Performance-Based Design for Evacuation

ABSTRACT

The increasing number of crowd disasters has promoted a greater responsibility in designing buildings that allow a safe evacuation in case of emergency. Consequently, there has been an investment in developing tools that can assess the evacuation performance of a building. The employment of these tools has been essentially restricted to the final stages of the design process. This application is rather limited, as in final stages the architect is conditioned in the flexibility to implement relevant changes. Performance-Based Design (PBD) is a design approach that attempts to solve this problem. Using PBD, the architect integrates quantifiable performance feedbacks from the early stages of design. Hence, the architect is able to develop an informed design process, ensuring a final result that is an optimized version of the building, concerning pre-defined performance criteria.

In the development of a project, the architect continuously considers alternative exploration paths. However, in the context of PBD, the time and work required to evaluate design alternatives inhibit the number of variations that the architect is willing to try, thus constraining the exploration process. Parametric Modeling (PM) presents itself as a potential solution to this problem. In PM the architect, instead of defining a specific design, develops a model that defines a design concept. That model allows to automatically generate variations within that design concept.

In this work we explore the combination of PM and evacuation simulation tools, within the context of PBD. We expect that, in the combination of these emerging technologies, one can make a more profitable application of evacuation simulation tools in the development of safer architectural projects.

KEYWORDS

Parametric Modeling; Performance-Based Design; Evacuation; Simulation
I. INTRODUCTION

The increasing number of crowd disasters has awakened the need to evaluate buildings’ evacuation performance. Information available in building design guidance documents is insufficient to efficiently address safety requirements and traditional methods of assessing the evacuation performance, namely post-construction drills, raise practical, ethical, and financial problems, which calls into question their viability. The effectiveness of an evacuation can literally mean the difference between life and death for large groups of people. Driven by the urgency of improving safety in public spaces, and the inadequacy of existing mechanisms to assess buildings’ evacuation performance, evacuation simulation has been gaining a lot of attention in recent years.

Evacuation simulation tools are mainly applied in final stages of the design process, to assess the building’s safety performance. However, the performance of a building is strongly determined by decisions made in initial design stages and, in final stages, there is not enough flexibility to implement relevant changes in the design. Performance-Based Design (PBD) is a design approach that attempts to solve this problem. Using PBD, the architect integrates quantifiable performance feedback from the early stages of design. Hence, the architect is able to develop an informed design process, ensuring a final result that is an optimized version of the building, concerning pre-defined performance criteria.

The major difficulty in resorting to simulation tools to drive the design process is that, on providing evaluation results, they do not inform on how to modify the building to improve performance. On the other hand, it is in initial design stages that architects consider the largest number of design possibilities. However, the time and work required to develop different versions of the model for testing purposes inhibit the number of variations that the architect is willing to try, thus constraining the exploration process.

On the other side, there is a modeling paradigm, known as Parametric Modeling (PM), in which the architect, instead of defining a specific design, develops a model that defines a design concept. That model allows to automatically generate variations within that design concept. In this work we explore the combination of PM with evacuation simulation tools, within the context of PBD. By resorting to PM and evacuation simulation tools, one is able to test a wider sample of design alternatives and perform an informed design process regarding evacuation performance.

II. LITERATURE REVIEW

1. PARAMETRIC DESIGN

Parametric design is a design paradigm that has gained a lot of attention in architecture (Puusepp, 2011).

In Parametric Modeling (PM), instead of creating one design solution and changing it by direct manipulation, as in conventional design tools, the designer develops a generic model which accommodates variations according to a particular design logic (Woodbury, 2010).

The construction of the parametric model is done through associative geometry, i.e. the object is defined through its constituent elements and the relationships between them. This associative geometry implies the establishment of a hierarchy of dependencies, where “some geometric attributes are expressed through independent parameters, which act like inputs to the model, while other attributes receive data from them and are dependently variable” (Turrin, Von Buelow, & Stouffs, 2011, p. 660). The chain of dependencies is responsible for the propagation of changes in the model: changing the input parameters will cause a coordinated
global update, generating a variation which maintain “the essential conditions of the topological relationship” (Oxman, 2009, p. 9). The ease of generating model variations allows and encourages the designer to explore a broader design space (Nicholas & Burry, 2007). In modeling a parametric system, the designer has two tasks: defining schemata and constraints, and find significant instances among the solution space (Aish & Woodbury, 2005). These tasks are also usually presented as the disadvantages of parametric design (Woodbury, 2010). First, there is a bigger effort in parameterizing a model than just representing a design. It requires a prior study in order to capture the guidelines and constraints that bind the design together and hold the variations the designer wants to explore. The second task corresponds to the identification of valid or relevant instances of the parametric design.

2 PERFORMANCE-BASED DESIGN

The design task is interdisciplinary, as each architectural project must integrate and satisfy requirements from different fields (Turrin et al., 2011). Traditionally, in the conceptual phase, only few of those requirements are considered, which mainly address aesthetical and functional performances, postponing other disciplines to later stages of the process (Shi, 2010; Turrin et al., 2011). Performance-Based Design (PBD) is a design approach in which the designer emphasizes the building’s quantifiable and physical performances without neglecting functional and aesthetical requirements (Kolarevic, 2004; Shi & Yang, 2013; Turrin et al., 2011).

PBD arises from the integration of design synthesis with design evaluation processes. Design synthesis supports generation and transformation of a geometrical model, while design evaluation supports analytical evaluation of the design’s performance, based on a simulation of its behavior. In the combination of these two processes, in the context of PBD, the design generation is oriented by performance evaluations. PBD has an active attitude regarding performance criteria, instead of a reactive one.

In a PBD approach, the architect develops a model, which is then evaluated on the simulation program, the architect then analyzes the results and changes the model accordingly in order to improve the performance of the building. It is an iterative process, composed of synthesis-evaluation-analysis cycles, converging step-wise to a better performing solution (Oxman, 2009).

2.1 SYNTHESIS

There are different methodologies for performing design synthesis, ranging from manual manipulation in CAD tools to parametric design. The choice of one methodology over another lies on the complexity of the task and on the operator’s skills. More complex tasks require greater control over the tools. However, as the tools grow in the level of control they provide to the user, the expertise they require also increase, thus sometimes the user is restricted on the range of tools to choose from.

In context of PBD the focus is on experimenting design alternatives. Hence, PM have been pointed out as one fundamental ingredient in the advancement of PBD. The aptitude of rapidly producing a solution space allows one to experiment performance analysis in design alternatives, and compare results (Gerber, Lin, Pan, & Solmaz, 2012). In developing a parametric model, in the context of PBD, the main goal is that the model allows variations of key aspects that affect the performances being analyzed. The parametric model should not only reflect design formal intentions as should also be meaningful regarding performance requirements (Turrin et al., 2011).
2.2 EVALUATION

Design evaluation concerns the assessment of the performance of a design solution, based on a simulation (Kalay, 2004). A simulation is an imitation of an operation of a real-world system, either done by hand, or computer. It implies the development of a model which, once validated, can be used to investigate the behavior of the system (Banks, Nelson, Carson, & Nicol, 1984). This analytical model is a simplification of the system, according to the subject of investigation (Law & Kelton, 1991). Unfortunately, analytical models do not coincide with the models produced in modeling tools, and in most cases cannot be directly extracted from them since not only programs have portability issues among them, causing information losses (Branco, 2017), but often analytical models also require additional information that is not available in geometric models.

The potential to evaluate different scenarios and the success of the PBD is dependent on the use we make of the collected information from evaluations. Defining the next iteration inputs based on previous analysis outputs and according to pre-defined performance targets is not a trivial task. In the context of shifting from a conventional use of simulation tools to a context of PBD it is useful to resort to decision support and optimization techniques (Malkawi, 2004).

2.3 ANALYSIS

There are different mechanisms through which designers can collect information from evaluation results. The most intuitive approach is to test scenarios of interest and make decisions based on the comparison of results. However, in only testing specific design solutions, one becomes restricted to choose among the tested ones, taking the risk of missing on better performing alternatives that were not tested. Additionally, with increasing number of potential variations, the identification of scenarios of interest becomes a challenging task.

Sensitivity analysis (SA) is a mechanism in which the designer, based on evaluation results, collects information on the reliability and influence of design parameters on building’s performance. By understanding the interdependencies between model’s parameters and evaluation results, one is able to make a substantiated decision regarding all potential design variations, and not just those that have been tested. However, such an exhaustive analysis becomes a massive task with increasing number of parameters.

Thus, for more complex systems, architects resort to mechanisms that automate the exploration of the solution space, according to pre-defined objectives, i.e., mechanisms that drive an optimization process.

3 EVACUATION SIMULATION

Evacuation performance is a serious concern. Driven by the urgency of improving safety in public spaces, and the inefficiency of both regulations (Kobes, Helsloot, de Vries, & Post, 2010; Pan, Han, Law, & Latombe, 2006) and post-construction drills in assisting in the design of safer spaces, there has been increased efforts in the development of evacuation simulation tools. Scientific progress allied to the growth in computational power have led to the development of new modeling and simulation tools.

In the development of evacuation simulation models one needs to contemplate human behavior. Modeling human behavior is not a trivial task, as there are numerous factors that influence a person’s behavior and a lot of uncertainty associated with these factors. Yet, given the relevance of modeling human behavior, that extends beyond the scope of architecture and evacuation, it is not surprising to see the emergence of several different
modeling approaches. These different approaches vary in the method through which they cope with the different factors that affect human behavior. The main obstacle in the development of these models is the acquisition of data for calibration and validation (Schadschneider, Klüpfel, Kretz, Rogsch, & Seyfried, 2009). This difficulty is accentuated for panic behavior, as panic evacuations are unexpected and real life experiments are either dangerous or unrealistic (Almeida, Rosseti, & Coelho, 2011; Helbing, Farkas, & Vicsek, 2000; Jain & McLean, 2008).

Given the significant lack of information, evacuation simulation tools do not contemplate a great part of the characteristics of panic behavior. As result, in this models, qualitative behaviors of evacuation are observed, but with potentially large quantitative deviations. Even though they are not fit to accurately predict buildings’ evacuation performance in panic scenarios, they can be used in a comparative manner.

III. PROPOSED SOLUTION

4 PERFORMANCE-BASED DESIGN FOR EVACUATION

A PBD process is composed of cycles of synthesis, evaluation, and analysis, that promote an informed design process. Each of the subprocesses that compose the cycle, independently, can be employed in several distinct ways.

We propose a PBD that combines PM as a design synthesis method and evacuation simulation tools as evaluation mechanism and criteria. The mediation between both is achieved through SA (Figure 1).

Both evacuation simulation and PBD are hot research topics, with numerous examples of applications. However, the application of PBD with evacuation performance purposes is a rather unexplored combination, partially because practical evacuation simulation tools emerged only recently and, partially, because differently from other performance criteria that affect the everyday use of the building, evacuation performance is only relevant when a dramatic situation occurs.

We expect that from the combination of these emerging technologies, one is able to make a more profitable appropriation of evacuation simulation tools in the development of safer spaces. The integration of PM allows the rapid generation of model's variations, allowing to test a wider number of alternatives, thus performing a more sustained analysis. Concerning the analysis mechanism, SA, compared to other mechanisms, provides greater confidence in the results, as one has a general knowledge on the system's behavior.

5 CASE STUDY

In order to evaluate the validity of our proposed approach, we implement it in a fictional case study. We choose to develop a relatively simple case study that is easy to understand and work with, and that still can provide relevant information that can be extrapolated to more complex contexts.
From a context perspective, we define a building typology. Among buildings’ typologies that accommodate great concentrations of people, we choose to develop a shopping mall, due to layout flexibility and generic population.

In order to reduce the concept of a shopping mall to the essence relevant for evacuation performance, we only work with layout configuration and circulation elements, we also reduce the building to a single floor, and introduce regularity and symmetry in its configuration. From the convergence of these characteristics we develop a building concept which consists on a single story quadrangular shopping mall in which stores are placed in concentric rings, interleaved by corridors. In the center there is a central atrium, from which a set of main corridors breaks the rings and gives access to the building’s exit (Figure 2).

5.1 SYNTHESIS

We started by developing the PM of our case study. Figure 3 summarizes the model’s parameters, which are:

- number of transversal corridors;
- corridors’ width;
- size of the stores’ doors;
- size of the mall’s exit doors;
- number of shop-rings;
- area of the central atrium

5.2 EVALUATION

For the simulation tool, we reviewed existing software, namely Building Exodus, Pathfinder, Pedgo, Simulex, Simwalk, and Steps, and then filtered the list according to a hierarchy of criteria. As a result of the selection process, Pathfinder was the chosen tool to perform the evaluations.

For each layout configuration, it is necessary to construct the analytical model in the evaluation tool. The construction of the analytical model follows four steps: (1) generation of the CAD file, (2) importation of the file into Pathfinder; (3) identification of the analytical model components from the imported geometry, and (4) placement of agents in the model.

Since we resorted to a parametric description of the model, the generation of the CAD file was almost automatic, and it was only necessary to provide the values for the different parameters. Pathfinder allows the importation of CAD files: from the imported geometry, Pathfinder’s toolbox provides a group of tools that assist in the identification of the different circulation elements.

The last task in the construction of the analytical model is the provision of the number of
pedestrians to evacuate the building. Pedestrians are placed randomly in the model, by default, and pedestrians’ characteristics are also the ones assigned by default. Since we were only considering safety requirements, namely, evacuation times, and the number of parameters was not extensive, we were able to make an exhaustive analysis for each variable. Supported on the parametric model capability to easily create a substantial solution space, we evaluated variations of one parameter, while maintaining the others unchanged, repeating this process for all the parameters. An additional variable was included in all simulations - the number of people inside the mall. Since higher values of human concentration inside public buildings are usually related with emergency evacuation disasters, if we increase the number of users, the geometric implications on the evacuation performance will become clearer. This method also allows us to evaluate the maximum number of people that the building can afford.

5.3 ANALYSIS

After executing all the simulations, we organized the simulation results into a set of graphs (Figure 4).

From this first evaluation cycle we were able to draw some relevant conclusions. Globally, as the number of people increases, the effects of changing parameters on evacuation times are accentuated. Moreover, by the slope variation between different concentrations of people, it is possible to understand the relevance of each parameter. Although some variables revealed trends in behavior, such as the variables visible in Figure 4B, C, D, and F, others have a more complex and unpredictable behavior, as is the example of Figure 4E and A. This can be a result of the associative geometry of the parametric model: as the model is adapted geometrically, the combination of different and, sometimes, contradictory impacts on the evacuation performance leads to unexpected results. For a clarification of these situations we proceeded with a deeper analysis for this parameters. Regarding the parameter corridors width, considering the critical influence of the exit doors’ size in the evacuation performance, we performed another PBD cycle in which we analyze the impact of varying the corridors’ width accompanied by exit doors’ of the same size. From the analysis we could conclude that when the exit doors size match the corridors width, the evacuation performance turned out to be more linear.

We also analyzed the results obtained from the number of concentric corridors variable. Since by changing the number of concentric rings we affect the number of intersection areas, and considering that the width of the corridors influences the congestion on those intersections, we further explored the relation between the number of concentric corridors and different corridor widths. From the evaluation results we concluded that when the number of concentric corridors increases, the evacuation time also increases. If we increase the corridors’ width we can alleviate intersections and, when this happens, changing the number of concentric corridors becomes less relevant.

Regarding the modeled shopping mall, the analysis allowed us to conclude that for the optimization of the design’s evacuation performance we should:

- Minimize the number of concentric rings;
- Maximize corridor widths;
- Use exit doors with the same width as corridors;
- Maximize transversal corridors;
5.4 RESULTS

Even though the results of the study seem rather intuitive, it successfully demonstrated the relevance of the approach, as well as its limitations. Because in an architectonic project all the elements must be in consonance, when the architect changes one characteristic, the whole design must be adjusted. In the adaptation of the model to changes, different elements of the design are affected, which can have contrasting effects on the performance. Assessing and understanding the outcomes of design alterations is not straightforward. Hence the relevance of a mechanism that takes advantage
of design evaluations to support the design process.
In order to achieve an efficient analysis of simulation results, one has to perform multiple evaluations. In that context it was also demonstrated the relevance of PM in the generation of design variations. By the traditional means, we would not have been able to test as many design alternatives, and make such an exhaustive analysis.
On the other side, the construction of the analytical model, even though it is simplified by the evaluation tool, is a laborious and tedious task, inhibiting the number of evaluations one is willing to perform. It is also perceptible that the analysis of results through SA was feasible because we were working with few parameters. From the case study we can make assumptions regarding more complex designs. When the scale of the project increases, changing one parameter will necessarily require adjusting a wider number of design elements, which increases the difficulty on assessing the performance and establishing correlations. Additionally, for more complex designs, as the number of parameters increase, the amount of potential outcomes due to combinations of changing parameters (such as corridors' width and door size) increases exponentially. An exhaustive analysis of each parameter individually becomes impracticable.
Furthermore, with increasing design complexity, the relevance of PM is significantly accentuated. On the one side, testing design alternatives by the traditional means requires a lot of work in generating variations of complex models, thus, the PM capability to generate design variations increases in relevance. On the other side, since there are more interdependencies between models’ parameters, in order to draw relevant conclusions one may have to perform more evaluations., thus, the capability of PM to automatically generate variations is accentuated again. However, the relevance that the PM advantages receive in a complex design context is equivalent to the relevance that the disadvantages of constructing the analytical model receive. We’ve mentioned that the work implied in building the analytical model is one drawback of the case study. In increased complexity not only one has to construct a wider number of analytical models, but also, each analytical model requires more work and time in the construction.
In summary, the advantages and disadvantages identified for the case study are accentuated for more complex situations. However, as the complexity of the task increases the disadvantages may become so substantial that the cost of performing a fruitful PBD becomes prohibitive. Additional methods that simplify the construction of the analytical model and that assist the processing of the evaluation results may take the approach to the next level.

IV. CONCLUSIONS
In this work we proposed the combination of PM with evacuation simulation tools, within the context of PBD. The aim is to promote an informed design process, regarding evacuation performance. The integration of PM allows to test and compare a greater number of model variations, thus have a more sustained PBD process and, potentially, ensure a safer design solution, decreasing the number of casualties in case of accident.
To evaluate our proposal, we resorted to a hypothetical shopping mall as case study. The case study allowed the identification of the potential of the approach, as well as its limitations.
In the future we plan to explore the application of the approach in a real life context. In order to cope with the inherent complexity of a real project, we will have to adjust the workflow to include more sophisticated mechanisms. Firstly,
regarding the mediation between evaluation and synthesis, we will resort to optimization mechanisms, additionally we will consider multiple performance requirements in the optimization process. Secondly, regarding the communication between tools, we want to automate the construction of the analytical model, and also to close the PBD cycle, by automating the communication between the different tools involved in the process – evaluation tools, optimization algorithm and PM. Finally, we will explore the application of PBD throughout the entire design process, from initial concept to furniture.

Additionally, we would like to enlarge the scope of our approach by applying it in different contexts, such as conceive event venues.

REFERENCES


