Engineering Performance Simulations in Architectural Design Conception

Atrium in Shenyang: a case study on thermal mass

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Abstract. The paper tackles the integration of engineering performance simulations in the conceptual phase of architectural design, with specific focus on parametric design processes. A general framework is exemplified, in which the use of performance simulations and the learning process of the designer are discussed in relation to the parameterization process. A specific case study is presented more in details regarding the design of an atrium for the reuse of an existing building in Shenyang-China. Performance simulations concerning the thermal comfort in the atrium are presented and discussed in relation to the general framework.

Keywords. Conceptual design; building simulation tools.

INTRODUCTION
Since the requirements on the actual performance of buildings are becoming ever tighter, accurate data regarding the performance of the buildings is becoming increasingly important in the early phases of design. This paper tackles the role of digital modelling and engineering performance simulations in the conceptual phase of architectural design. The first part of the paper focuses on a theoretical framework for performance oriented parametric design, in which the design process is decomposed into and related to the design knowledge available during the design conception and its parameterization process; moreover, this part describes some general case studies. The second part of the paper grounds and exemplifies the framework, by discussing one specific case study on numerically assessed design alternatives for achieving indoor thermal comfort. The analysis of alternative design solutions is presented by showing the learning process of the designer through a comparative study. One chosen alternative is then presented in details, by undertaking the integration of parametric modeling and performance simulations during the design process. The parameterization process of the design concept is discussed based on the analysis previously illustrated; focusing on design innovation, emphasis is given to the importance of extracting knowledge from the numeric analysis.
DESIGN PROCESSES TOWARDS INNOVATIVE DESIGN SOLUTIONS

Background theories
Design processes towards innovative design solutions have been tackled and theorized from a number of different perspectives. Geoffrey Broadbent (1969) refers to four types of design methods, which he calls pragmatic, iconic, analogical and canonic. Pragmatic design makes use of available techniques without relevant innovation; iconic design recalls existent solutions and tends to replicate them; canonic design relies on rules and regulations as guidelines; analogical design makes use of analogies with other fields to define new ways for structuring the problems and their solutions. While all these four methods can be used to generate design alternatives by exploring various concepts, it is especially the last one that allows for major innovation. It is widely acknowledged that looking for innovative solutions for new design concepts deeply relies not only on the previous experience of the designer, but also on his/her real-time learning process. The importance of pre-structures, presuppositions or protomodels as the origins of solution concepts (Roozenburg and Cross, 1991) is recognized, but leads to an evolving design path in which the learning process is an integral part of the exploratory design activity. In a puzzle-making approach (Alexander et al., 1977), designers begin with a kit of forms, including materials and shape, subject to modification according to certain rules until they achieve some desired functional qualities; inductive reasoning is used with the aid of metaphors, symbols, and case studies (Kalay, 1999).

Analogical reasoning implies learning from previous or other problems similar to the actual problem by retrieving and transferring chains of reasoning and knowledge to the actual problem (Veloso, 1994); it is quite beneficial to problem-solving processes including design (Goldschmidt, 2001; Goldschmidt and Smolkov, 2006). A number of design methods are based on abduction (Tomiyama et al., 2003), using logic and abductive reasoning; according to this, a design solution is defined by means of axioms and theorems, respectively intended as design knowledge and properties of other design solutions. Specifically, following Roozenberg’s (1993) distinction, ‘abduction’ in design theory and knowledge-based design systems is explanatory abduction while the reasoning towards new solutions for design problems follows the pattern of innovative abduction.

Integration of engineering disciplines and Performance Simulation Tools
Within the broadly theorized field described above, focus is given here on the integration of engineering disciplines in the conceptual phase of architectural design. Their use to trigger the design creativity is approached in opposition to post-engineering processes. In traditional post-engineering processes, technical performances are mostly considered and verified in late stages; the design variations eventually necessary to satisfy the technical requirements are tailored upon preconceived and constraining architectural designs. In contrast with this attitude, the use of engineering performances is proposed in order to inspire or even drive the concept improvements or the generation of new alternative concepts; this implies that engineering feedbacks are an integral part of the analogical method and a support for innovative abduction. Aiming at this, building Performance Simulation Tools and their use in the early phase of the design play a crucial role. This perspective is in line with a number of previous and well-known studies, such as the ones of Mahdavi and Lam (1991), according to whom systematic “front-end” studies based on digital simulations to aid preliminary design decisions should be preferred over the traditional approach, in which the role of building simulation is relegated to the “back-end” of the design process. The use of feedbacks from analysis software to re-evaluate design decisions is also emphasized by Caldas and Norford (2003), who point out that by using simulation tools, it is possible to engage in a design practice based on feedback loops between making design decisions and evaluating their environmental impact, as a way to inform the on-going process of design. However,
the view proposed here differs from previous works due to its focus on the use of numeric design assessments as part of the learning process of the designer, to achieve innovative design solutions.

**Design knowledge acquisition in parametric design**

In a previous publication, the authors proposed a parametric design framework for performance-oriented design, in which the use of numeric design assessments are related to the learning process and knowledge available or generated during the design process. Three phases are distinguished in the parametric design development. During the first phase, strategy-definition, the parameterization is addressed based on the analysis of design challenges; during the second phase, model-building, the parametric model is constructed; during the third phase, solution-assessment, the design alternatives embedded into the parametric model are explored based on performance evaluations (Turrin et al., 2013). Numeric design assessments play a crucial role both in the first and in the third phase. According to this framework, three general types of processes are distinguished, in which the solution space of the parametric models is differently set. This usually occurs according to the knowledge the designer has or gains before or when defining the parameterization strategy, in respect to a set of selected performances. The first includes design processes in which little knowledge is available during the parameterization process, with consequent need of enlarging the design solution space for broad performance explorations. This leads to large parametric solutions spaces; and usually implies intense use of numeric assessments in the solution-assessment phase. The second includes design processes in which relevant knowledge is available during the parameterization process, with consequent chance of bounding the solution space into a more confined collection of alternative design solutions. This leads to narrowed parametric solution spaces; and, unless knowledge is already available, it implies some use of numeric assessment both in the strategy-definition and solution-assessment phases. The third includes design processes in which a clear (mostly bijective) relation between geometry and performance can be set during the parameterization process; this allows consistently relating different geometric solutions with different performance requirements, which leads to bijectively deterministic parametric solution spaces; and, unless knowledge is already available, it implies intense use of numeric assessments in the strategy-definition phase. A substantial difference across the three cases consists of the way in which the initial design concept (here named primary generator according to Darke, 1979) is conceived in relation to the considered performances. Numeric design assessments are considered a means for extracting knowledge to be used (or re-used) in the conception of (new) primary generators.

Four examples are mentioned here following; additional details can be found in previous publications. The first example (Turrin et al., 2013) concerns the design of an envelope controlling effects of direct and indirect daylight in the interior space; it was developed by a student (Friedhoff Calvo, 2010). The primary generator was developed based on Escher’s tessellations, with intuitively defined modular variations from permeable to impermeable to daylight. In order to explore the daylight effects in alternative designs, the geometry of the primary generator was parameterized. Considering the intuitive nature of the design, the parameterization aimed at a broad solution space, to reduce the risk of excluding meaningful design alternatives. As a consequence, further computational support (i.e. search algorithms) was needed in combination with performance simulation tools during the solution-assessment. Focusing on the learning process of the designer, the use of search algorithms is addressed in the following example. The second example (Turrin et al., 2011) concerns the design of an envelope that reduces the solar gain but allows a high daylight level. The primary generator was developed based on well-known principles of shading and orientation, but applied on complex geometry. The geometry of the primary generator was parameterized in order
to lead to a large solutions space; and a search for well performing solutions was performed based on a genetic algorithm optimization, in combination with performance simulation tools. The generated solutions were stored in a database and analyzed in order to extract information from badly performing, sub-optimal, and well performing solutions, aiming at an explicit understanding of trends between geometric design variables and resulting performances, toward design knowledge generation. The third example (Turrin et al., 2013) concerns the design of an envelope to control the daylight effect on the enclosed spaces; it was developed by a student for his M.Sc. graduation project (Van Kersbergen, 2011). The primary generator was developed only after an extensive number of preliminary performance simulations on different basic primary generators. The geometry of the chosen primary generator was parameterized based on the results of the previous analyses, in order to lead to a narrowed solutions space; and, during the solution-assessment, performance simulations were run only on chosen design alternatives. Based on the increased correspondence between the actual and desired solutions space, as it was expected, the chosen options showed performances quite close to the desired requirements. This attitude towards amplifying the learning process (by means of numeric assessments) before parameterizing and even conceiving the primary generator is shown in its extreme consequences in the fourth example. The fourth example concerns the design of an acoustic absorber which was developed by a student for her M.Sc. thesis (Setaki, 2012). Intensive work was invested in performance measurements of samples, which not only increased the design knowledge, but also formalized it. Only when a clear relation was formalized, the primary generator was conceived. A parametric model was made based on the formalized relation, in order to bijectively relate specific acoustic requirements with correspondent geometric design alternatives. So far, this case showed mostly full coincidence between the actual and the desired solution space of the parametric models.

With reference to this framework, the following section presents in detail one case study from a practice-based design process for an atrium. The performances considered in this project focus mainly on passive climatic control.

**STUDIES FOR AN ATRIUM IN SHENYANG**

The atrium is part of a larger project developed by GWS, a company located in Beijing. The project consists of the conversion of a tobacco factory into office buildings, organized in three blocks around a courtyard. The atrium is located in one of the three buildings, developed along an East-West axis, on the northern side of the plot. The building is organized in five floors and has a total volume of approximately 130,000 cubic meters. GWS developed a number of design alternatives, in most of which the atrium is located on the top two floors and occupies a volume of approximately 8,000 cubic meters. The spaces around the atrium are mainly offices or flexible areas, for which the atrium acts as a distribution space. The work presented in this paper is a part of the output of a collaboration between GWS in China and an interdisciplinary team at TUDelft, in the Netherlands. The collaboration assumed the general setting of the overall project as given, while focusing on the atrium and related roof. A number of design options were developed, by considering performances for passive climatic comfort and, in general, reduction of energy consumption during use.

The following sections present the preliminary numeric analyses run on the building, based on which challenges and potentials to reach the design goals were identified. Based on these results, specific sub-goals were established, which decompose the design requirements into more specific tasks.

**Strategy-definition phase: preliminary performance simulations**

Shenyang is located in the fifth level of Chinese climate zones, defined as “coolest level”; within this level, the area belongs to the class B, which corresponds to the most moderate class of the “coolest zone”. According to the Shenyang IWEC weather sta-
The winter peak happens between December and February, with the coldest hour at 5am, typically below -10 degrees Celsius; the summer peak happens between June and August with temperatures generally above 25 degrees Celsius at 2pm.

The work presented in this paper focuses on thermal comfort, and specifically on passive measures for achieving thermal comfort; while considerations on daylight are taken into account as side criterion only. A number of preliminary numeric analyses were run on the given building, in order to identify expected problems and potentials for passive climate comfort. Simulations of thermal comfort based on Predicted Mean Vote (ASHRAE, 2010), and of air, mean radiant and operative temperatures were performed on the whole building for both a whole year, and with focus on periods in which worst conditions occur for risk of overheating (July) and coldness (January). Simulations were run both in free-running-mode (without mechanical heating and cooling) with no occupancy and no internal heat loads (in order to measure the effect of the building only, for passive thermal comfort); and by including HVAC systems, occupancy and internal heat loads. Design Builder (DesignBuilder Software Ltd) was selected as building performance simulation tool. Moreover, daylight conditions were studied for the floors where the atrium is included, at equinoxes and solstices, using Radiance via Diva for Rhino. Regarding the passive thermal comfort, digital simulations were systematically run on a set of different variations concerning several material properties of the external walls, roof and glazing (different levels of insulation); air tightness of the building; and thermal mass. Insulation levels (U-value) varied from 0.35 to 0.25 W/(m2·K) for the external walls, from 0.25 to 0.15 W/(m2·K) for the flat roof and from 1.978 to 1.415 W/(m2·K) for external glazing; air tightness varied from 0.7 to 0.2 ac/h; different thicknesses of the floor determined the thermal mass, in heavy concrete; some options were tested also with natural ventilation. The building was modeled based on its external envelope, subdivision into floors and atrium. The model consisted of 34 real and virtual thermal zones, 4 of which regarded the atrium; these latter are named 4a and 4b for bottom and top part of the atrium on the fourth floor; and 5a, 5b respectively on the fifth floor.

**Results**

The results showed that higher insulation results in higher indoor temperatures both in winter and in summer; and higher leakage implies lower indoor summer and winter temperatures. The effects of occupancy, internal heat loads, increased insulation and increased air tightness were expected to be beneficial in winter, and unfavorable in summer. Summer thermal comfort increased when including ventilation. Both for July and January (daily values), a comparison was also made in case of additional thermal mass distributed on the floors surrounding the atrium. The thermal zone corresponding to the bottom area of the atrium was obviously the one affected the most by the effect of thermal mass, since it lies on a floor, differently than the other three thermal zones. Some of the results are summarized in Table 1. In addition to the comparison between operative temperatures, relevant information was extracted also from the analyses of air and radiant temperatures; and from the behavior of the PMV, especially on the bottom thermal zone. In this zone, in case of little thermal mass, the PMV varied from 2.8 (2nd July) to 4.9 (18th July); in case of additional thermal mass, the PMV varied from 1.7 (4th July) to 3.9 (24th July), which clearly showed the delaying and peak-shaving effect of the thermal mass. Finally, a simulation was run adding the effect of thermal mass and natural ventilation (5 ac/h), showing additional benefits. As an example, in the bottom thermal zone the PMV varied from 0.3 (4th July) to 2.2 (18th July). Finally, a series of shadow analyses were made, which pointed out correspondence between solar gains and temperatures.

**Conclusions and specific sub-goals**

According to the preliminary analyses, the whole building and the atrium especially had critical thermal discomfort both in winter and in summer. The
analyses showed also that it is possible to reduce thermal discomfort by means of passive strategies, both in summer and in winter. Specific sub-goals were identified. Considering the local climate, calibrating the design first based on the cold winter period was recommended. This clearly included increasing the insulation, air tightness and solar gain of the building as much as possible. However, this challenged summer thermal comfort. As also confirmed in the preliminary analyses, thermal mass and summer ventilation positively impacted summer comfort. Among these factors, the work illustrated in the following sections focuses on the distribution of thermal mass, natural ventilation and shading, since these factors highly depend (also) on the geometry of the overall spatial configuration of the atrium. Specifically, investigations on thermal mass were taken as starting point for the next phase of the strategy-definition phase, in which the parameterization strategy was more specifically addressed.

**THERMAL MASS AS DESIGN DRIVER**

The principles described above were investigated as design drivers, by making use of digital simulations to study their thermal behavior in conjunction with the design exploration of a large range of design possibilities. Especially when considering the dimensions of the atrium and its value as representative space for the new office building, conceiving such a thermal system with emphasis on its iconic value (in addition to its technical thermal function) was proposed as beneficial for the project. A relevant part of the strategy definition phase focused on thermal mass. The following sections summarize its main aspects.

**Additional analysis on thermal mass**

A set of additional analyses were carried out regarding the effects of quantity and distribution of thermal mass within the atrium. The effect of different distributions of additional thermal mass was analyzed for four vertical (virtual) thermal zones of the atrium, with and without natural ventilation and shading. Among the analyzed options, the one with external shading, diurnal and nocturnal ventilation (10ac/h), and higher concentration of thermal mass on the top part of the atrium showed the best performance for summer thermal comfort. The results are visible in Table 1 and clearly show the accumulation of heat in the thermal mass and the cooling effect of ventilation, as well as the reduction of overheating through the addition of external shading on the glazed roof. Additional tests were run accentuating the uneven distribution of thermal mass across the levels. These analyses showed that additional thermal mass on the top level leads to beneficial effects, while changes in the bottom level had minor effects on the thermal performances. Since minimizing the use of additional material and structural load is generally desirable, the option of reducing the additional thermal mass on the bottom level and distributing it more on the top level was used for further investigations. External shading further reduced the maximum temperatures as can be seen from Table 2.

<table>
<thead>
<tr>
<th>U-value (W/(m²·K))</th>
<th>Air t. (ac/h)</th>
<th>Vent. (ac/h)</th>
<th>Th.M.</th>
<th>Min. Win. temp. (°C)</th>
<th>Max. Sum. temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall 0.35</td>
<td>0.25</td>
<td>1.978</td>
<td>0.7</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>Roof 0.25</td>
<td>0.15</td>
<td>1.415</td>
<td>0.7</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>Glazing 0.35</td>
<td>0.25</td>
<td>1.978</td>
<td>0.2</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>0.25</td>
<td>0.15</td>
<td>1.415</td>
<td>0.2</td>
<td>0</td>
<td>No</td>
</tr>
<tr>
<td>0.25</td>
<td>0.15</td>
<td>1.415</td>
<td>0.2</td>
<td>5</td>
<td>No</td>
</tr>
<tr>
<td>0.25</td>
<td>0.15</td>
<td>1.415</td>
<td>0.2</td>
<td>10</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 1

Minimum Winter and Maximum Summer operative temperatures (temp.) in various for insulation (U-value), air tightness (Air t.), natural ventilation (Vent.), and additional thermal mass (Th.M.).
Based on the preliminary analyses, geometric properties were extracted for the aspects having positive impact on the design goals; for different primary generators, the attributes of these geometric properties were parameterized in order to investigate geometric alternatives. Examples are provided in the following section.

**Primary generator and parameterization process**

Focusing on the satisfaction of the primary goal of the design at hand (namely the improvement of the thermal performance of the atrium), the numeric analyses described above enabled the quantification of a suitable distribution of thermal mass across the vertical levels of the atrium. This information allowed to identify a first numeric rule based on which geometric options were to be designed. Various primary generators and related parameterization processes were developed to explore different design directions responding to this rule. Within the boundaries of this rule, additional aspects were considered in order to enhance the thermal benefits and to include other criteria, such as structural performance and daylight. The primary generators were developed considering the thermal benefits of exposing the mass to winter solar radiation and protecting it from the summer one. Additionally, they were developed considering that the heat accumulated during the winter days from the atrium should be released toward the surrounding areas (back areas), which is where the thermal benefits are especially required. Based on a shadow analysis in Ecotect (Autodesk), the areas irradiated in summer were distributed along all the levels of the atrium on its north, east and west sides; while the areas of the atrium irradiated in winter were located on the north side of the top level of the atrium only. These latter areas were therefore chosen for distributing the thermal mass. The other criteria were addressed within the subdomains of this design space (detailed arrangement, form, material and construction of the system), based on the absence of significant degrees of conflict with the main objective (thermal performance). Among the explored directions, one is exemplified here following, in which a set of sliding panels was proposed for the atrium; this resulted in a set of vertical panels in concrete, anchored along the north side and the top part of the south side. In this design option, the effect of thermal mass was focused on the diurnal fluctuations, leading to an active thickness of 10 to 15 cm for concrete. Considering that at the back of a 5 cm thick concrete panel the fluctuation is 72% of the fluctuation at the front and at the back of a 10 cm panel it is 51%, the need of releasing heat toward the back areas was to be addressed. Instead of rotating the heavy panels, fixed panels were combined with sliding thermal insulation to prevent nocturnal release of accumulated heat toward the atrium; and to favor the thermal behavior at the back of the panels. Figure 1 illustrates the principle.

Given the suitable distribution of thermal mass across the vertical levels, the general layout of the panels was treated as a layout problem, in which the requirements for mass distribution may correspond to several panel layout solutions. A parametric

<table>
<thead>
<tr>
<th>ventilation</th>
<th>shading</th>
<th>thermal mass</th>
<th>Max. operative temperature (deg. C.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>no</td>
<td>no</td>
<td>no</td>
<td>42.0 43.5 48.5 53.4</td>
</tr>
<tr>
<td>no</td>
<td>no</td>
<td>floor 5b</td>
<td>41.8 43.2 47.8 48.1</td>
</tr>
<tr>
<td>no</td>
<td>no</td>
<td>floor 5a, b</td>
<td>41.6 45.4 57.2 49.7</td>
</tr>
<tr>
<td>no</td>
<td>no</td>
<td>floor 4b, 5a, b</td>
<td>41.6 49.2 57.4 49.9</td>
</tr>
<tr>
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<td>no</td>
<td>floor 4a, b, 5a, b</td>
<td>41.6 50.3 59.6 51.0</td>
</tr>
<tr>
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<td>yes</td>
<td>floor 4a, b, 5a, b</td>
<td>34.8 34.8 39.6 41.1</td>
</tr>
<tr>
<td>10 ac/h</td>
<td>yes</td>
<td>floor 4b, 5a, bx2,</td>
<td>33.8 32.8 35.3 41.1</td>
</tr>
</tbody>
</table>

Table 2

Maximum summer operative temperatures of simulated variants for ventilation, shading and thermal mass distribution in the atrium.
model was established in order to investigate layout alternatives, both by decreasing the dimensions of the panels from the topmost to the lowermost part of the atrium, and by reducing the amount of panels in the same fashion. The latter scheme was preferred since it allowed for mostly uninhibited access to the atrium floor. In this option, the parameterization included the number and the dimensions of the panels (and therefore also affected their intervals), by generating a narrowed solution space. Figure 2 schematizes this option (and suggests possible alignment of the vertical panels with the structure of the roof).

A separate parametric process regarded the form of the panels. In this case, the parameterization aimed at a large solution space, later explored with the support of genetic algorithms during the solution-assessment phase. A number of requirements were specified with regard to thermal, functional and structural performance. Specifically, the total thermal mass should approximate the distribution that resulted from the thermal calculations and the panels of the topmost floors should be exposed as much as possible to the south, so as to receive adequate sun radiation during wintertime. Moreover, the form of the panels should be such as to allow for the sliding insulation panels to slide in front and behind the thermal masses. Finally, given that the panels covered the full height of the atrium and were anchored to the building structure in limited locations, efficient distribution of loads should be achieved, so as to minimize deflections resulting from their own weight as well as from occasional horizontal loads. A number of geometric properties affecting these requirements were parameterized; and a multi-objective optimization problem with three objectives and two constraints was formulated. The objectives were: the approximation of the calculated thermal mass distribution; the maximization of surface exposure to the south and the minimization of deflection under several load-cases. The constraints regarded the suitability of the shape for sliding panels and their curvature (for fabrication considerations). In the preliminary stage of the solution-assessment, the parametric model embedded finite element calculations (via Karamba3d), in order to obtain data about the stresses and displacements; simple geometrical operations were used to evaluate functional adequacy and exposure to solar radiation; and, a multi-objective genetic algorithm was used to search for non-dominated solutions. Given that the objective functions are conflicting, a set of non-dominated solutions was obtained. Selection among them was performed so that the selected one would perform adequately with respect
to all goals, as well as according to aesthetic preference. Figure 3 exemplifies the panels.

CONCLUSIONS
The paper presented the studies for an atrium in Shenyang, for which a number of design proposals were developed based on performance-oriented parametric investigations. The process was exemplified according to a parametric framework in which aspects affecting the thermal behavior of the atrium were discussed as design drivers. The process included an extensive number of performance simulations, whose role regarded both the strategy-definition phase and the solution-assessment phase. Larger emphasis was given to the strategy-definition phase, in order to highlight the relevance of preliminary knowledge. Additionally to this aspect, a conclusive remark is proposed on the crucial role played by performance simulations in enhancing the interdisciplinarity of the process, also by heightening the brainstorming across the various disciplines involved in the design process.

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