. Scrum Agile software development methods [43] are an example of more “democratic” and empowered cross-disciplinary iterative design, in which both requirements and solutions are collaboratively developed by interdisciplinary teams. Another example is Concurrent Engineering design management system [44, 45], which is primarily used in aerospace industry and supporting parallelization of multidisciplinary tasks. The AEC industry is beginning to adopt new organizational and contractual structures (i.e. AIA Integrated Project Delivery) to encourage more integrated design processes, although these have not had a large impact in high-rise design practice.

### ***Goals***

As illustrated, goals are often ambiguous and defined without the participation of all AEC disciplines. We believe the current goal definition model leads to significant inefficiencies in the overall conceptual design process. Both the client and architects may lack specialized knowledge to allow them to establish a comprehensive set of project goals. Furthermore, architects often

clarify project goals during the design process. This may lead to unsystematic shifts within the design space due to important guidelines being omitted early in the design process. While some goal ambiguity may aid in creative design, a lack of initial goal clarity leads to starting the design process with broad design spaces that are hard to efficiently explore. As a result, few options are generated and analyzed in depth.

In addition, verbal communication of established goals may lead to further omissions and misinterpretations, especially among the junior design team members. Understanding and managing these requirements early in the design process is a major challenge today. Consequently, the AEC industry would benefit from a formal methodology used to determine explicit design requirements to help guide the generation of design options.

### ***Options***

Translating such requirements into a wide range of design options that designers can quickly analyze and choose from is essential. With current methods, a multidisciplinary team averaging 12 people can normally produce only three design options in 5 weeks - a poor result that we have discovered in other segments of the AEC industry as well [46]. Among possible causes are the unclear goal definitions and the prevalently used design tools that support developing only single, static solutions. The relationships among design information are difficult to establish, manage, and resolve with these tools, making design modifications hard to quickly coordinate. This explains why there is no significant difference in the time needed to develop new design options, once an initial design has been proposed. The AEC industry would benefit from a formal methodology to translate requirements efficiently into multiple design options.

### *Analyses*

The current inability to conduct multidisciplinary model-based analysis efficiently is in part caused by the nature of AEC tools. The design and analysis tools are not well integrated and require substantial time investment in structuring the information for discipline-specific needs. For example, the architect-generated geometry is generally unusable by structural engineers, who need to reconstruct it in a suitable format (i.e., wireframe with attributes describing material properties and load conditions). Current design approaches do not support efficiently calculating even rudimentary model-based analyses, such as cost or area, which in turn discourage designers from exploring a larger segment of the design space. Finally, engineers are normally engaged after architects have already chosen a preferred design option, which leads to inconsistencies in the types of analyses performed on each generated option. Consequently, the AEC industry would benefit from a design model that includes engineers much earlier in the conceptual design process to help develop robust design and analysis strategies, starting early in conceptual design.

### *Decisions*

Designers tend to use only a limited selection of high-rise design criteria when making early design decisions. Bounded rationality theory [9] provides an explanation. Concurrent consideration of multiple criteria with today's design methods overwhelms designers, who instead break down the problem into sub problems leading, according to Goldschmidt [12], to partial interconnected solutions. These solutions are synthesized into adequate designs through multiple consecutive manual corrections as illustrated in the case study. The notion of adequacy,

however, is compromised when the criteria used in making these decisions are architecturally biased.

This paper observed, through case studies and a survey, that design organizations during the conceptual design of high-rises treat goals informally and search through a relatively narrow part of the design space. Design theory and our own experience suggest that significantly better performing buildings are remaining undiscovered. Deficiencies in current conceptual design process lead to solutions with mediocre daylighting, and excessive thermal loads and energy demands, thus making the cost of operating or retrofitting traditional high-rises prohibitive. The lack of a comprehensive and systematic method of defining multi-stakeholder and multidisciplinary goals, managing their evolution, and generating and choosing among design options that respond to identified goals is a major impediment to more successful design.

## References

1. United Nations, (2004). *World population to grow from 6.5 billion to 9.1 billion by 2050*. Accessed at [http://www.un.org/esa/population/publications/WPP2004/2004\\_Revision\\_press\\_release\\_Final.pdf](http://www.un.org/esa/population/publications/WPP2004/2004_Revision_press_release_Final.pdf)
2. McElfish, J. (2007). *Ten Things Wrong With Sprawl*. Environmental Law Institute report.
3. Kienast, F. Jaeger, J. (2006). *Degree of urban sprawl in Switzerland: Quantitative analysis 1940–2002 and implications for regional planning*. Swiss Federal Institute of Forest, Snow and Landscape Research; ETH.
4. Yeang, K. (1996). *The Skyscraper Bioclimatically Considered – a design primer*. Academy Editions.
5. Chartered Institution of Building Services Engineers. (1997). *Natural Ventilation in Non-Domestic Buildings*. Applications Manual AM10. The Chartered Institution of Building Services Engineers, London.

6. Kaplan, D., (2004). *High Performance High-Rise Residential Buildings*. AIA Center for Building Performance. Symposium on Building Performance.
7. Akin, Ö. (2001). *Variants of design cognition*. Design Knowing and Learning: Cognition in Design Education. Eastman, C., Newstetter, W., & McCracken, M., Eds., pp. 105–124. New York: Elsevier.
8. Haymaker, J., Chachere, J., (2007). *Coordinating goals, preferences, options, and analyses for the Stanford Living Laboratory feasibility study*. Intelligent Computing in Engineering and Architecture 13th EG-ICE Revised Selected Papers. Lecture Notes in Computer Science, Vol. 4200/2006. Springer-Verlag, Berlin, Heidelberg, New York, 320-327.
9. Simon, H. (1991). *Bounded Rationality and Organizational Learning*, Organization Science 2(1): 125-134.
10. Woodbury, R., Burrow, A., (2006), 20, 63-82, *Whither Design Space?*, Artificial Intelligence for Engineering Design, Analysis and Manufacturing
11. Krishnamurti, R. (2006), 20, 95-103, *Explicit design space?*, Artificial Intelligence for Engineering Design, Analysis and Manufacturing.
12. Goldschmidt, G., (2006), 20, 105-111, *Quo vadis, design space explorer?*, Artificial Intelligence for Engineering Design, Analysis and Manufacturing
13. Rolland, C.; Pernici, C. (1998). *A Comprehensive View of Process Engineering*. Proceedings of the 10th International Conference CAiSE'98, B. Lecture Notes in Computer Science 1413. Pisa, Italy: Springer.
14. Froese, T. (1996). *Models of Construction Process Information*". pp. 183-193. Journal of Computing in Civil Engineering.
15. International Alliance for Interoperability, *Data Modelling Using EXPRESS-G for IFC Development*,  
Accesses at  
[http://www.iai-international.org/Model/documentation/Data\\_Modelling\\_Using\\_EXPRESS-G\\_for\\_IFC\\_Development.pdf](http://www.iai-international.org/Model/documentation/Data_Modelling_Using_EXPRESS-G_for_IFC_Development.pdf)
16. Integrated Definition Methods. Accessed at <http://www.idef.com/idef0.html>

17. Haymaker, J. et. al. (2004). *Engineering test cases to motivate the formalization of an AEC project model as a directed acyclic graph of views and dependencies*, Itcon Vol. 9.
18. Tapping, D., Shuker, T. (2002). *Value Stream Management*. Productivity Press.
19. McCuen, T., Suermann, P. (2007). *The Interactive Capability Maturity Model*. Accessed at [http://www.aecbytes.com/viewpoint/2007/issue\\_33.html](http://www.aecbytes.com/viewpoint/2007/issue_33.html)
20. Kunz, J., Gilligan, B., (2007). *Value from VDC / BIM Use*. Accessed at <http://cife.stanford.edu/VDCSurvey.pdf>
21. Frampton, K. (1992). *Modern Architecture: A Critical History*. Thames & Hudson; 3 Sub edition.
22. American Society of Heating, Refrigeration and Air-conditioning Engineers (ASRAE), (1989). *Handbook on fundamentals*.
23. Council on Tall Buildings and Urban Habitat, (2000). *Architecture of Tall Buildings*. pp. 95, 102-106. McGraw-Hill, Inc.
24. Eisele, J., Kloft, E., (2002). *High-rise Manual - Typology and Design, Construction and Technology*. Birkhauser - Publishers for Architecture
25. Schueller, W. (1986). *High-rise buildings structures*. 2<sup>nd</sup> edition, Robert E. Krieger Publication Company.
26. Ulitskii, V. M., Shashkin, A. G., Shashkin, K. G., (2003). *Geotechnical Problems Associated with the Construction of High-rise Buildings. Foreign Experience and Domestic Practice*. Soil Mechanics and Foundation Engineering, Vol. 40, No.5. pp. 182.
27. Khan, Y. (2004). *Engineering Architecture: The Vision of Fazlur R. Khan*. W. W. Norton & Company. pp. 260.
28. Pelli, C. (1991). *Carnegie Hall Tower*, Completed building in Manhattan, New York.
29. Morphosis, (2006). *Phare Tower*. Paris, France. Project currently under development. Skidmore, Owings, & Merrill, (2007). *Transbay Tower*. San Francisco, CA. Competition entry.
30. Joachim, M. (2006). *Ecotransology - Integrated Design for Urban Mobility*. PhD Thesis, MIT.

31. Danaher, M. (2000). *Expert Systems – A Design Application*. Proceedings, 22<sup>nd</sup> International Conference, Information Technology Interfaces, Pula, Croatia.
32. Maher, M.L., Fenves, S.J. (1985). *Hi-Rise: A Knowledge-Based Expert System for the Preliminary Structural Design of High Rise Buildings*. Department of Civil Engineering, Carnegie-Mellon University, Pittsburgh, USA.
33. Sabouni, A.R., AI-Mourad, O.M. (1997). *Quantitative knowledge based approach for preliminary design of tall buildings*, Artificial Intelligence in Engineering, 11.
34. Haber, D., Karshenas, S. (1990). *Conceptual; An expert system for conceptual structural design*. Microcomputers in Civil Engineering, 5,2, pp 119-125.
35. Fleming, J., Elghadamsi, E., Tanik, M. (1990). *A knowledge-based approach to preliminary design of structures*. Journal of Energy Resources Technology, ASME, Vol 1 12, 4, pp. 213 - 219.
36. Domeshek, E., Kolodner, J. (1992). *A case-based design aid for architecture*. Artificial Intelligence in Design 92, J. S.Gero, Ed., Kluwer Academic Publishers, The Netherlands, pp. 497-516.
37. Baker, W. F. (2008). *Extending Structure and Architecture - Studies in Structural Topology*. The John A. Blume Distinguished Lecture Series, Stanford University. April 17, 2008.
38. Whitehead, H. (2003). *Laws of Form. Architecture in the Digital Age: Design and Manufacturing*. Taylor & Francis.
39. Hartmann, T., Fischer, M., Haymaker, J. (2008). “Implementing information systems with project teams using ethnographic–action research,” Advanced Engineering Informatics, In Press.
40. Survey conducted between January – May, 2008. 20 participants from the following firms: Skidmore, Owings & Merrill LLP (SOM), Kohn Pedersen Fox Architects (KPF), Adrian Smith + Gordon Gill Architecture, Hellmuth, Obatta, Kassabaum (HOK), HWI Architects, Atkins, Arquitectonica.
41. Sutton, R. (2002). *Weird Ideas that Work - 11.5 practices for promoting, managing, and sustaining innovation*. The Free Press, New York, NY.

42. Sosa, M., Eppinger, S., Pich, M., McKendrick, D., Stout, S. (2002). *Factors that Influence Technical Communication in Distributed Product Development: An Empirical Study in the Telecommunications Industry*. IEEE Transactions on Engineering Management, vol. 49, no. 1, pp. 45-58
43. Schwaber, K., Beedle, M. Agile (2001). *Software Development with Scrum*. Prentice Hall
44. Prasad, B. (1995). *Concurrent Engineering Fundamentals: Integrated product development*. Prentice Hall Professional Technical Reference.
45. Ma, Y., Chen, G., Thimm, G. (2008). *Paradigm Shift: Unified and Associative Feature-based Concurrent Engineering and Collaborative Engineering*, Journal of Intelligent Manufacturing, , DOI 10.1007/s10845-008-0128-y
46. Flager, F., Haymaker, J. (2007). "A Comparison of Multidisciplinary Design, Analysis and Optimization Processes in the Building Construction and Aerospace Industries," 24th International Conference on Information Technology in Construction, I. Smith (ed.), pp. 625-630.